Value Chain Concept for Power Electronics based Products

by

Julian Demetz

Submitted to the Sloan School of Management and the Department of Aeronautics and Astronautics
in partial fulfillment of the requirements for the degrees of

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and

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Abstract

Integration of renewable energy, general decentralization of generating power and a high degree of automation may trigger a technological change in grid infrastructure, away from electromechanical products and towards more flexible power electronics based products. Maschinenfabrik Reinhausen (MR), a premium manufacturer for specialized components and equipment for the electrical distribution and transmission grid, is seeking to expand its capabilities within the power electronics domain. The goal for this thesis was to provide MR suggestions for the design of a value chain for power electronics based products for the mid-voltage distribution grid market. Such suggestions have been developed based on the analysis of external market forces with Porter's Five Forces Model, the assessment of a possible level of vertical integration based on MR's current technical capabilities, and the analysis of uncertainties of market parameters with a NPV model and Monte Carlo Simulation.

The thesis shows further how the deployment of FMEA and reliability engineering can effectively address the high costs of power electronics based products and concerns of customers regarding the reliability of the technology.

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I dedicate my time at MIT and this thesis to my mother Ingrid, my father Helmar, and my sister Valentina. Without their support, patience and love I would not have gotten here.

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Chapter 1

Introduction

The thesis research is based on a problem statement formulated by the German company *Maschinenfabrik Reinhausen (MR)*. MR is a partner company of the *MIT Leaders for Global Operations* program since 2016. The main part of the research has been conducted in the period from February 2017 to August 2017 at the company's headquarter in Regensburg, Germany.

1.1 Maschinenfabrik Reinhausen (MR)

MR is a manufacturer of components for the regulation of transformers, and specialized equipment for controlling power quality in electrical distribution and transmission grids. Founded in 1868, MR has established itself as the market and technology leader in the field of electromechanical regulation systems for electrical power systems.In 1926 Dr. Bernhard Jensen, invented the high-speed resistor-type tap-changer that allowed the transmission ratio of transformers to be changed under load without interruption [1]. MR is the leading manufacturer of *On-Load-Tap-Changers (OLTCs)* and is serving all major manufacturers of regulating transformers. For certain, very demanding applications, MR is considered the only supplier to be able to deliver a suitable product. The long and continued history of technical innovation, highest manufacturing quality, proven reliability of its products, and a global presence have helped MR secure a dominant market position and made it a trusted partner to its customers.

However, MR has recognized that the ongoing changes in the electrical grid, like integra-

[1]Source: MR's company homepage (www.reinhausen.com)

tion of renewable generation, general decentralization of generating power and a high degree of automation will require the adoption and utilization of new technologies. The field of *power electronics (PE)* has been identified as such a technology and its successful adoption regarded as strategically critical for MR.

Chapter 2

Background

The goal of this chapter is to provide background information on transmission and distribution grids, challenges related to the integration of renewable energy, MR's role in this environment and the potential of power electronics to advance grid infrastructure.

2.1 The Distribution Grid and Current Trends

Before the start of penetration of wind and solar energy in the late 90s, electrical power used to be generated in isolated power plants outside inhabited areas. These power plants, based on conventional power sources such a nuclear, coal, natural gas but also on renewable sources such as hydro, have capacities of more than 1000 MW and hence enough to supply electricity to towns and even larger cities. Once generated, the power needs to be made available to consumers at home or in businesses. This is accomplished in two steps:

1. The electrical energy is transported from the generating station through a substation via a transmission grid to a distribution substation.

2. From the distribution substation the electrical energy is distributed via a distribution grid to the individual consumers.

The transmission grid is operated at high voltage alternating current (AC, as opposed to direct current or DC) with voltage levels greater than 110kV and up to 765kV [1]. High voltage is used in order to minimize losses when the electrical energy is transported over long distances. The distribution grid, on the other hand, is operated at medium or low voltage levels commonly ranging from 34.5kV down to 600V [2]. These are referred to as primary or secondary distribution grids.

Electromechanical power transformers are used to step up or step down the voltage from one level to the other. Step-up transformers at the generating station transform the voltage of the electrical power delivered by the generator of the power plant from the generator voltage of around 20-22kV to the aforementioned high voltage levels. At the distribution substation the electrical power is then transformed to the lower voltage levels by step-down transformers. Arrays of circuit breakers and busbars can then split and direct the electrical power to the designated consumer. A diagram of such an electric power system is visualized in figure 2-1.

Since storage capacity in current electrical systems is still very limited, it is required that

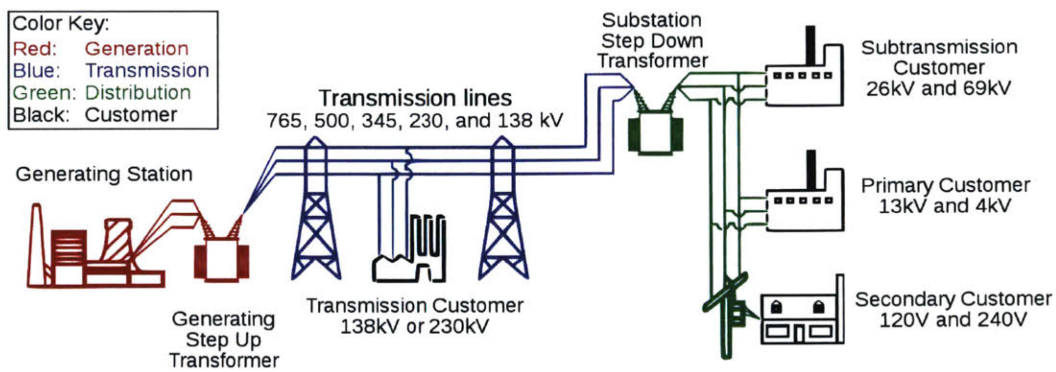

Figure 2-1: Diagram of an electric power system *(Source: United States Department of Energy)*

electrical energy production matches demand (load) at all times. This is not only important to satisfy the energy demand itself, but also to maintain a stable grid. Current electricity grids have been designed to handle the variable nature of loads, which are following a cyclical pattern over the course of the day. In times where the sole source of electrical energy were the large centralized power plants, supply could rather easily be adjusted to match load variability by slightly lowering or increasing the plant's output. This way grid voltage levels and other important grid stabilizing mechanisms, such as the supply of reactive power, could be maintained.

Today, wind and solar energy add new challenges for grid operators through supply-side variability. Driven by renewable energy legislation, energy generated by wind and solar often has priority to be fed into the grid over energy coming from conventional sources. However, the availability of these sources is dependent from the presence of wind and direct sunlight radiation without obstruction by clouds. These are major sources of variability. The presence of this additional wind and solar power on electric grids can cause coal or natural gasfired plants to turn on and off more often or to modify their output levels more frequently to accommodate changes in variable generation [3]. As a consequence, also the transmission and distribution substations are subject to higher wear and tear, since the distribution of power from different sources at unsteady intervals requires faster and more frequent switching at the substations. Since wind and solar power plants are mainly feeding into the distribution grid this becomes especially relevant for the distribution substations. A general layout of an electricity grid with decentralized power generation is visualized in figure 2-2.

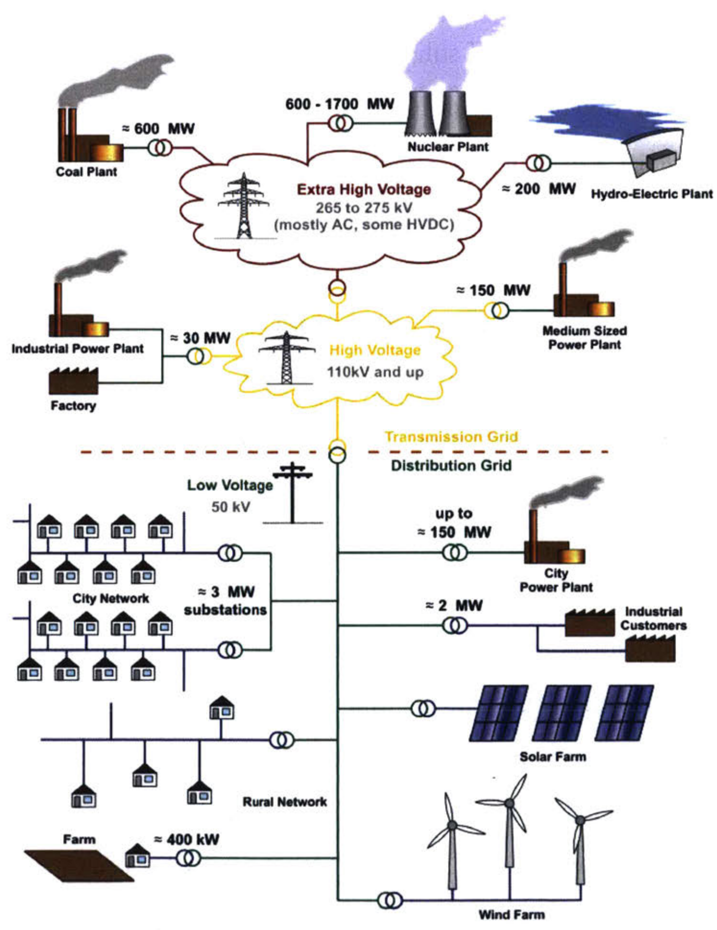

Figure 2-2: General layout of electricity networks. Voltages and depictions of electrical lines are typical for Germany and other European systems (*Source: wikimedia.org, authored by MBizon, via Wikimedia Commons*).

2.2 Applications of Power Electronics in the Distribution Grid

Power electronics based systems are currently regarded to be in the best position to satisfy the more demanding power control requirements originating from supply variability. The accommodation of these requirements is necessary to fully unlock the benefits of solar and wind: clean and cheap energy.

Power electronics is the application of solid state electronics (semiconductors) to the control and conversion of electric power. The simplest semiconductor is a diode, a component which is able to block or release current flow depending on a voltage applied to the diode itself and hence can act as a switch[4]. In actual power electronic devices more sophisticated semiconductor switches such as thyristors, metal oxide semiconductor field effect transistors (MOSFETs), and insulated gate bipolar transistors (IGBTs) are used. The advantage of power electronic over electromechanical switches is not only their ability to perform faster and more frequent switching (milliseconds versus several seconds and frequencies of several hundred MHz), but also their compact size (cigarette package size for high power modules versus shoe box size and larger for electromechanical switches). This allows the development of compact and very versatile converter topologies such as modular-multilevel converter (MMC), solid state transformer (SST), or unified power flow controller (UPFC) [5]. These converter systems can, through the transformation of AC into DC and back into AC, manipulate incoming power inputs to match almost any requirement on the output side in terms of phase-angle, frequency, current and voltage. On top of that, power quality functions, such as the supply of reactive power and harmonic filtering can be realized with these devices. On the downside, power electronics are more expensive and less reliable than electromechanical systems. However, new high performance semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN), and continued growth of renewable energy may eventually push conventional power transformers to their limits and make power electronics economically viable.

2.3 MR and its Role as a Supplier of the Transformer Industry

Today, regulating transformers with steel core and copper windings are the primary devices used in distribution networks around the globe to transform voltage and provide isolation [1]. The technology has matured over decades without major changes which led to low costs and a very high degree of reliability. A key component of regulating transformers is the on-load-tap-changer or OLTC. Ideally, power supply matches power demand at any time and voltage levels at the distribution substations and hence at each winding of the power transformer are supposed to be constant. If this were the case, no (voltage) regulation would be needed and the transformer could be designed with a fixed ratio of input voltage and output voltage V_1/V_2. In reality, however, this is not the case. Latencies, losses and other instabilities require that the transformer ratio can be adjusted to a certain extend, typically in the range of $+/-10\%$. This functionality is provided by the OLTC, a motorized, electromechanical device which is able to change the ratio of a transformer by adding or subtracting turns from either the primary or the secondary winding. The transformer is therefore equipped with a regulating or tap winding which is connected to the OLTC [6]. An MR Oiltap® M® OLTC is pictured in figure 2-3.

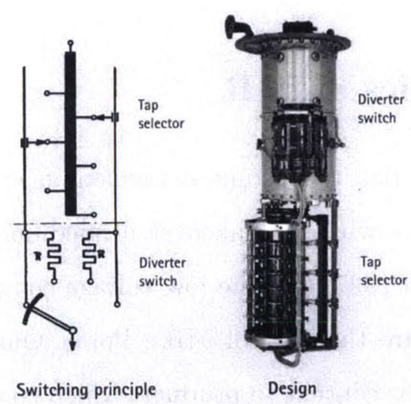

Figure 2-3: OLTC design principle: diverter switch with tap selector of OILTAP® M® (Source:[6])

MR's OLTC value chain is highly vertically integrated. The key mechanical subassembly groups such as diverter switches, tap selector mechanism, and glass-fiber insulating shell are

[1]Isolation is the ability to couple one circuit to another without the use of direct wire connections. Transformers provide this important feature by design [4]

engineered, developed and manufactured in-house. A highly skilled workforce has perfected mechanical manufacturing process such as metal milling, and welding but also winding and curing of fiber composite material over time to ensure meeting the high customer expectations. Hence, production starts for many of these products with the raw materials, such as metal or copper sheets, glass fiber spools and resins. Casted components are sourced but undergo several steps within MR's manufacturing line before being ready for assembly.

Without a doubt the OLTC is a critical product for regulating transformers and in lack of alternatives for grid infrastructure demand for both power and distribution transformers has been healthy in the past and is projected to be growing with a compound annual growth rate of 3.9% between 2015 and 2020 [7]. Furthermore, transformer manufacturers are unwilling to make compromises on the quality of the OLTC and hence willing to pay a premium for it. The OLTC has experienced only small incremental changes over the past five decades because the technology is so reliable that major changes were not required and customers did not ask for it. This favorable market environment and its own abilities have made MR a very successful company, both technologically and financially.

However, today's strength could turn into MR's weakness in the future if traditional transformers were substituted by power electronics devices. Since OLTCs are still MR's most important product group, declining demand would hit MR's financial position.

2.4 Power Electronics at MR

MR is of course aware of the risk to become dependent from one product group and has started to diversify its business with the takeover of medium-voltage reactive power compensation from Siemens AG in 1997, and the low voltage compensation systems from AEG in 2003 [2]. These businesses are the core of MR's Power Quality division (MR PQ). The term power quality refers in this context to products which contribute to the stabilization of the grid by ensuring that causes for instabilities such as harmonics, lack or excess of reactive power, are compensated (hence compensation devices). These instabilities can originate from industries which pull a large amount of power from the grid such as electric steel or large manufacturing plants, but are also induced by wind and solar energy plants. Modern wind turbines, for instance, require to operate at a fixed power factor[3], often equal to 1, and

[2]Source: MR's company homepage (www.reinhausen.com)

[3]power factor is the ratio between active and apparent power in AC circuits, also see 4.10

hence are unable to supply reactive power to the grid.

Current compensation systems offered by PQ are, among others, static VAR compensators (SVC), static synchronous compensators (STATCOM), and filters. The active components of these systems are often realized with power electronics, e.g. thyristors. Through it's PQ division MR has built first expertise in power electronics. Recently, it has establishment a PE competence center within PQ, which is tasked to define MR's future roadmap in the space and drive research and development of converter based systems such as SST, UPFC and others.

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Chapter 3

Problem Statement

Today MR offers with their OLTC product lines critical components for regulating transformers, but does not offer products which cover the full functionality of regulating transformers. This would change if MR were to develop and commercialize PE-products such as SSTs, since SSTs technically include the functionality of regulating transformers. With this step, MR moves from being a manufacturer of intermediate products to being a direct supplier to end customers and hence, potentially tapping into the business of their current OLTC customer. This step down the supply chain is considered forward integration [8] and is illustrated in diagram 3-1.
For MR it raises the question whether current OLTC customers would feel threatened and in consequence stop buying MR's OLTCs as an act of retaliation. This is certainly something MR does want to avoid and a question which needs to be answered before major investments are undertaken to develop the intended PE-products.

For the thesis research it was requested to investigate the following two aspects:

1. Power electronics are based on semiconductor components which require scale to be manufactured economically. Further, the development and manufacturing of PE-based systems require a different labor skill set than electromechanical products. Which level of vertical integration for specific PE-based products would make economic and strategic sense for MR? Should MR build a similarly high degree of vertical integration as in its OLTC business?

2. The technology shift from electro-mechanical devices towards power electronics enables MR to develop products, such as solid state transformers, which may make traditional

transformer technology obsolete in the long term. This imposes the risk of cannibalization of own products, such as the OLTCs, and direct competition to the transformers manufactured by current customers. Additionally it may raise competition with current suppliers, who are already active in the PE space (see also 5.1). How can these risks be evaluated and mitigated?

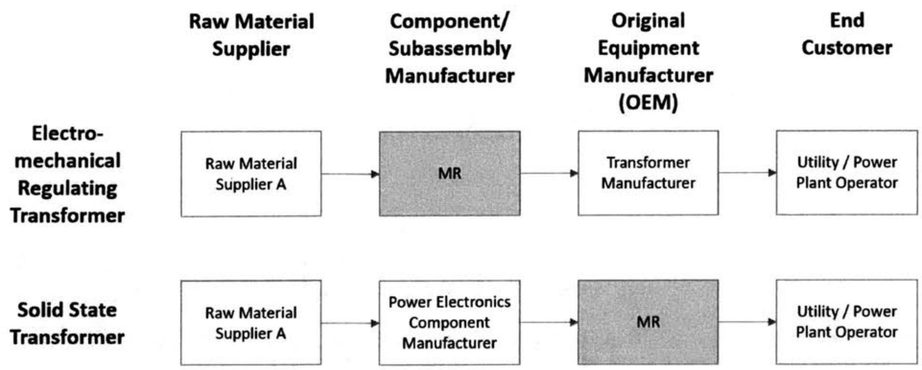

Figure 3-1: Forward integration in the transformer value chain

Over the course of the project it has been identified that cost and reliability of the technology are major unknowns and currently inhibit the proliferation of the technology and related products. It hence has been decided to investigate a method that enables the company to quickly evaluate the reliability of PE-based systems and use the results to realize cost reductions through optimized spare part/maintenance strategies, and/or by highlighting over-engineered components (which can be replaced with cheaper ones).

The capability of supplying a reliability study to customers is of special interest to MR, because customers more frequently ask for such studies so they can provide them to regulators (to show compliance with current regulations), and lenders (to ensure them, that their capital is invested in a quality product).

Cost reductions through spare part optimization may benefit either MR or its customers depending on who owns the spare parts. If the customer were to own the spare parts, MR can create value for the customer by advising them on an optimal spare part strategy. This could just strengthen the customer relationship but also be charged as an additional service and hence generate profit for MR. If MR were to own the spare parts, e.g. in service contracts where a technical availability is guaranteed and customers pay a yearly flat rate to the service provider, spare part optimization can improve MR's profit from that specific contract. In either way, spare part optimization generates value which can be monetized.

3.1 Approach and Methodology

After an initial scoping phase it became clear that *level of vertical integration* 1 and *market reactions* 2 are closely connected and that the value chain concept will be heavily influenced by the market environment in which the future PE-product shall compete. Hence, this leads to focus first on the analysis of market reactions and then on the formulation of suggestions for a PE value chain. The individual problems are approached as follows:

The study of market reactions, more precisely of reactions of customers and suppliers, is a qualitative analysis which provides answers to the following questions:

- Would current customers of on-load-tap-changers stop buying from MR if MR were to forward integrate in the field of power electronics? If yes, which moves would trigger retaliation?
- Would current suppliers stop supplying to MR if MR were to forward integrate in the field of power electronics? If yes, which moves would trigger retaliation?

In answering these questions it is essential to evaluate the market power of each player, since this is a critical factor in assessing whether a player can actually afford retaliation. *Porter's five forces* 4.3 framework will be adopted to assess market power of customers and suppliers. Different scenarios under which retaliation could be possible will be described to help answering the above questions.
Further, this work attempts to assess whether a player could benefit from a first-mover advantage (FMA). A case study based on a simplified PE-product will showcase the financial impact of a late or early entrance in a market with first-mover advantage.
Finally, the inputs will be summarized in a suggestion for the future PE-value chain, highlighting what are thought to be differentiators for a successful market entry with the envisioned PE-products.

For the evaluation of the system reliability a *Failure Mode and Effect Analysis (FMEA)* and a subsequent reliability analysis will be piloted on a current customer project, a Static Var Compensator (SVC) for a large steel plant. The FMEA will focus on the active functional groups, the Thyristor Controlled Reactor (TCR). The results from the FMEA will then be used to perform the preliminary reliability study of the system. A reliability block diagram (RBD) will be modeled, from which we derive common reliability metrics such as *Mean Time To Failure (MTTF)*, *Mean Time To Repair (MTTR)*, and *System Availability*. The reliability model shall then be used to showcase the optimization of the spare part strategy for the system with focus on minimizing the cost of system downtime.

Due to the different natures of the two main topics, the thesis is structured in two parts: the first part will cover market reactions and subsequent definition of a value chain concept and the second part will cover the technical content related to FMEA and reliability analysis.

The thesis roadmap in figure 3-2 illustrates the interaction between the chapters and appendices.

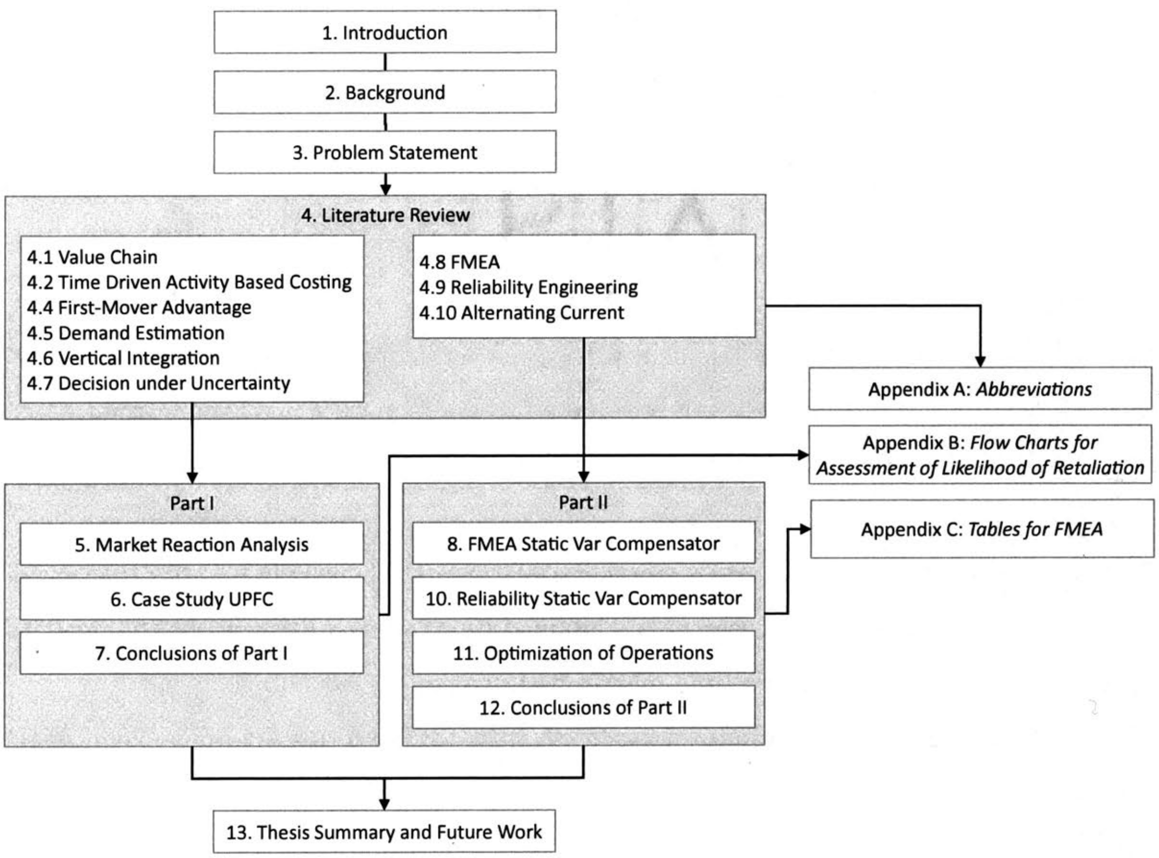

Figure 3-2: Thesis roadmap showing interactions between chapters and appendices

Chapter 4

Literature Review

This chapter will describe the current common approaches to value chain analysis and important related topics, such as Porter's five forces and first-mover advantage (FMA) found in literature. It also includes basic technical concepts to better understand the technical systems analyzed in the second part of this thesis.

4.1 Value Chain by Porter

Porter, 1985 [9] first described the concept in his book *Competitive Advantage: Creating and Sustaining Superior Performance.* The underlying idea is the view of manufacturing (or service) organization as an interconnected system of different stages, in which the output of one stage is the input to the next stage. Transformation processes in each stage are adding value to the product flowing through the value chain. These transformation processes themselves consume resources, such as money, labor, materials, equipment, facilities, and overhead. The value added across all stages of the value chain is supposed to be larger than the cost of consumed resources, creating a positive margin. The value chain is divided into the primary activities *inbound logistics, operations, outbound logistics, marketing & sales, service* and the supportive activities *firm infrastructure, human resource management, technology, and procurement.*Figure 4-1 shows the classic illustration of Porter's value chain.

A firm itself can have multiple value chains, e.g. one value chain for each product or product group. These value chains themselves are connected upstream with the supplier's value chain, and downstream with the customer's value chain. This is an important point to take into account when assessing such options as forward or backward integration. The

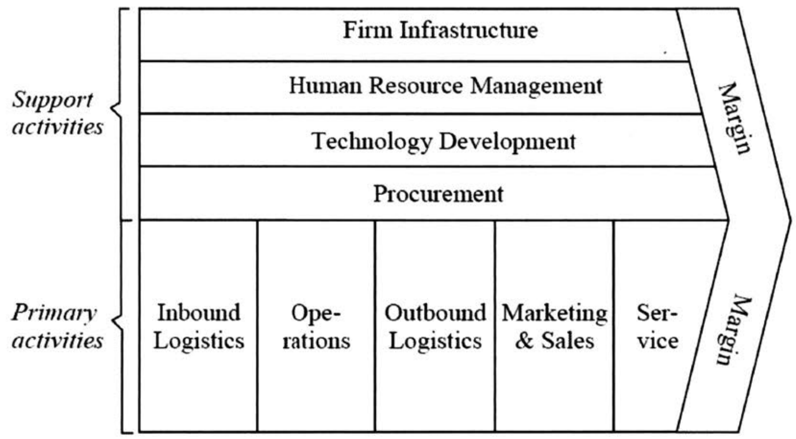

Figure 4-1: Michael E. Porter's Value Chain

concept of embedded value chains in represented in figure 4-2.

The metric by which added value ($\Delta value$) at each stage is measured is simply the difference

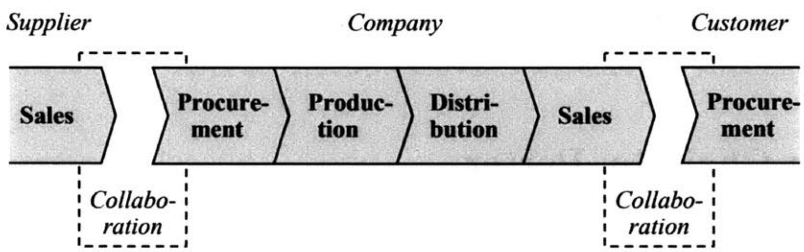

Figure 4-2: A firm's value chain conncted to supplier's and customer's value chains, Source: [10]

between the cost of a product at the beginning of a stage and the price which can be charged to the next stage downstream [11]:

$$c_{i+1} = c_i + \Delta value$$

. This is straightforward, however it hides the underlying reason(s) why a downstream stage is actually willing to pay more for the product after it passed the upstream stage's transformation process. As pointed out by Jodlbauer, 2012 [12] it is beneficial for each value chain participant to understand the value drivers that are important to its direct customer and the end-customer to establish value based relationships required to put both supplier and customer in a strong competitive positions. Jodlbauer, 2012 [12] lists the following examples for value drivers:

- Cost reduction
- Accessing new technologies
- Accessing new markets/customers
- Specialist skills to enable the organization to focus on the core business
- Increase speed of new product development/time-to-market
- Spreading risk across multiple partners

Ultimately, every organization seeks to maximize the value added by its value chain: $max(\Delta value)$.

4.2 Time Driven Activity Based Costing

In order to assess and evaluate value chains from a quantitative perspective, it becomes important to be able to measure the costs accrued in each of the stages of the value chain and its individual activities. A common method to measure cost is *activity based costing* or simply *ABC*. ABC uses the total cost of a functional unit over a defined time period, e.g. a department, and tries to break it down to the single activities performed in that department. To do so, surveys are conducted to identify the percentage of their time employees spend on a single activity. Divided by the activity quantity over the same period this yields cost-driver rates and unit times for each activity. An example calculation for a service back-office operation is shown in figure 4-3. The main downside with this (top-down) approach is that the surveys usually ad up to 100%, which means inefficiencies in the activities are hidden and their unit time overstates the actual amount of time required to perform the activity.

To overcome this, Kaplan, 2006 [13] suggest to adopt Time Driven Activity Based Costing,

Employees	4
Hours per day	8
Days per week	5
Minute per week	9600
Department cost per week	$ 8,000.00
Cost per minute	$ 0.83

Activity	% of Time Spent	Assigned Cost	Activity Quantity	Cost-Driver Rate	Unit time (min)
Schedule service orders	50%	$ 4,000.00	400	$ 10.00	12
Issue purchase order for spare parts	20%	$ 1,600.00	400	$ 4.00	4.8
Review completed service orders	30%	$ 2,400.00	320	$ 7.50	9
	100%	**$ 8,000.00**			

Figure 4-3: Activity based costing for service back-office operations

a variation of ABC. Managers will assume a practical capacity of their department, e.g. 80% of the theoretical available time and compute a cost per minute for the department. Then, for each activity the unit time is defined or measured. Together with the activity quantity this yields the total (actual) minutes the department spent on a specific activity and, multiplied by the actual cost per minute the total cost of the activity. This approach further reveals which share of the actual practical capacity has been translated into productive work. In the example in figure 4-4 we can see that only 7440 minutes of the 7680 minute, and hence 97%, have been used for productive work.

Time Driven Activity Based Costing is hence a bottom up approach, since the time required

Employees	4
Hours per day	8
Days per week	5
Minute per week	9600
Department cost per week	$ 3,000.00
Assumed practical capacity	80%
Actual practical capacity (min)	7680
Actual cost per minute	$ 1.04

Activity	Unit Time (min)	Activity Quantity	Total Minutes	Total Cost
Schedule service orders	9	400	3600	$ 3,750.00
Issue purchase order for spare parts	4	400	1600	$ 1,666.67
Review completed service orders	7	320	2240	$ 2,333.33
			7440	**$ 7,750.00**
	Productive share of practical capacity		97%	

Figure 4-4: Time driven activity based costing for service back-office operations

for an activity is measured directly. It is better suited for the analysis of value chains, since it allows to differentiate between productive work and inefficiencies. It should be noted however, that not all productive work is also value adding work. In the example, the activity *review of completed service orders* may very well be argued to not be value adding for the end-customer.

4.3 Porter's Five Forces

Value chains are embedded in a competitive market environment and hence, a company needs, in order to be successful, take the market environment into consideration when designing the value chain. The arguably most prominent model to analyze competition is Porter's five forces model, which has first been introduced by Porter, 1998[14] and then further discussed in Porter, 2008 [15]. Porter derives five forces to assess the intensity of the competition and hence the attractiveness of a certain market. These forces are:

1. Bargaining power of suppliers
2. Threat of new entrants
3. Bargaining power of buyers
4. Threat of substitutes
5. Industry competition

Porter postulates, that the stronger the forces are, the more competitive and therefore the less attractive an industry tend to be. An industry with perfect competition, and hence no profitability (marginal cost equals demand's willingness to pay), is the most unattractive scenario within this framework.
In Porter, 2008 [15] Porter provides a series of questions which help evaluate the strength of each of the five forces.

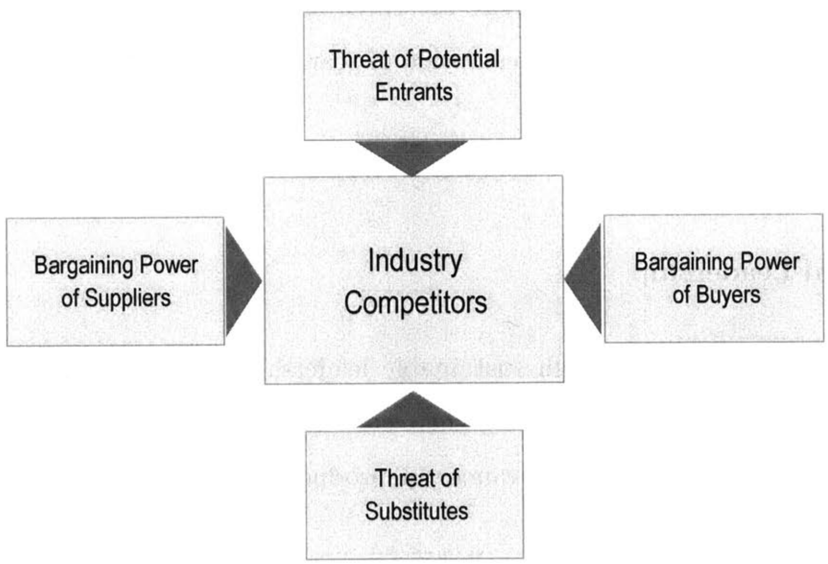

Figure 4-5: Porter's five forces

4.4 First-Mover Advantage

Porter's fifth force, industry competition, puts our focus to another important dimension when evaluating if and how to develop a new product or product category (in our case PE based products): the timing of entry in a new market relative to competition. This can happen as a first entrant before any competitor, together with competition, or as a follower, and hence, after at least one competitor. There may be benefits to enter a market first. This management concept is known as *first-mover advantage* (FMA) and depends on a variety of circumstances as we will see further down.

4.4.1 Mechanisms of First-Mover Advantage

First introduced by Lieberman, and Montgomery, 1988 [16], the FMA is the advantage gained by the first entrant of a market or segment. If the first entrant is not able to get an advantage of its first-mover status, followers have the opportunity to compete more effectively and ultimately do better than the incumbent. This is then referred to as as second-mover advantage.

According to Lieberman, 1988 [16] there are three mechanisms leading to first-mover advantages: technological leadership, preemption of scarce assets, and switching costs / buyer choice under uncertainty.

Technological Leadership

A firm can gain advantage through sustainable leadership in technology. This can either happen through learning and experience, where costs fall with cumulative output, or through success in patent or R&D, where advances in product or process are a function of R&D expenditure.

If a company can keep the learning proprietary and this way continuously lower their unit cost, then it will be difficult for another firm to compete profitably.

If a company achieves a technological break-through and is able to protect this break-through with a patent it can create a barrier to deter competitors from entering that market (at least for a certain time period). This can be observed in the pharmaceutical industry, where the successful development, approval and patenting of the active component of a drug can secure the patent holder a monopoly status in that segment. However, Lieberman, 1988 [16], also found that in most industries, patents confer only weak protection, are easy to work around, or have transitory value given the pace of technological change.

Preemption of Scarce Assets

The first-mover firm may be able to gain advantage by preempting rivals in the acquisition of scarce assets. These assets, which already exists and are not created by the first-mover, may be physical resources or other process inputs, or relate to positioning in space, including geographic space, product space, shelf space, etc.
Preemption of input factors can happen if a firm has superior information and can e.g. source assets at costs below those that will prevail later market. This includes natural resource deposits, prime retail or manufacturing locations. Preemption of locations in geographic and product characteristics space can happen if the first-mover can select the most attractive niches and may be able to take strategic actions that limit the amount of space available.

Switching Costs and Buyer Choice under Uncertainty

Buyers may incur switching costs when changing supplier. These switching costs can arise from transaction costs incurred when a buyer adapts to a seller's product, e.g. time and resources spent on qualifying a new supplier, software for a new operating systems, training of employees to use a new machine. A late-entrant needs to invest in extra resources in order to attract customers away from the first-mover firm, e.g. buy providing substantial discounts or offering services for free.
A related topic deals with imperfect information. If a customer is satisfied with the current (the first-mover's) product and is unsure about the objective quality or added value of the second-mover's product, they may rationally stick with the current product or service. Brand loyalty of this sort may be particularly strong in low-cost "convenience-goods", such as razors [17].

However, for any example of a first-mover being able to gain a dominant position in the market there is most likely a counter example where the first mover fails. Apple, for instance, was not the first company to enter the market of portable hard-drive-disc based digital music players. HanGo Electronics sold its PJB-100® already in 1999 ,two years before Apple launched its iPod® in 2001. Nevertheless it was Apple, who dominated the market in the years to come. Neither was Amazon the first online retailer of books. Jeff Bezos started Amazon in 1994, but Charles M. Stack had launched Book Stacks Unlimited or books.com already in 1992.

These examples show that it is not sufficient to be first in a market to be successful, but that other factors are important as well. Markides, 2013 [18] emphasizes that the right business model is critical to initial and sustainable success. The first mover needs to undertake a series of actions that help grow the market from a niche to a mass market to increase its probabilities to succeed and deter followers from enter. Such actions can be:

- Target the average customer rather then early adopters.
- Support low prices by driving down costs.
- Reduce customer risk through branding and communication.
- Build the distribution that can serve the mass market.
- Create alliances with key suppliers and producers of complementary goods.
- Protect the market by exploiting first mover advantages.

Blank, 2010 [19] points out, that in order to be successful a firm must understand in detail the customer problem and how the firm's product is going to solve it. This is often where first-movers fail and fast-followers learn by observing the first-mover fail.

4.4.2 Likelihood of First-Mover Advantage

Suarez and Lanzolla, 2005 [20] provide a framework which helps firms to evaluate the likelihood of a FMA in dependence of the pace of the technological evolution in one market and the pace of the market evolution. The framework hence attempts to describe under which industry dynamics the FMA mechanisms introduced earlier alre likely to succeed.

The pace of technological evolution refers to the rates at which products' underlying technologies advance. For instance manufactured glass dates back to about 3500 bc, when Middle Eastern artisans heated crushed quartz to make glazes for ceramic vessels. But it took 3000 years for the next technological change, glassblowing, and only in the 20th century the float-glass process was invented. By contrast, a computer today is very different than one made even ten years ago. Suarez and Lanzolla claim, that the faster or more disruptive the evolution of technology, the greater the challenge for any one company to control it and as a consequence the more difficult for a company to leverage a FMA.

The pace of market evolution can vary very much across different product categories. For example, the markets for vacuum cleaners and fixed telephones developed much more slowly than the markets for VCRs and cellular phones.

The market penetration and performance improvement of most new product categories follow similar trajectories - slowly at first, picking up speed, then level off, roughly reassembling the shape of an 'S'. But the rate at which they change varies dramatically as shown in figure 4-6. If one can hardly keep up with innovations around a specific product then the tech-

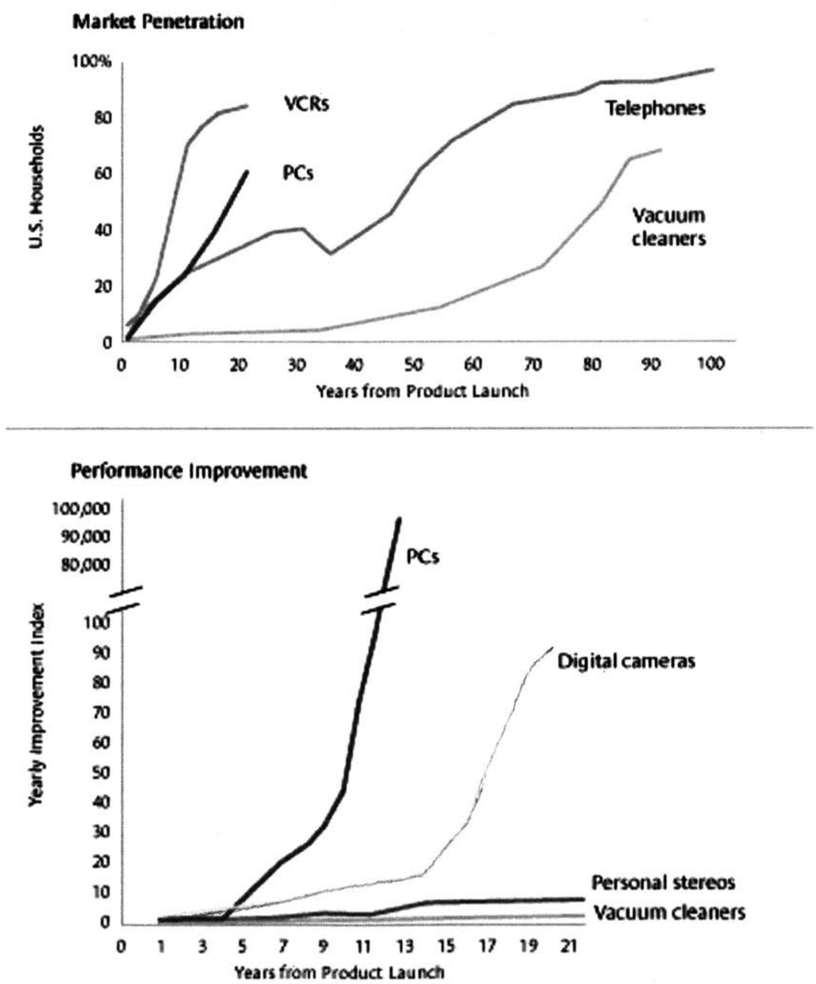

Figure 4-6: Market penetration and performance improvement index relative to product launch for different products. *Source: [20]*

nological evolution is probably happening rapidly. Similar, if the market for that product is growing at a pace where someone struggles to keep up with demand, then the market is probably evolving fast (fast consumer adoption of new product). The authors divide different combinations of pace of technological evolution and market evolution in four categories, summarized in figure 4-7. In each of the four quadrants the likelihood of a FMA will be

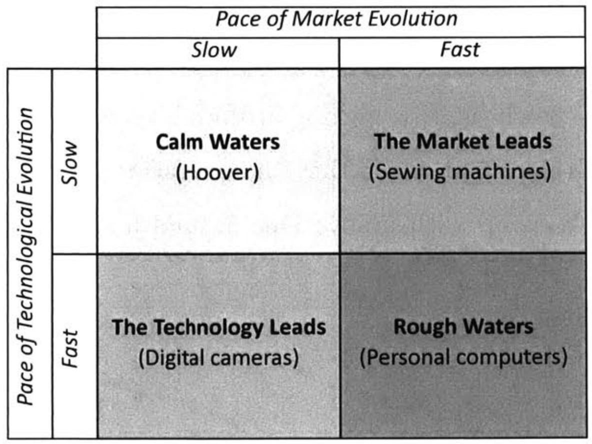

Figure 4-7: The combined effects of market and technological change *Source: [20]*

different.

Calm Waters Gradual evolution in both technology and market provides first movers with the best conditions for creating a dominant position that is long lasting. This stems from the characteristic that with a gradual pace of change in the technology, it is hard for later entrants to differentiate their products from those of the first entrant. An initially slow pace of the market growth also tends to favor the first mover by giving it time to cultivate and satisfy new market segments.
Example: In 1908, in Ohio, William Henry Hoover produced the first commercial bag-on-a-stick vacuum cleaner. However, as late as 1930, fewer than 5% of households had purchased one. The technology changed as slowly as the market. When innovation did occur, the change was enduring. In 1935, Hoover encased the vacuum cleaner's components in a streamlined canister, creating a technological blueprint that persists to this day. In such a steady environment, Hoover managed to keep up-to-date technologically and to meet demand. The company's machines became the reference point within the category [20].

The Market Leads When the market adopts a new product very rapidly it may be difficult for the first-mover to keep up with demand, due to limited resources and skills, which may lead to insufficient supply- and distribution capacities. The first-mover is likely to reap only short-term benefits from his pioneering status.

Example: Elias Howe introduced the first commercial sewing machine in the late 1840s, but the machines made by Isaac Singer, a later entrant with greater resources, were soon able to find more customers than Howe's. The basic sewing machine changed little over the next half-dozen years, but demand increased to such an extent that Singer began expanding into Europe[20].

The Technology Leads Low market adoption but rapid technological change will put a first-mover under great pressure, since flat sales and hence low profits (or even losses) may not allow them to keep up with the change. As a consequence pioneers are unlikely to gain short-term advantages. Substantial financial possibilities are required for a company to enter such a market first, survive in its hostile environment, and withstand a considerable delay before obtaining a durable first-mover advantage.

Example: In 1981, Sony launched the first digital camera, the Mavica®. Sales of digital cameras did not begin to gather momentum for at least ten years, and sales continued to be modest for another decade, during which the fast pace of technological improvement rendered products obsolete within a year. A key area of improvement was the density of information a digital image could handle. In the early 1980s, a high-end camera could produce images with up to 60,000 pixels. By 2000, the pixel count had reached 5 million. Sony's considerable financial resources and technological capabilities allowed it to stay on top of the category and grab a commanding share of the slowly evolving market. In 2003, Sony was still the leader in the U.S. market, with about a 22% market share[20].

Rough Waters Rapid technological innovation and rapid consumer acceptance, may leave first-movers highly vulnerable. Both considerable financial and technological resources are required to keep up with the pace and have a chance to reap either short or long term FMAs. If a product's underlying technology changes very rapidly, the item quickly becomes obsolete. More often than not, such products are overtaken by versions from new entrants, which aren't burdened by maintaining and servicing older product lines and can innovate without fear of cannibalizing prior investments. A fast-growing market adds to a first mover's challenges by opening attractive new competitive spaces for later entrants to exploit. The incumbent tends to be at a disadvantage, since it often lacks the production capacity or marketing reach to serve a rapidly expanding customer base.

Example: One company who managed to stay afloat and keep competitors behind in such rough waters was and is Intel. By putting all its technical and marketing muscle behind its product development process and being paranoid about competition, Intel has been able to dominate a product category in which markets keep expanding and technology keeps changing at a furious pace [20].

The authors summarize their findings of likelihood of either short-lived or durable FMAs relative to the situation a company faces in the below framework 4-8.

	First-Mover Advantage		
	Short-lived	**Durable**	**Key Resources Required**
Calm Waters	**Unlikely** Even if attainable, advantage is not large	**Very likely** Moving first will almost certainly pay off	Brand awareness helpful, but resources less crucial here
The Market Leads	**Very likely** Even if you can't dominate the category, you should be able to hold onto your customer base	**Likely** Make sure your have the resources to address all market segments as they emerge	Large-scale marketing, distribution, and production
The Technology Leads	**Very unlikely** A fast changing technology in a slow-growing market is the enemy of short term gains.	**Unlikely** Fast technological change will give later entrants lots of weapons for attacking you.	Strong R&D and new product development, deep pockets
Rough Waters	**Unlikely** A quick-in, quick-out strategy may make good sense here, unless your resources are awesome.	**Unlikely** There's little chance of long-term success, even if you are a good swimmer. These conditions are the worst.	Large-scale marketing, distribution, production, and strong R&D (all at once)

Figure 4-8: Framework for assessment of FMA *Source: [20]*

4.4.3 Likelihood of FMA in the market for Power Regulation and Control Equipment for the Medium-Voltage Distribution Grid

Based on the literature research it became clear, that being first is not sufficient to become and stay successful in a new market. Other preconditions, mainly the identification of a true customer need, and the definition of a superior business model, need to be fulfilled first in order to take advantage of the first-mover status. Assuming MR is capable of satisfying the preconditions we need to understand how likely a FMA is in the market for power regulation and control equipment for the medium-voltage distribution grid and which FMA mechanisms apply.

If the past of the market can be used as an indication of the future than the pace of evolution of the market for equipment for the mid-voltage distribution grid is certainly slow. MR, for instance, still services transformers which have been in operation for more than 50 years. The reason for this slow paced evolution may lie in the fact that proven reliability is critical when selecting the product. Power grids are the backbone of modern economies and are costly infrastructure projects. Customers, hence, are less likely to take on risks and experiment with technology which has not yet demonstrated to run stable and reliable in real life scenario. Even if a customer may be willing to adopt the new technology but relies on financing from banks or other lenders, the experiment is likely to not fly. In large energy project financing banks are highly sensitive to risks and are unlikely to release funds for unproven technologies.

The pace of technological evolution has also been slow in the past. The first transformer has been invented in 1885. The invention of OLTCs in 1926 has enabled the realization of regulating transformers. The basic design has since then only seen incremental improvement. This may have been driven by the conservative market who did not ask and did not want drastic changes and also from the long lifetime of the products. Once commissioned, power control and regulation equipment is seldom retired before 20 years of operation. A switch to a semiconductor based technology may accelerate the technological development but since reliability and long product lifetime will still remain critical, chances are that development cycles will not occur at the same frequency as we see in consumer products such as personal computers.

These assumptions would put the market in the upper left quadrant, the Calm Waters Suarez and Lanzolla's framework introduced in section 4.4.2. This means, that the first-mover could benefit from a durable FMA. From the three mechanisms introduced in section 4.4.1, the most likely to generate a FMA are *technological leadership* and *switching costs.* A versatile, and reliable design e.g. for a converter module or an IGBT-cell has the potential to set industry standards and be used in products for different applications. Especially, if connected with a strong brand name of a trusted industry partner which MR without doubt is.

It hence, makes sense, that MR also focuses on timing its market entry before the the competition in order to leverage a likely FMA.

4.5 Demand estimation with Bass-Diffusion-Model

Project business cases and their economical viability are strongly tied to demand estimates of the envisioned product. Only if a minimum demand over a certain period materializes, the product has a chance to become economically viable. However, it is challenging to identify demand scenarios, especially if the product or its underlying technology are new. This is also true for the case study of the PE-system, which we will be discussing in chapter 6. Today, MR has only a limited visibility of the future demand, which may not be sufficient to model demand for the full product life-cycle. One way to overcome this limitation is the application of the Bass-Diffusion-model, which can be used to estimate demand based on product and market parameters.

Bass, 1969 [21], developed a model to forecast the long-term sales pattern of new technologies and new durable products under two types of conditions [22]:

- the company has recently introduces the product or technology and has observed its sales for a few time periods
- the company has not yet introduced the product or technology, but it is similar to existing products or technologies whose sales history is known.

The *Bass-Diffusion-Model* relies on the theory of adoption and diffusion. In this theory innovators decide to adopt an innovation independently of the decision of other individuals in a social system and hence may dare to test the new product before anybody else. Imitators, on the other hand, are influenced in the timing of adoption by the decisions of the other members of the social system. An important assumption of the Bass-model is, that eventually all potential buyers m will adopt the new product. The group of potential buyers m is assumed to be constant over the entire life cycle of the product and hence need to be determined beforehand. The model relies on two additional parameters:

- p...coefficient of innovation
- q...coefficient of imitation

These parameters are industry specific and can be determined e.g. by a regression analysis of comparable products.

With the three parameters m, p, q, the Bass-model takes on the following form:

$$n(t) = \frac{dN(t)}{dt} = p(m - N(t)) + \frac{q}{m}N(t)(m - N(t)) \tag{4.1}$$

with

$n(t)$...Number of customers who will purchase the product at time t

$N(t)$...Total number of adopters of the product up to time t

The Bass-model can be solved as follows:

Cumulative number of adopters:

$$N(t) = m\frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p}e^{-(p+q)t}}$$

Number of adopters in period t:

$$n(t) = m\frac{p(p+q)^2 e^{-(p+q)t}}{[p + qe^{-(p+q)t}]^2}$$

Time of peak adoption:

$$T^* = -\frac{1}{p+q} ln\frac{p}{q}$$

Number of adopters at peak time:

$$n(T^*) = \frac{1}{4q}(p+q)^2$$

Figure 4-9 illustrates the quantities $n(t)$ and $N(t)$ over time assuming parameters $p = 0.03$, $q = 0.8$, and $m = 1100$.

4.6 Vertical Integration

Value chain analysis inevitably leads to the question of which elements of the value chain should the organization internalize and which outsource. In short, which level of vertical integration should an organization adopt in regards to the competitive market environment it is operating in. In Beckmann, 2007 [23] the vertical integration decision is anchored around two questions:

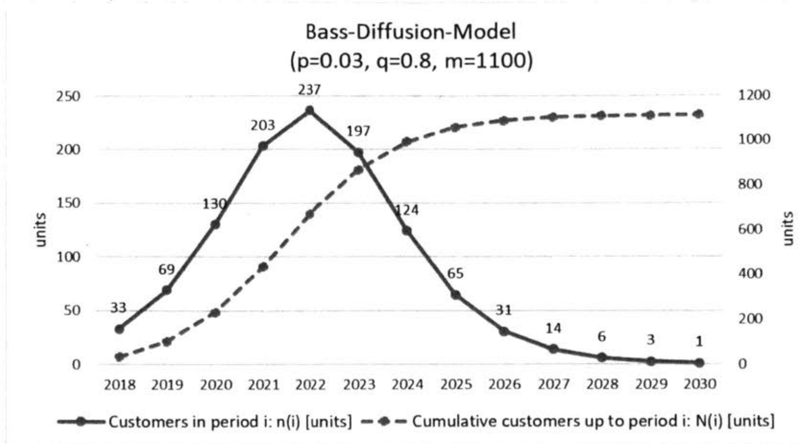

Figure 4-9: Example of Bass-Diffusion-Model

- How much of the value chain should my company own, and for the owned activities, how much should be performed in house?
- Under what conditions should my company change the amount of the value chain it owns? In what direction - toward my suppliers or toward customers - should I make those changes?

To help answering the questions it suggests that four sets of factors need to be taken into account:

- *Strategic factors* help the company determine the level of vertical integration based on the choice of core capabilities the company wants to compete.
- *Market factors* consider the availability of supply for the components of the value chain the company chooses not to own.
- *Product and technology factors* determine the strategic value of owning a specific technology if it is closely linked to the quality or features of the final product. This could be both a process or product technology and the outcome of the assessment may depend on the maturity of the technology in question: it may be valuable to own the technology when it is new, but choose to outsource it when it becomes a commodity.
- *Economic factors* help in the assessment of the financial implications of integrating or disintegrating an activity. This is mainly driven by the total cost (investment costs + operating costs) of owning or outsourcing an activity.

Figure 4-10 summarizes important factors for and against vertical integration:

	Vertically Integrate to	Vertically Disintegrate to
Strategic Factors	Develop and retain core essential capabilities.	Access a core or essential capability externally while working on its development internally.
Market Factors	Control cost, quality, features/innovativeness and environmental performance in unreliable markets. Shift power relationships in the industry. Reduce dependency (due to asset specificity) on suppliers.	Leverage competition among suppliers to access best-in-class performance. Aggregate demand at suppliers thus generating economies of scale and improved responsiveness to variability in demand.
Product and Technology Factors	Control integral or critical technologies. Integrate design and production or service delivery under uncertain conditions.	Access current technologies not available internally. Obtain leverage available from modular product architectures.
Economic Factors	Minimize transportation and logistics costs. Minimize transactions (contracting and coordination) costs.	Access lower production or service delivery costs. Minimize investment costs.

Figure 4-10: Factors for and against vertical integration, Source: [23]

4.7 Decisions under Uncertainty

It is highly unlikely that any business decision is taken with full information. Usually there is uncertainty involved. This is also the case when making decision regarding the set up of value chains for future products. For instance, the decision whether to invest in a factory to manufacture a specific product could be either good or bad depending on whether there will be a high or low demand for the product. However, the actual demand, is often not known in advance. In Dixit, 1994 [24] the authors compare the opportunity to invest to a financial option, which can be valued and analyzed accordingly.

The authors exemplify the value of delaying a decision and hence the value of flexibility in a simple example, reproduced below in a shortened form:

A firm is trying to decide whether to invest in a widget factory. The investment is irreversible. The factory can be built at cost $I = \$1600$ *and will produce one widget per year forever. Currently the price for a widget is* $P = \$200$*, but next year the price will change. With probability* $p = 0.5$ *it will rise to* $\$300$ *or fall to* $\$100$*. The price will remain at that* *level forever (see figure 4-11).*

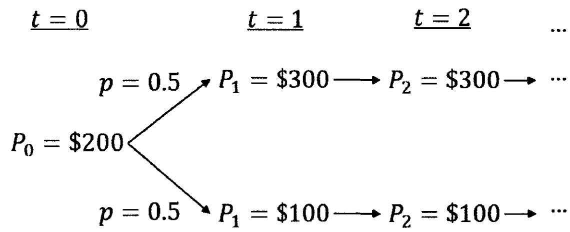

Figure 4-11: Price of widgets

Suppose the investment occurs now and assuming a discount rate of 10% the net present value (NPV) of this transaction is given by:

$$NPV = -1600 + \sum_{t=0}^{\infty} \frac{200}{1.1^t} = -1600 + 2200 = \$600$$

The current value of the widget factory exceeds the investment cost and hence it seems that it is a good investment.
The conclusion is incorrect, however, because the calculation ignores a cost - the opportunity cost of investing now, rather than waiting and keeping open the possibility of not investing should the price fall. To see this, the NPV of this project is calculated a second time, this time assuming that instead of investing now, the investment is delayed one year and only made if the price for the widgets goes up. In this case the NPV is given by:

$$NPV = 0.5 \left[\frac{-1600}{1.1} + \sum_{t=1}^{\infty} \frac{300}{1.1^t} \right] = \frac{850}{1.1} = \$773$$

The NPV today is \$773*, whereas it is only* \$600 *if the investment in the factory is done now. Clearly it is better to wait than to invest right away.*

Uncertainty may not only affect one of the input variables of the NPV analysis (in the above example the future price of the widget) but most likely others as well, e.g. the cost of the factory itself. Also, there may be more than two possible values for each input variable. Each input variable may belong to a range of possible values which occur with different frequencies and hence the possible outcomes will also belong to a range. In this case we are not dealing anymore with discrete deterministic input variables but with uncertain random input variables and hence input distributions. One method to deal with input distributions, and hence account for uncertainty in an analysis, is to perform a Monte Carlo simulation.

4.7.1 Monte Carlo Simulation

Monte Carlo simulation is a method of estimating the value of an unknown quantity using the principles of inferential statistics. This means that by observing statistics of a random sample of a population conclusions about the population itself can be inferred. The key fact is that a random sample tends to exhibit the same properties as the population from which it is drawn [25].

In problems where we want to get an understanding of the range of possible outcomes due to random input variables, Monte Carlo simulation can be used to run multiple trials in which the input variables are selected at random in each trial (from the range of possible values). Each trial will result in a different outcome and together these outcomes will give a distribution. Although the number of trials is limited, the resulting distribution will be a fair representation of the entire population of possible outcomes, due to the aforementioned property of random samples.

In financial and business related problems, such as the estimation of the NPV of an investment, this approach will provide better understanding of the risks and opportunities of the transaction: instead of one single NPV it will provide the entire range outcomes, from the worst (lowest negative NPV) to the best (highest positive NPV) possible outcome.

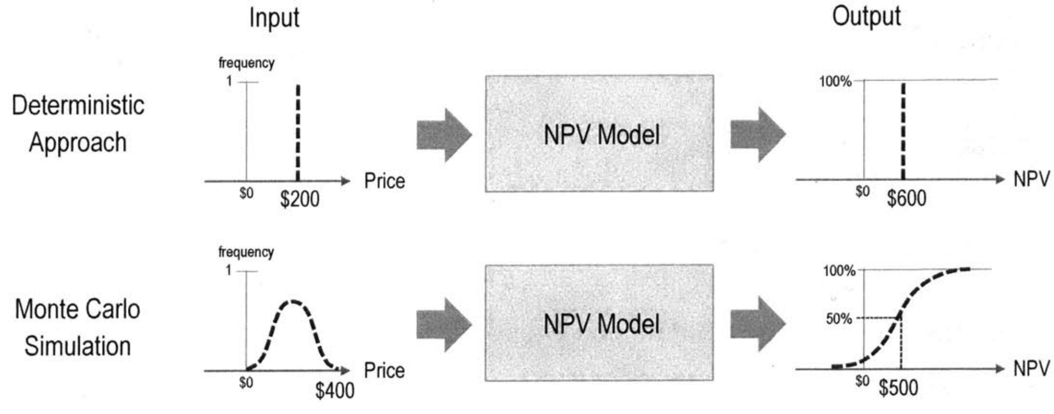

Figure 4-12: Comparison between deterministic analysis and Monte Carlo simulation

4.8 Failure Mode and Effects Analysis

Failure Mode and Effect Analysis (FMEA) is an engineering technique used to define, identify, and eliminate known and/or potential failures, problems, errors, and so on from the system, design, process, and/or service before they reach the customer [26].

It is also one of the most important early preventive actions in system, design, process, or service, which will prevent failure and errors from occurring and reaching the customer [27]. From a practical perspective the FMEA offers the advantage that there is no specific constraint in regards to the timing of the application of the FMEA during the engineering process. Although the FMEA should definitely be started at the beginning of the development process it can also be deployed when e.g. a system has been almost fully conceived, as it was the case in this project. Of course, one has to keep in mind that a late deployment of the FMEA also means that required changes to the system, design, process, or service triggered by the FMEA may be more expensive, or even technically impossible to implement. Once initiated, the FMEA is a *living* tool which will support the system, design, process, or service over its entire life-cycle. It is important to keep the "living" aspect in mind, since the full benefit of the FMEA can only be reaped if it is maintained and updated along the development of the underlying system, design, process or service. The true philosophy of FMEA is continuous improvement with the long-term goal to completely eliminate failure[27], or for PE to seek failure resistant and failure tolerant solutions[1].

According to Stamatis, 2003 [27] "The FMEA will identify corrective actions required to prevent failures from reaching the customer, thereby assuring the highest durability, quality, and reliability possible in a product or service". If performed correctly, the FMEA will yield the following outputs:

- Identify known and potential failure modes
- Identifies the causes and effects of each failure mode
- Prioritizes the identified failure modes according to the risk priority number (RPN) - the product of frequency of occurrence, severity, and detection
- Provides for problem follow-up and corrective action

[1] according to MR SME

Stamatis, 2003 [27] distinguishes between four different types of FMEA:

System FMEA Focus on minimization of failure effects on the system with the objective to maximize system quality, reliability, cost, and maintainability.

Design FMEA Focus on minimization of failure effects on the design with the objective to maximize design quality, reliability, cost, and maintainability.

Process FMEA Focus on minimization of failure effects on the total process[2] with the objective to maximize the total process quality, reliability, cost, and maintainability, and productivity.

Service FMEA Focus on minimization of service failures on the total organization with the objective to maximize the customer satisfaction through quality reliability and service.

4.9 Reliability Engineering

The capability to assess the reliability of a system or product and be able to provide this information to the customers becomes critical if one attempts to introduce a new technology into a market where reliability is key factor.
The discipline of reliability engineering provides the necessary techniques and tools to carry out such assessments. As pointed out by Birolini, 2017 [35] the term reliability is often used for reliability, availability, maintainability, and safety (RAMS). Reliability engineering comprises quantitative and qualitative techniques to calculate or estimate these important aspects related to the operation of equipment. It is important to acknowledge that reliability engineering techniques use (failure) probabilities as their inputs and hence will yield also probabilities of certain events to occur or not occur as their output. Clear *yes* or *no* answers will not be given and the practitioner needs to learn how to interpret these uncertainties. Following a few basic concepts of reliability engineering are introduced, which have been used during the project.

Reliability is the ability of an item to remain functional over a determined period of time or, quantitatively, the probability that no operational interruption will occur during a

[2] "total process" entails generally all processes involved to deliver a service or a product. In the case of the SVC the focus would be on the manufacturing process

stated time interval [35]. The term *functional* can also be interpreted as *the ability to perform a required function.* Reliability is generally denoted with R and, because it is a probability, assumes values from 0 to 1. Since the reliability of an item is dependent of environmental, and operational conditions, and the state of the item itself (e.g. new out of the factory or used), reliability values cannot be evaluated without taking these conditions into consideration.

Failure occurs when the item stops performing its required function [35]. As we have seen already when discussing the FMEA, failures can have different modes (symptoms), root causes, and effects. Furthermore Birolini, 2017 [35] introduces *failure mechanism* as a category to classify failures. The mechanism is the process that leads to a failure.

Failure Rate is the ratio of items failed over a specific time interval over the original population of items. The *empirical failure rate* is defined as

$$\hat{\lambda}(t) = \frac{\bar{v}(t) - \bar{v}(t+\delta t)}{\bar{v}(t)\delta t} \tag{4.2}$$

where $\hat{v}(t)$ is the number of items which have not failed at time t, and $\hat{v}(t+\delta t)$ the number of items which have not failed at time $t+\delta t$. Subsequently $\hat{\lambda}(t)\delta t$ is the ratio of items failed in the interval $(t, t+\delta t]$ to the number of items still operating at time t [35]. The *empirical reliability function* at time t

$$\hat{R}(t) = \bar{v}(t)/n \tag{4.3}$$

is the ratio of items which have not failed at time t to the initial population of items n. In many practical applications $\lambda(t) = \lambda$, can be assumed and for $n \rightarrow \infty$ and together with $\delta t \rightarrow 0$, $\hat{\lambda}(t)$ converges to the *instantaneous failure rate*

$$\hat{\lambda}(t) = \frac{-dR(t)/dt}{R(t)} \tag{4.4}$$

and the *reliability function* 4.3 can be rewritten as

$$R(t) = e^{-\lambda t} \qquad (for \lambda(x) = \lambda, t > 0, R(0) = 1) \tag{4.5}$$

We will see later on, that for our calculations λ for each component of the SVC can be obtained from the *FIT* values in table 9-6.

Mean Time To Failure (MTTF) expresses the mean of the failure free time $\tau > 0$ and can be written as

$$MTTF = E[\tau] = \int_0^\infty R(t)dt \qquad (for MTTF < \infty) \tag{4.6}$$

For an item new out of factory MTTF can hence be interpreted as the mean time until the first failure occurs. For $\lambda(x) = \lambda$ mean time to failure becomes $MTTF = 1/\lambda$.

Mean Time Between Failures (MTBF) is closely related to MTTF and it expands the concept to repairable items. However, if we assume a constant (time independent) failure rate λ also for repairable items and further assuming items to be *as-good-as-new after each repair* after a repair, consecutive failure-free times or *mean operating time between failures* becomes [35]:

$$MTBF = 1/\lambda \qquad (for \lambda(x) = \lambda, \text{ x starting at 0 after each repair/renewal}) \tag{4.7}$$

Mean Time To Repair (MTTR) If an item is repairable, mean time to repair denotes the mean time it requires to put the item back into a *as-good-as-new-state.* MTTR is hence dependent from factors such as availability of material and tools for the repair, availability of spare parts (for repair of systems), availability of qualified resources to perform the repair, and the duration of the repair itself

Availability is the ratio of mean time to failure of an item and the sum of mean time to failure and mean time to repair of the same item. It is an important metric for equipment operators to quantify and hence schedule the actual time an asset is available to perform useful work.

$$Availability = MTTF/(MTTF + MTTR) \tag{4.8}$$

Failure rate for a large population of items over their lifetime is often represented with a *bathtub curve*, which, according to Birolini, 2017 [35] can be divided into three segments:

1. *Early failures*: $\lambda(t)$ decreases rapidly over time; failure in this phase are attributed to randomly distributed wekanesses in materials, components, or production processes.

2. *Failures with constant (or nearly so) failure rate*: $\lambda(t)$ is approximately constant; failures in this period ar Poisson distributed and often sudden.

3. *Wear-out failures*: $\lambda(t)$ increases with time; failures in this period are attributed to aging, wear-out, fatigue, etc. (e.g corrosion or electromigration).

A *bathtub curve* for a large population for statistically identical and independent items is represented in figure including the three segments 4-13.

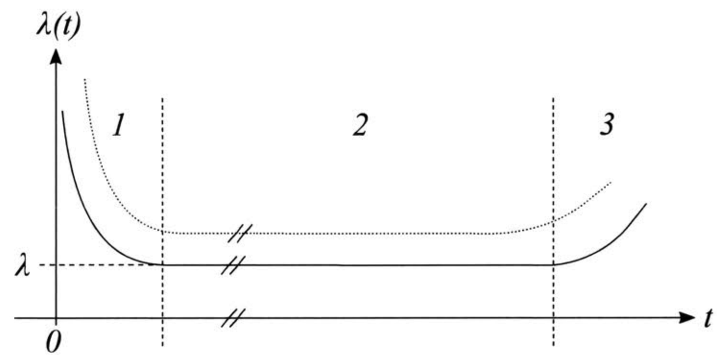

Figure 4-13: Batthub curve: failure rate over time for a large population of statistically identical items. The dotted line is showing failure rate for the same population under different environmental and operational conditions.

4.10 Alternating Current

The systems discussed in this thesis are all operating in alternating current (AC) grids. It is hence important to understand the basics of this form of electricity.
In alternating current circuits we can map power in a complex space and identify three components: apparent power S (measured in Volt Ampere, $[VA]$), active power P (Watts, $[W]$), and reactive power Q (Volt Ampere reactive, $[VAr]$). To note is, that all units for each power component are identical since, after all, they are just components of the same

unit of power. The components are related to each other as follows [28]:

$$S = VI^* = |S|\angle\varphi \tag{4.9}$$

$$P = |S|\cos\varphi \tag{4.10}$$

$$Q_{total} = Q_{capcitive} + Q_{inductive} = |S|\sin\varphi \tag{4.11}$$

The differentiation is made to be able to easily distinguish between the components, since most electrical ac circuits need to comply to individual requirements for each power component. The three components can be illustrated in a vector diagram as shown in 4-14.

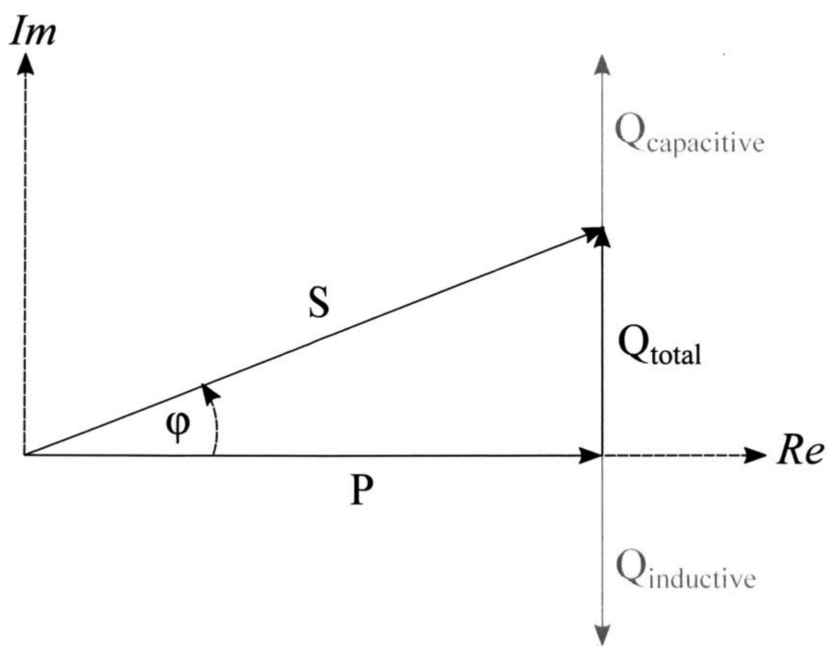

Figure 4-14: AC power components in the complex space

Apparent power is the vector sum of active and reactive power. In AC circuits active power is caused by resistive loads, such as electric motors or the electrodes in an electric discharge furnace as used in this steel plant. Reactive power on the other side is caused by capacitive or inductive loads. It cannot perform actual work, but it is necessary to stabilize the grid. Reactive current is out of phase by 90° and more specifically +90° for capacitive and -90° for inductive reactive power. The power factor (PF) is the ratio of active power to apparent power. From 4.9 we get

$$PF = \frac{P}{|S|} = \cos\varphi \tag{4.12}$$

4.11 Gap in the State of the Art

Ample research has been conducted on the structure of value chains and optimal level of vertical integration. However, no examples have been found which show how market forces and uncertainty of market parameters, such as demand, price, cost, and timing of market entry relative to competition may influence the value chain design for a future product category.

This project is an attempt to address this gap by showing how the analysis of prevailing market forces and the acknowledgment of uncertainty of market parameters can help defining the value chain for future power electronics based products for the medium-voltage distribution grid market. Specifically, the project is trying to accomplish this by attempting to answer the following questions:

- How do external market forces (suppliers, customers and competition) influence the value chain setup?
- Which market parameters are the main sources of uncertainty?
- Which insights can be gathered by evaluating the impact of uncertainty?

Part I

Definition of a Value Chain Concept for Power Electronics

In the first part of the thesis we will be using Porter's five forces model (see 4.3) to frame the market environment for the envisioned power electronics product, and subsequently build different scenarios within that market environment. A case study on a simplified PE-product, a *Unified Power Flow Controller (UPFC)*, will further highlight the importance of different market parameters and make an attempt to quantify their impact on the financial performance of the UPFC. For this purposes a *present value* model will be used. Based on the acquired insights a recommendation for the value chain design for MR's power electronics products will be provided in the last chapter of this part.

Chapter 5

Market Reaction

The first important question we have to answer is, whether it is actually a good idea for MR to develop PE-based products in the first place. The reason we are asking this question is the fact, that development of PE-products would represent, to certain extend, a forward integration of MR along the value chain: MR would not longer only supply electromechanical components, mainly OLTCs, to the manufacturers of traditional regulating power transformers, but potentially be able to develop substitutes for transformer, e.g. *solid state transformer (SST)*, which could be sold directly to the end customer, such as utilities or grid operators.

5.1 Background and Market Definition

The PE-products considered for this analysis, and specifically SSTs, are mainly targeted for applications in the medium-voltage AC distribution grid. SSTs use power electronic AC/DC and DC/AC converters which are coupled by a high frequency transformer to achieve voltage conversion and isolation. A schematic of an SST is illustrated in figure 5-1. The power electronic devices used in SSTs are typically *insulated gate bipolar transistors (IGBTs)*, semiconductors with rated voltages of currently up to 6.5kV that are particularly suited for medium voltage applications (>600V and up to <66kV).

Today, oil-cooled copper and steel core transformer are used globally in distribution networks to transform voltage and provide isolation [29]. The technology has matured over decades without major changes which lead to low costs. However, due to the increasing growth of decentralized power generation such as wind and photo-voltaic, more sophisti-

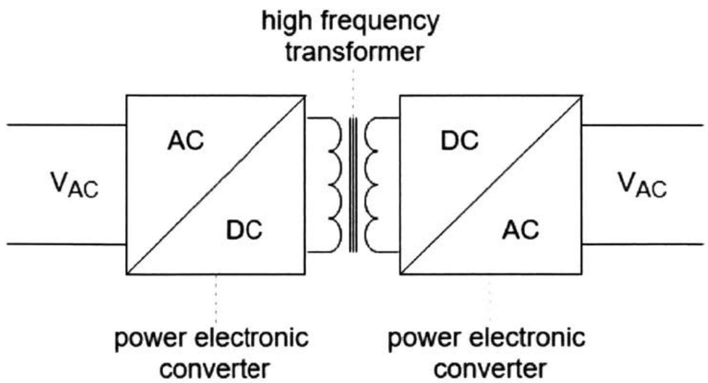

Figure 5-1: Schematic of a Solid State Transformer (SST)

cated controls, faster and more frequent switching, may be required to balance power sources and consumers (smart grids). These requirements could push conventional electro-mechanic LFTs to their limits and make the currently more expensive solid state technology, and hence SSTs economically viable. Further, it is important to acknowledge, that SSTs can offer additional functions and benefits on top of the basic functions *voltage conversion* and *isolation* [29]:

- Active power filtering of harmonic content on the input.
- Perfect voltage regulation
- All measurements of currents, power and voltage are inherent to the system and hence available to the system.
- The output could be at a different frequency than the input.
- Ability to connect to a system with a different phase than the host system.
- Voltage dip and sag ride through capability (with enough energy storage)

Additional advantages of SST are reduced size, and reduced weight. On the other hand, SSTs are less reliable than the simple but extremely robust and almost maintenance free architecture of power transformers, which requires little less than periodical oil changes and cleaning. This is a major downside, since grid infrastructure is the backbone of modern economies and hence reliability of the system a critical factor. Conventional power transformer, offer further useful lifetimes of multiple decades, durations which PE-based products are unlikely to achieve.

A comprehensive overview of advantages, disadvantages and applications of SSTs can be found in [30].

The highlighted features make SSTs not a 1:1 replacement of conventional LFTs, but more sophisticated devices with a substantially wider range of applications. SSTs are not an incremental evolution of LFTs. Based on different technologies, SSTs further require different engineering/manufacturing technologies and competencies. Analogies could be the switch from analog to digital technology in telecommunications or photography.

Based on these facts two important assumptions are introduced, which will be used going forward:

1. *PE-products, such as SSTs, are not 1:1 substitute for conventional LFTs and will sell alongside the conventional business in the midterm future (5-10yrs) generating revenue in addition to the current MR product lines (no cannibalization)*

2. *PE-products, such as SSTs, have the potential to replace LFTs in the long term, similar as smart-phones have replaced conventional cellular phones over time or digital photo cameras have replaced analogue ones*[1]

Hence, when we talk about *market*, we mean the market of PE based products such as SSTs, which provide not only voltage transformation and isolation, but also power quality functions, such as reactive power supply and harmonic filtering. However, it is not limited to SSTs, but can also include other advanced power control and regulation devices such as *unified power flow controller (UPFCs).* we will further specify that for now we are only looking at products for medium voltage (<66kV) applications. In summary that lets us define that we are looking at the market for power regulation and control equipment for the medium-voltage distribution grid. It shall be noted that in this context the role of the end customer (e.g. utility or grid operator) becomes critical, since they will ultimately decide whether PE-based transformers are going to substitute the current technology or not.

5.2 Forward Integration and Risk of Retaliation

Today MR offers with their OLTC product lines critical components for regulating transformers, but does not offer products which cover the full functionality of regulating trans-

[1] with the difference that "long term" for power system components comprises a horizon of approximately 50 years, whereas the change in the two examples occurred in around 10 years

formers. This would change if MR were to develop and commercialize PE-products such as SSTs, since SSTs technically include the functionality of regulating transformers. With this step MR moves from being a supplier of intermediate products to being a provider of an end customer product and hence, potentially tap into the business of their OLTC customer. This step down the supply chain is considered *forward integration* [8].

For MR it raises the question whether current OLTC customers would feel threatened and in consequence stop buying MR's OLTCs as an act of retaliation. This is certainly something MR does want to avoid and a question which needs to be answered before major investments are undertaken to develop the intended PE-products.

On the other side we have also assumed earlier, that SSTs would not be 1:1 replacements of LFTs but intended for more niche/sophisticated applications and hence allow a co-existence of a PE-market and a conventional LFT-market. If this assumption is true, the risk of retaliation would be limited considerably. However, we would still want to find out how vulnerable MR is to retaliation from customers.

In the same way retaliation could also originate from MR's suppliers who are already active in the PE-market 5-2.

Figure 5-2: Risk of retaliation in connection with forward integration

5.3 Retaliation from Customer

The risk scenario for MR originates from the supplier-customer relationship as illustrated in 5-3. Some of MR's important OLTC customers make their own efforts to develop competencies in the PE-domain and could hence feel threatened both in their current (transformer-) and in their future (PE-) business. In order to evaluate the risk of retaliation from customers we go back to Porter's five forces model and look at the relationship between supplier (in this case MR) and customers and their respective bargaining power.

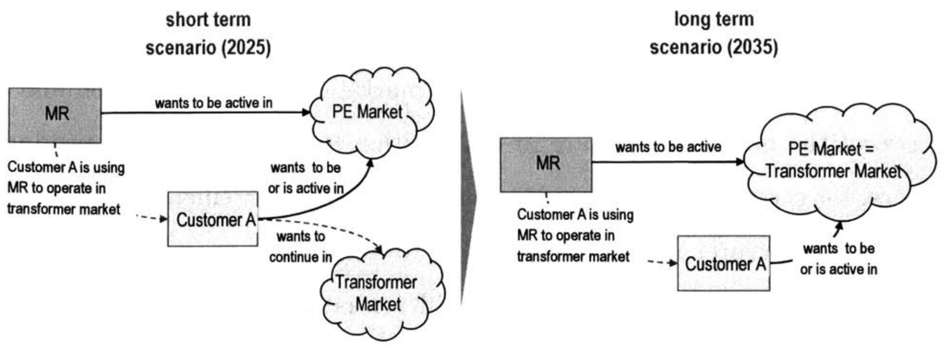

Figure 5-3: Risk scenario for customer retaliation

MR will be at risk to suffer retaliation if its customers do not think MR is an essential part of their business success and can be replaced easily with a third party. In short, the customer is *not* dependent on MR. In Porter's five forces model we can test this by assessing the customer's and MR's bargaining power and test the following hypothesis:

- *If the customer has a high and MR a low bargaining power then MR is at risk to suffer retaliation.*

5.3.1 Bargaining Power of Customer

To assess the bargaining power of customers we will have to run through a set of qualitative statements which are formulated from the point of view of the customer [15]. Every statement which can be confirmed will increase the customer's bargaining power over the supplier i.e. MR. A higher bargaining power means that the customer is *less* dependent on the supplier. The analysis concluded the following answers for each question:

1. **S:** *The product the buyer purchases represents a significant fraction of the buyer's costs or purchases.*

   Evidence: The OLTC represents approximately 5%-15% of the total costs of a power transformer. Hence, it is a "minor" component in terms of costs.

   Interpretation: Customers are likely to be price insensitive due to relatively low share of the OLTC of total (transformer) product costs.

   ⇒ lowers customer's bargaining power

2. **S:** *The products the buyer purchases are standard or undifferentiated.*

   Evidence: the supplier base for OLTC is small: the top 8 suppliers have a market share of appr. 94%, the top 4 of 83%, and the top 2 of 65%[2]

The products are specialized and for some market segments (e.g. premium segment) only two of the nine suppliers are in the position to supply the right products[3]. Furthermore, for certain high end applications customer requirements are so specific, that only one manufacturer is currently capable to fulfill them.

Interpretation: Substantial product differentiation is likely to lower bargaining power of buyers

⇒ lowers customer's bargaining power

3. **S:** *The buyer faces few switching costs.*

   Evidence: Considering that the top 2 suppliers own 65% of the OLTC market, a transformer manufacturer risks to face a supply shortage if it drops the top 1 supplier. This may have a negative impact on its own delivery schedule and may force him to qualify additional suppliers, change design of own products, and face less favorable purchasing conditions. The probability of incurring (high) switching costs, is substantial.

   Interpretation: A limited supplier base and specialization on certain applications may incur high costs to buyer when switching/dropping supplier. Hence switching costs are <u>not</u> low.

   ⇒ lowers customer's bargaining power

4. **S:** *The buyer earn low profits.*

   Evidence: Profits of power and distribution transformer are estimated to be in the range of 3%-10% depending on segment and geography. This is not very high, however not uncommon in the industrial goods sector[4]

   Interpretation: Low to medium margins on final product will push buyers to demand low prices.

   ⇒ increases customer's bargaining power

5. **S:** *Buyers pose a credible threat of backward integration.*

   Evidence: From the top 10 transformer manufacturers only two produce tap changers as well (ABB and Hyundai Heavy Industries). Both have rather low market shares

[2]Source: MR internal market study

[3]Source: expert opinion

[4]Source: financial statements of of relevant competitors for financial year 2016

(ABB 7% and HHI 1% in the medium-voltage market [5]). Tap changer development and production is not seen by the transformer manufacturers as strategic competency to own in-house and hence backward integration is unlikely. Main factors for this are:

- tap-changers represent a minor share of final product value (in terms of cost) and hence total volume is limited and small compared to transformer volume.
- high degree of specialty knowledge required for R&D and production.
- mature technology which may be seen as not having future development potential and threatened to be replaced by power electronics solutions, although not in the short run.

Interpretation: Low strategic relevance of tap-changer technology for (most) transformer OEMs make backward integration unlikely.
⇒ lowers customer's bargaining power

6. **S:** *The industry's product is unimportant to the quality of the buyers' products or services.*
   Evidence: Tap changers fulfill a core functionality within modern power/distribution transformers, where they allow to balance power generation with power demand. Transformers do not work without OLTCs, similar as combustion engine powered cars do not work without a gearbox.
   Interpretation: Tap changers are critical to the functionality of a transformer and hence buyers need to have suppliers for it.
   ⇒ lowers customer's bargaining power

7. **S:** *The buyer has have full information (demand, actual market prices, supplier costs).*
   Evidence: Customers know market size and hence demand, market prices and to a certain extend supplier costs.
   Interpretation: Knowledge about demand, market prices, and supplier allows buyers to push prices down. However, it will not make them less dependent from the supplier base, since they still need their product
   ⇒ increases customer's bargaining power

[5]Source: MR internal market study

Five out of seven statements were were not confirmed. It can hence be stated that the bargaining power of customers is low. This indicates a fairly high degree of dependency of buyers from the supplier base and as such also from MR as the market leader in OLTCs.

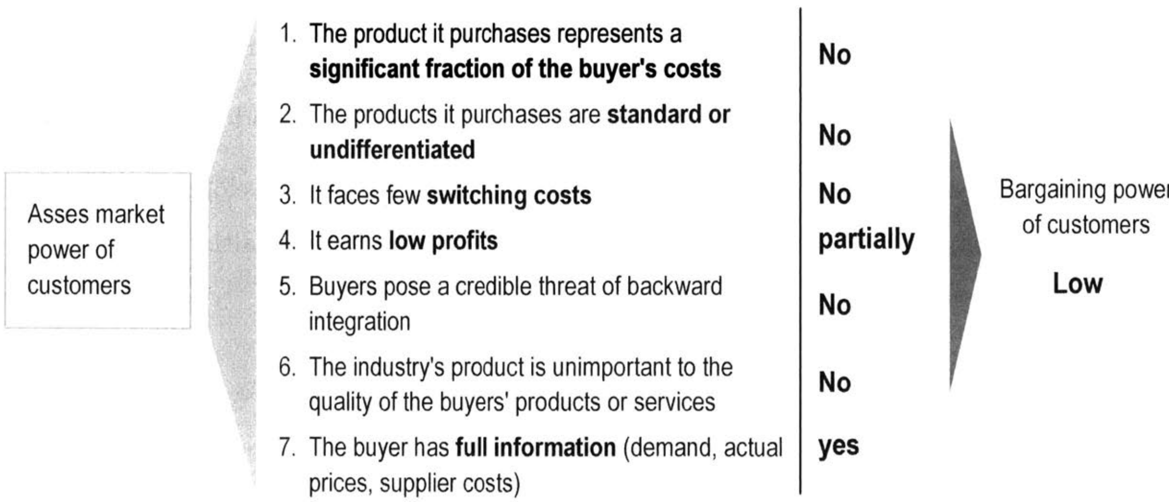

Figure 5-4: Assessment of customer's bargaining power

5.3.2 Bargaining Power of MR

Next, we will evaluate the second part of the hypothesis on page 63 in a similar fashion. MR will have a high bargaining power towards their customer if most of the following statements can be confirmed.

1. **S:** *The supplier base is dominated by a few companies and is it more concentrated than the industry it sells to.*

   Evidence: The entire OLTC supplier base consists of basically eight companies, who own 94.4% of the market. The top 4 suppliers have a 83% and the top 2 players 66% market share. Besides the top 2 players, none of the others can be considered to be able to supply all segments (basic, medium and premium) nor all markets. Hence the supplier base is highly concentrated and specialized.[6]

   Interpretation: High concentration and specialization of supplier base favors suppliers.

   ⇒ increases MR's bargaining power

[6]Source: MR internal market study

2. **S:** *The supplier is not obliged to contend with other substitute products to the industry.*

   Evidence: Currently there is no substitute for OLTCs for regulated transformers. Electromechanical tap-changers are the only viable way. In the long term SSTs may substitute current electromechanical transformer.

   Interpretation: Buyers are forced to source or manufacture tap-changers for the time being.

   ⇒ increases MR's bargaining power

3. **S:** *The industry is not an important customer of the supplier group.*

   Evidence: MR generates an important portion of its revenue with their tap-changer business.

   Interpretation: MR is dependent on the transformer manufacturer buying their product.

   ⇒ decreases MR's bargaining power

4. **S:** *The suppliers' product is an important input to the buyer's business.*

   Evidence: Tap-changers are an essential component for regulated transformers and cannot be substituted with any other product so far.

   Interpretation: Buyers are forced to source or manufacture tap-changers.

   ⇒ increases MR's bargaining power

5. **S:** *The supplier's products are differentiated or have built up switching costs.*

   Evidence: By consulting utility companies and power plant operators, MR manages to lock in tap changer specifications which are only fulfilled by MR's own tap changers. Of the eight main tap-changer suppliers only two are considered to be able to cover all segments and voltage levels[7]

   Interpretation: MR's products are highly differentiated.

   ⇒ increases MR's bargaining power

6. **S:** *The supplier pose a credible threat of forward integration.*

   Evidence: MR will not be able to forward integrate in the current power or distribution transformer business.

   Interpretation: MR is dependent on the transformer manufacturer buying their

[7]Source: MR internal market study

product.

⇒ decreases MR's bargaining power

Four out of six statement have been confirmed. We hence can state that MR's bargaining power is *high*. It is important to note however, that there is no other application for MR's main product, the OLTC, than in current LFTs. If transformer manufacturers should change technology, the product becomes obsolete and MR will loose a very important revenue stream. Although this is not a short term scenario, it is a long term risk which needs to be acknowledged in the company's long term strategy.

Based on these results the initial hypothesis (page 63) can be rejected and we conclude

Figure 5-5: Assessment of MR's bargaining power

that if MR were to develop competencies and products in the PE-market, it would currently not face a risk of retaliation from their core customers.

Flow chart B-1 (in Appendix) has been developed to provide a tool to quickly assess the likelihood of customer retaliation based on Porter's method to assess bargaining power of customers. To gain more certainty about whether a customer will retaliate or not, a close analysis of the specific MR-customer relationship has to be carried out. Soft aspects such as the intra-personal relationship between sales engineer and customer purchaser will become relevant at this point.

5.4 Retaliation from Supplier

For the assessment of a possible retaliation from suppliers we cannot adopt the same analysis as for the risk originating from customers. The reason is, that the supplier base is too inhomogeneous and differentiated. Practically, this means that the set of questions from the Porter model would have to be asked to too many different supplier groups. These supplier groups would first need to be characterized and identified, which was not possible to be done during the time frame of this project.

Therefore, in order to still get an estimate of risk, scenarios were defined in which a supplier would have an incentive to retaliate. After their definition, the scenarios were discussed with members of MR's sourcing organization, who evaluated if any of the scenarios were currently applicable to MR.

The following two scenarios have been developed:

1. **Scenario:** a supplier is already active in the PE-market MR wants to enter, but is also supplying components to MR, which would enable MR to enter the PE-market in the first place.

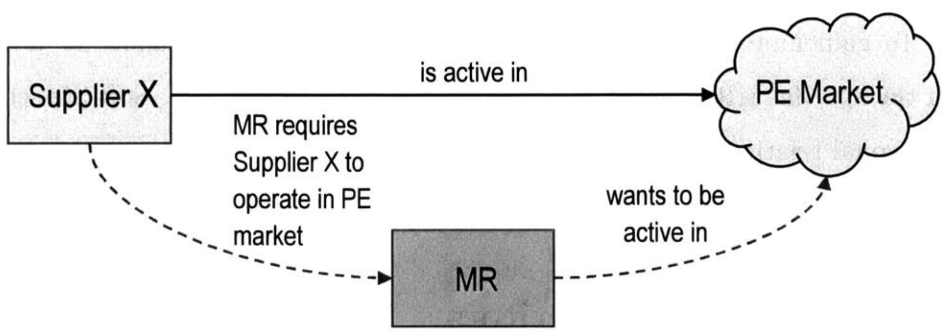

Figure 5-6: Supplier retaliation scenario 1

2. **Scenario:** a supplier is already active in the PE-market MR wants to enter, but is also supplying components to MR, which MR requires for its core OLTC business.

The underlying assumption of these two scenarios is, that a supplier may consider retaliation if they think that they will loose more profit due to MR's entry in the PE market (e.g. through lost market share to MR) than they can profit from selling products to MR. Retaliation would hurt MR especially if the supplier retaliating was a single source supplier to MR.

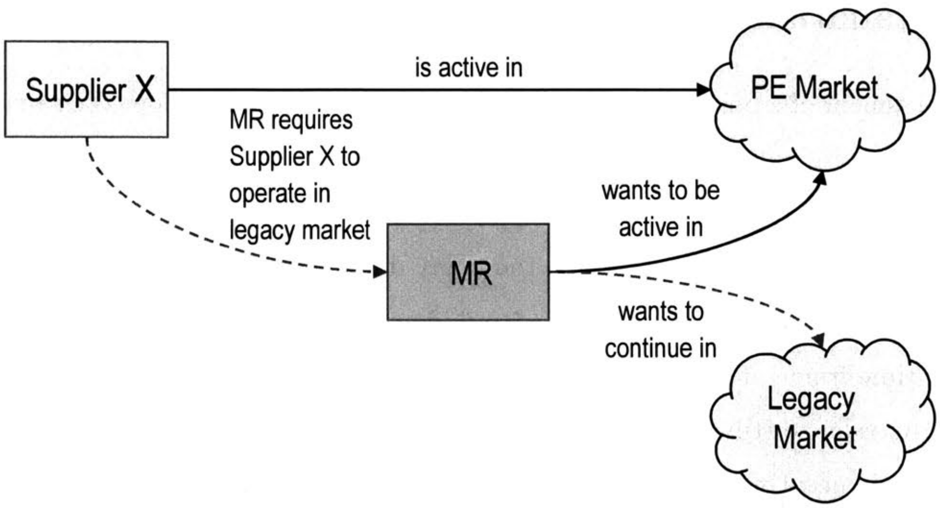

Figure 5-7: Supplier retaliation scenario 2

The opinion of the sourcing representatives was, that MR, although engaged in several single sourcing relationships, is not exposed to either of the two scenarios. Hence, for the scope of this work, we conclude, that the risk of retaliation from suppliers is low.
Flowchart B-2 (in Appendix) has been developed to provide a tool to quickly assess the likelihood of supplier retaliation based on Porter's method to assess bargaining power of suppliers. To gain more certainty about whether a supplier will retaliate or not, a close analysis of the specific MR-supplier relationship has to be carried out. Soft aspects such as the intra-personal relationship between MR purchaser and supplier sales representative will become relevant at this point.

5.5 Reaction from Competitors

As last part of the market reaction analysis we look at the (possible) competition in the PE-market and try to evaluate their potential moves. At the time of this report there was no knowledge about a commercially available solid state transformer for the medium-voltage distribution grid. However, subject matter experts and leading market research institutes agree, that SSTs and other power electronics devices, will play a key role in the design of *smart grids*, [31], [7]. In addition to the assumptions from page 61 we add two other assumptions for this part of the analysis (and restate the previous assumptions for completeness):

1. *PE-product, such as SSTs, are not 1:1 substitute for conventional LFTs and will sell*

alongside the conventional business in the midterm future (5-10yrs) generating on top-revenue to current MR product lines (no cannibalization)

2. *PE-products, such as SSTs, have the potential to replace LFTs in the long term, similar as smart-phones have replaced conventional cellular phones over time or digital photo cameras have replaced analogue ones*

3. *There will be a short term demand for PE-products, such as SSTs for the medium-voltage distribution grids. However, there is still a high degree of uncertainty about demand volume*

4. *No-large CAPEX investments required to enter the PE-market*

Assumption no. 3 is based on the figures of market research from *Frost & Sullivan* [7] and MR internal market study [32], which are both indicating (small) demand in 2020.
Assumption no. 4 is based on the fact, that power electronic devices such as SSTs and UPFCs will have a much higher share of sourced components compared to MR's current OLTC product line as shown by [33] and as will be seen for a simplified UPFC architecture in the next section. Specifically this assumption includes that no investment will be made in semiconductor fabrication capacity for the power electronic components, e.g. IGBTs.
Building on these assumptions and according to economic theory, we state that somebody will fill the future demand for the product as soon as their marginal cost drops below the demand's willingness to pay. It is also known, that *Siemens*, a German industrial manufacturing company, is working on own solutions for the same PE-market MR is targeting. It is probable that, whoever is able to offer the right product at the right price first, will be able to capture a substantial share of the then present demand, leaving less for the subsequent entrants. Also, if the product fulfills expectations and requirements, it will strengthen the manufacturers track-record, giving them an additional edge over competition for further sales. This may be easier for industrial giants like *ABB*, a Swedish-Swiss industrial manufacturing company, and *Siemens* who may be able to offer the new technology as part of a comprehensive (smart grid) infrastructure solution. However, it is also possible that smaller but more agile players like MR can identify the right application first. MR's strong brand and industry-wide recognized high quality standards are certainly helpful in this context.
It is hence thinkable, without being able to prove it at this point, that first movers have an

advantage in the PE-market for medium-voltage applications. The point we are trying to make here is, that time to market relative to the competition matters. It is more important to be first than fast.

Chapter 6

Case Study: Unified Power Flow Controller

The case study is an attempt to evaluate the impact of uncertainty on the Expected Net Present Value (ENPV) of a power electronics based unified power flow controller (UPFC). Specifically we will evaluate how timing of market entry relative to competition, different demand scenarios, uncertainties about development costs and development duration may impact the commercial success of the developed product. The insights from the analysis shall help develop suggestions for MR on what to focus during the product development of their PE products.

6.1 Introduction

The product under consideration is UPFC. A UPFC is an electrical device for providing fast-acting reactive power compensation on electricity networks. The technology is still under development and it is not clear yet, how the new technology will be received by customers. Besides demand, the early stage in the development cycle of the product is a source for other uncertainties such as development and manufacturing costs, development time, and possible competition.

The revenue from sales of the envisioned power flow controller will not be the only source of value for MR. The development of the technology, resulting patents and the build-up of know-how and new skills among the company's workforce represent an important strategic value to MR and are, at this point, the main driver for the entire project. The case study will not attempt to evaluate the strategic value of the technology development and its potential to generate sales other than the one related to the power flow controller.

Note: *All numbers in this analysis are disguised in order to not disclose proprietary information*

6.2 Purpose of Analysis

The purpose of this analysis is to identify options to improve the ENPV of MR's UPFC. To do so, it is necessary to identify first which uncertainties could affect the project in a negative way. Second, we will need to evaluate the scale of their negative impact, and third, identify ways to hedge against or prevent that negative impact. We could also say that we are improving the ENPV of the project by trying to minimize the effective downside of the uncertainties involved in the project.

6.3 System description

The power flow controller analyzed in this study is designed for applications in the medium-voltage grid($<$66kV), which is expected to be subject to more demanding requirements in the future as explained in section 2.2. While the product design and development are not finalized yet, the preliminary BOM is providing guidance on which components and modules could be developed and manufactured in-house.

A workshop conducted with subject matter experts of MR has indicated that 70% of the bill of material (BOM), measured in terms of cost of the BOM-items, will be sourced. Hence, only 30% of the BOM will be taken into consideration for potential in-house manufacturing. This represents a major shift compared to MR's electromechanical products, which are almost entirely manufactured in-house, starting from sourced raw materials.

For the analysis presented in this report we will assume the BOM-cost structure as given. This is mainly driven by the fact, that it would be virtually impossible for MR to build the capabilities and expertise required to increase the share of in-house manufacturing to percentages beyond 30%. An example are the IGBTs. These are manufactured in semiconductor fabrication plants, which require large quantities to be economically viable and well beyond MR's demand for their products. The bill of material is listed in appendix C-4.

6.4 Model description

The model used to carry out the analysis is a discounted cash flow model. The cash flows are calculated for the periods 2017 to 2030 and each year represents a period. It is assumed the product is discontinued after 2030 and hence no future revenue is generated from the product after 2030 [1]. The cash flows in each period are determined by

$$CF_i = (p - mc_i) \cdot q_i - fc_i \tag{6.1}$$

with

p...price per unit in EUR

mc_i...marginal cost per unit in EUR in period i

q_i...quanity sold in period i

fc_i...fixed costs in period i

The quantity q_i is the product of total demand in each period d_i and MR's market share s_{MR_i} in the same period.

$$q_i = d_i \cdot s_{MR_i}$$

Each cash flow is then discounted with the discount rate r to the present (year 2017, $i = 0$) giving us the discounted cash flows DCF_i for each period.

$$DCF_i = \frac{CF_i}{(1+r)^i}$$

The net present value NPV of the UPFC is then simply the sum of the discounted cash flows.

$$NPV = \sum_{i=0}^{n} DCF_i$$

Since the demand for the UPFC will be modeled as a random variable, the output of the model will not be a deterministic NPV but an expected NPV or $ENPV$, analogous to ENPV introduced in section 4.7. A Monte Carlo simulation of 2000 trials is used to calculate the ENPV.

[1]this assumes also that no revenue from service, maintenance and sales of spare parts is generated after 2030

6.4.1 Model parameters

The model relies on nine parameters which need to be set, which are explained in detail in the next sections.

1. Demand d_i, expressed in units per year.
2. Market share s_{MR_i}, expressed in %.
3. Market entry of MR, expressed as year.
4. Market entry of competition, expressed as year.
5. Unit price p_i, expressed in thousands of EUR (kEUR) and representing the market price at which the UPFC is sold.
6. Marginal cost of units in first period mc_1, expressed in thousands of EUR (kEUR).
7. Learning factor LF, expressed as a unit-less number smaller than 1 used to calculate a reduction in the marginal costs in dependency of the cumulative number of manufactured units.
8. Development costs, expressed in thousands of EUR (kEUR).
9. Discount rate r, expressed in % and representing the rate at which future cash flows are discounted

6.4.2 Demand

The power flow controller will be based on power electronics. Current equipment for the distribution grid, such as regulated transformer and on load tap changer, are based on electromechanical technology, an old but very reliable technology. The customers in the space value reliability above all and hence, require a very strong use case in order to adopt the new solution. So far, this use case is not very well defined and dependent on external factors such as the further growth of renewable energy sources and the price development of power electronics. MR has constructed two demand scenarios, one pessimistic and one optimistic, to account for the uncertainties. The optimistic scenario assumes that the new technology will be trusted by customers and chosen for most of the 66 kV applications in distribution grids. Under this scenario MR estimates cumulative market demand will be approximately 1500 units until 2025. To model demand after 2025 we assume that total cumulative demand m for the UPFC follows a Bass-diffusion curve with coefficient of innovation $p = 0.008$ and coefficient of imitation $q = 0.7$. The parameters have been chosen to approximate MR's demand estimations until 2025 and then model the end of the product life-cycle until its discontinuation in 2030 leading to a total cumulative demand of 2000 units. The long life-cycle of the product of 12 years is attributed to the characteristic of the market of being slow in adopting a new technology and new technologies emerge only at a low rate. The market is hence considered to fall into the *calm waters* quadrant of Suarez and Lanzolla's framework introduced in section 4.4.2 and illustrated in figure 4-8.

The pessimistic scenario assumes that the technology will only find utilization in a few very specific applications which require a high degree of customization. Under this scenario, the projected cumulative market demand totals only 250 units until 2025 and will also decrease to 0 until the year 2030 with a total cumulative demand of 500 until that point. The parameters q and p of the Bass-model are not changed for this model.

Thirdly, there is an average scenario, which assumes an average proliferation of the new technology. In this scenario cumulative demand will be 750 unit until 2025, and reach 1100 until 2030.

The analysis will account for the uncertainty in demand by assuming that there is a 33% probability of a high demand (optimistic scenario), a 33% probability of an average demand, and a 33% probability of a low demand (pessimistic scenario). Hence, the Monte Carlo simulation will randomly choose either three curves in each run. The three demand scenarios are summarized in figure 6-1

6.4.3 Market Share

The market share MR will be able to capture depends mainly on its market entry relative to its competition. According to section 4.4.3, a first-mover in the market for power regulation and control equipment for the medium-voltage distribution grid is likely to capture a first-mover advantage. This is reflected in the development of the market share. There are three possible scenarios:

1. MR enters market first

2. Competition enters market first

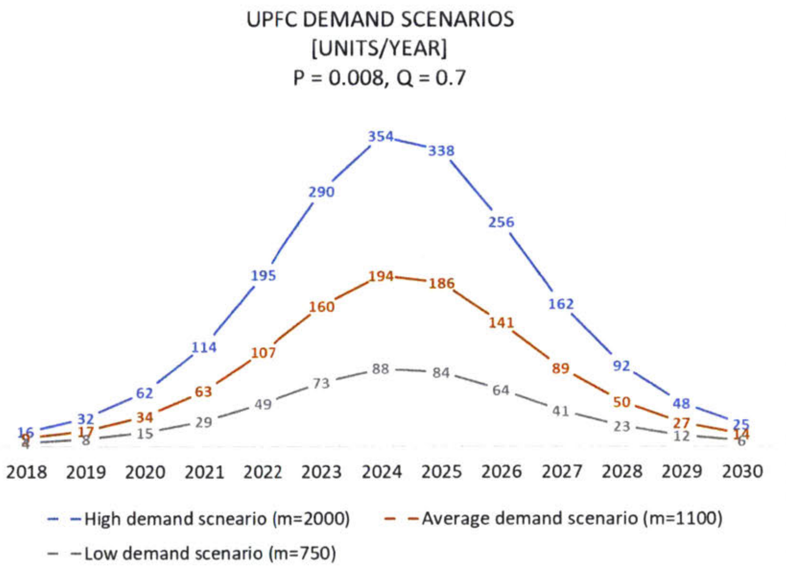

Figure 6-1: UPFC demand projections

3. MR enters market at the same time as competition

MR Enters Market First

If MR enters the market first, its initial market share will be 100% and capture all of the demand. Hence, in the periods without competition MR sales will equal demand:

$$q_i = d_i$$

As soon as competition enters, the demand will slowly decrease and converge to an expected long term market share of $s_{MR_{lt}} = 40\%$. MR's strong brand, which stands for quality, reliability, and innovation, and it's capability to reach similar market shares in current core products are the main drivers for selecting this value. The FMA is reflected in the slow decline of the market share over time. The decline follows an exponential function with a y-intercept of 1 (=100% market share) and an asymptote of 0.4.

$$s_{MR_i} = (1 - s_{MR_{lt}}) \cdot e^{-a \cdot i} + s_{MR_{lt}} \tag{6.2}$$

Coefficient a controls how rapidly the market share is going to decline. For this analysis it has been set to $a = 0.22$: the market share of the first-mover declines so that it reaches

50% in 2025. If the market share were to decrease faster, a has to be increased, if it were to decrease slower, a has to be decreased. In the extreme case of $a = 0$, market share stays constant at 100%. Since the sum of MR's and competition's market share needs to sum up to 100%, the market share of the competition is defined as:

$$s_{C_i} = 1 - s_{MR_i} \tag{6.3}$$

Figure 6-2 shows the market share development according equation 6.2 with $s_{MR_{lt}} = 40\%$ and $a = 0.22$.

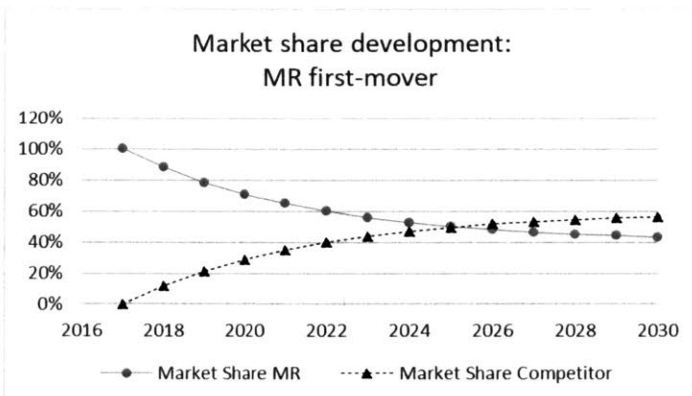

Figure 6-2: Market share development with MR as first-mover

Competition Enters Market First

If the competition enters the market first, MR will need to catch up and slowly build up market share year after year. The market share of the competition now follows equation 6.2 but with the asymptote set to $s_{C_{lt}} = 0.6$. Hence, the market share of the competition can be expressed as:

$$s_{C_i} = 0.4e^{-0.22i} + 0.6$$

MR's market share is then:

$$s_{MR_i} = 1 - s_{C_i}$$

This case is illustrated in figure 6-3.

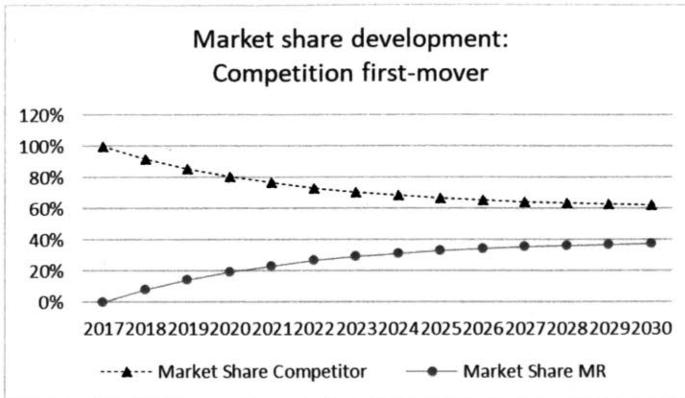

Figure 6-3: Market share development with competition as first-mover

MR and Competition Enter Market at the Same Time

If MR and competition were to enter the market at the same time, it is assumed that MR will be able to capture 40% and protect it over the lifetime of the product. However, it will not be able to grow it at the expenses of the competition, leading to a constant share. Respectively, the market share of the competition stays constant at 60%. Figure 6-4 shows this case.

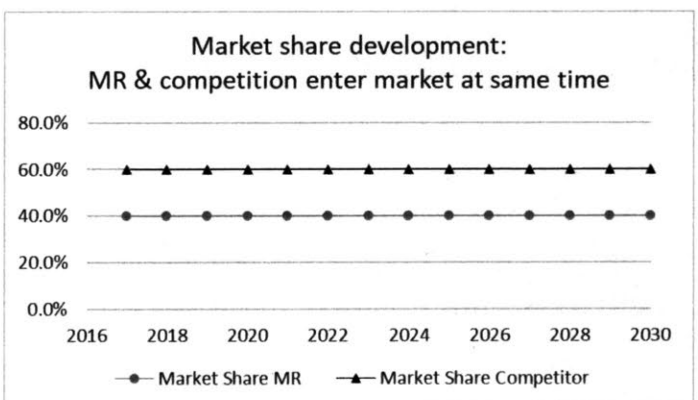

Figure 6-4: Market share development with MR and competition entering market at the same time

6.4.4 Market entry of MR

This parameter simply indicates when MR's product development is concluded and the UPFC is ready to be sold in the market. Only from this year onwards MR will generate revenue.

6.4.5 Market entry of competition

This parameter indicates in which year the competition enters the market with a product. In conjunction with the previous parameter *Market entry of MR* it is determined which market share curve the model applies for its calculations.

6.4.6 Marginal Cost

The marginal cost curve is assumed to be flat within one period, independently from the quantity produced. Hence, all units manufactured in the same period (=in the same year) have the same marginal cost. However, MR will benefit from a learning curve from one period to the next, resulting in lower marginal costs. If a component/sub-component is manufactured in-house variable costs include labor associated with in-house manufacturing of component as well as material costs of one unit. If the component is purchased, variable costs will be the purchasing price of the component from a supplier including marginalized set-up costs/fees charged by the supplier upfront to start development of the component. As stated later on in section 6.5 the current marginal cost of one UPFC is set to be EUR 1000k. If the marginal cost is not sufficiently low at market entry, the project could still yield a positive ENPV if the marginal cost drops below market price as more units are manufactured and MR benefits from the learning curve.

6.4.7 Learning factor

It is assumed that MR will be able to reduce their marginal costs from one period to the next as more units are being produced. Savings will originate from efficiency gains in the manufacturing processes. The effect of decreasing marginal costs as a function of the cumulative number of units produced is described by the following equation:

$$mc_i = mc_1 \cdot LF^{ln(\sum_0^{i-1} q_i + 1)}$$

where

$mc_i \cdots$ *resulting marginal costs for all units produced in period i*

$mc_1 \cdots$ *initial marginal cost valid for units produced in period 1*

$LF \cdots$ *learning factor,* $LF \epsilon [0, 1), \overset{!}{<} 1$ *to model declining marginal costs*

$q_i \cdots$ *number of units manufactured during period i*

The additional unit produced in the logarithmic expression makes sure that the equation solves for the first period when no units have been manufactured so far. Figure 6-5 shows the development of marginal costs in dependency of units produced and different learning factors.

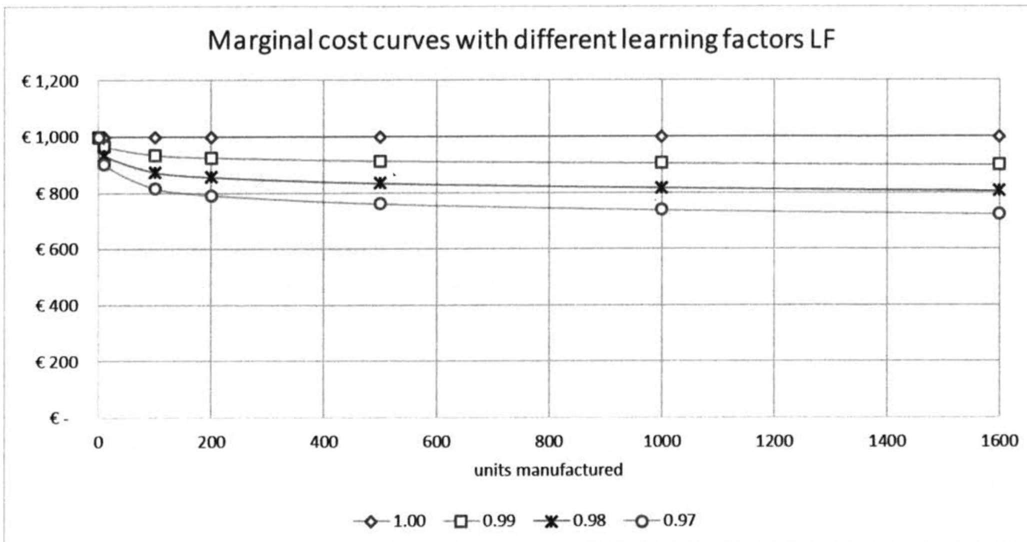

Figure 6-5: Marginal cost curves with different learning factors LF

As we can see a learning factor $LF = 1$ corresponds to no opportunity to reduce unit costs through learning. This could be the case when production is outsourced to a contract manufacturer at a fixed price per unit. Cost reductions from learning would be fully internalized by the contract manufacturer. With a learning factor $LF = 0.99$, the unit cost would drop by approximately 10% after 1600 units manufactured. Since cost savings will translate one to one to additional profit, a 10% unit cost reduction would represent already a very substantial improvement for the product business case. However, it is also an improvement which is very difficult to achieve, especially if a large share of the product is sourced and hence the cost of that share is fixed (=purchase price from suppliers). Additionally, changing raw material and labor costs could potentially offset any cost savings achieved through improvement of the production processes. Nevertheless, MR targets unit cost reductions of 10% over the lifetime of their products.

6.4.8 Market Price

The market price is the price, at which the product is intended to be sold in the market. As mentioned earlier MR's marketing department has found, that the market price for a UPFC with a voltage level of up to 66 kV could be around EUR 950k. This price would allow MR to work with its current BOM cost structure, since the assumed learning curve would make the marginal cost drop below the market price over the lifetime of the project (at least in the high scenario). If it turns out, that the market price is below marginal cost, MR could just stop the project and limit their losses to the already spent development costs.

6.4.9 Development Costs

Development cost includes upfront investment required to develop components and subcomponents of the product in-house, including specifications, simulations, technical drawings and manufacturing documentation [man-hours]. It also includes upfront investment for engineering time required to develop specifications for suppliers of the component, manage integration of the purchased component and all other MR internal engineering/ development work associated with the outsourcing of the components or subcomponents. Development costs also include the investment in subject matter expert knowledge in form of consulting services or hiring cost. The development costs are estimated to be EUR 6000k with the current configuration. Development costs would change if MR decides to insource more or less value of the product compared to the current configuration or if MR decides to assign more people to the development of the UPFC.

In the model the development costs are spread in equal fractions over the years prior to MR's market entry. Also, it has been agreed to not include other fixed costs than development costs in this evaluation[2]. Hence, the development costs in each period represent the only fixed costs fc_i from equation 6.1.

6.4.10 Discount Rate

The discount rate is used to discount the future cash flows to their present value. A discount rate of 12% is used for this analysis[3].

[2]it is assumed that other fixed cost related to the the UPFC, such as SG&A, and manufacturing floor space, machinery can be covered with current resources

[3]the discount rate used is purely exemplary and does not allow any conclusion on the discount rate MR may use for the evaluation of their projects

6.5 BOM cost structure

The current bill of materials of the UPFC is structured in four levels and contains 46 individual line items with a total item count of 5601 (see appendix C-4). The leveled structure helps to break down the product into main assembly groups and individual modules. Level 1 is the UPFC itself, level 2 comprises the modular multilevel converter (MMC), the pre-charging unit and individual components which are directly associated to the UPFC. On level 3 we place components associated with the MMC and the pre-charging unit. A major subassembly associated with the MMC, and hence also placed on level 3, are the IGBT cells. Level 4 finally contains all components which are constituents of the IGBT cells. The dependencies of this structure are visualized in figure 6-6.

	Level 1	Level 2	Level 3	Level 4
1	L1_UPFC	L2_Application Controller		
2		L2_Bypass Unit		
3		L2_Circuit Breaker		
4		L2_Contactor		
5		L2_Current Measurement		
6		L2_Discharging and Earthing Unit		
7		L2_Disconnector		
8		L2_Filters		
9		L2_MMC Converter	L3_Busbar	
10			L3_Current Measurement	
11			L3_IGBT Cell	L4_Busbar
12				L4_Capacitors
13				L4_Cell Bypass Unit
14				L4_Cell Control Circuit
15				L4_Cooling Unit
16				L4_Current Measurement
17				L4_Discharging Resistor
18				L4_Fiber Optic Cables
19				L4_Gate Driver
20				L4_IGBT
21				L4_Mechanical Frame
22				L4_Power Supply
23				L4_Snubber Capacitor
24				L4_Voltage Measurement
25			L3_Insulator	L4_Barrier Board
26				L4_Control Electrodes
27				L4_Isolation Systems
28			L3_MMC Cabinet	
29			L3_MMC Controller	
30		L2_Phase Leg Reactors		
31		L2_Pre Charging Unit	L3_Charging Resitstors	
32			L3_Circuit Breaker	
33			L3_Contactor	
34			L3_Disconnector	
35			L3_Transformer	
36		L2_Series Transformer		
37		L2_Shunt Transformer		
38		L2_Surge Arresters		
39		L2_Voltage Measurement		

Figure 6-6: Leveled structure of UPFC components

The BOM cost of the current UPFC configuration sums up to a total value of EUR 1m. These are distributed as follows:

- 80% (EUR 800k) of the cost is allocated to the 120 IGBT cells of the current UPFC configuration (level 3 and level 4)

- 19% (EUR 190k) are distributed among individual components of the UPFC (level 2) and the two MMCs (level 3)

- 1% (EUR 10k) are allocated to the pre-charging unit (level 3)

The 30% (EUR 300k) of the BOM which could be developed and manufactured in-house are almost entirely consolidated in the IGBT cells. Only EUR 30k or 3% of total BOM cost are not part of the IGBT cells. Figure 6-7 is providing a comprehensive overview of the BOM cost and table C-4 an overview of the BOM structure.

	buy		make			
	Sum of BOM qty	Sum of Product mix variable	Sum of BOM qty	Sum of Product mix variable	Total Sum of BOM qty	Total Sum of Product mix variable
L1_UPFC	59	€ 130.00	7	€ 10.00	66	€ 140.00
L2_MM Converter	588	€ 30.00	122	€ 10.00	710	€ 40.00
L3_IGBT Cell	3600	€ 450.00	1200	€ 270.00	4800	€ 720.00
L2_Pre Charging Unit	22	€ 90.00	2	€ 10.00	24	€ 100.00
Grand Total	**4269**	**€ 700.00**	**1331**	**€ 300.00**	**5600**	**€ 1,000.00**

Figure 6-7: UPFC BOM cost break down (cost figures in kEUR)

The BOM cost distribution gives a first idea on how to best tackle cost reduction initiatives. Assuming the current configuration will be final, MR should focus their efforts on a cost-efficient design and the development of manufacturing capabilities for IGBT cells. Further more, the purchasing department needs to get involved early on, since 70% of the BOM cost is within their responsibility. This is also in line with findings from the preceding LGO thesis project, carried out by Juan, 2017 [33]. A first market research conducted by MR indicates that the current total BOM cost is above the estimated viable market price [32].

6.6 Main assumptions for the analysis

The following three assumptions are made and valid for all parts of the analysis.

- For this project the company is assuming, that overheads will be covered by current staffing level in the company. Hence, the ENPV analysis does not include an additional overhead position.

- The company is expected to manufacture/assemble the new product with current underutilized production space, and equipment. Hence, no capacity costs are considered in this analysis.
- The company assumes manufacturing workers to be a fully variable resource. Hence, all labor is included in the marginal costs as outlined above.

6.7 Deterministic base case scenario

In the base case demand will follow the average demand distribution defined by the Bass-model with a total cumulative demand $m = 1100$ units. It is further assumed that MR enters the market in 2020 together with competition. The market shared distribution will hence be constant at 40% for MR and 60% for the competition over the product-lifecycle. The parameters used for the base scenario are summarized in figure 6-8. The base case scenario yields a NPV of -1.408 mEUR and would hence not be an economically viable case.

Longterm market share MR		40%
Market entry MR [year]		2020
Latest market entry Comp [year]		2020
Unit price [kEUR]	€	950.00
Unit cost in 1st period [kEUR]	€	1,000.00
Learning factor [-]		0.99
Development cost [kEUR]	€	6,000.00
Discount rate [%]		12%

Figure 6-8: Deterministic base case parameters

6.8 Sensitivity analysis of NPV

The sensitivity analysis will focus on changes in five parameters: demand, market entry of MR, market entry of competition, learning factor and development cost. Marginal cost and market price will be assumed to be at a level which allows MR to enter the market and are hence fixed.

To identify which of the uncertainties have the largest impact on the ENPV we compute the deterministic NPV of the project by changing only one parameter at the time. All other parameters are fixed at their values of the base case scenario. For each parameter we will look at the best and worst case. This gives us a better understanding of the underlying risks of the project, prior to running the Monte Carlo simulation. The sensitivity analysis reveals

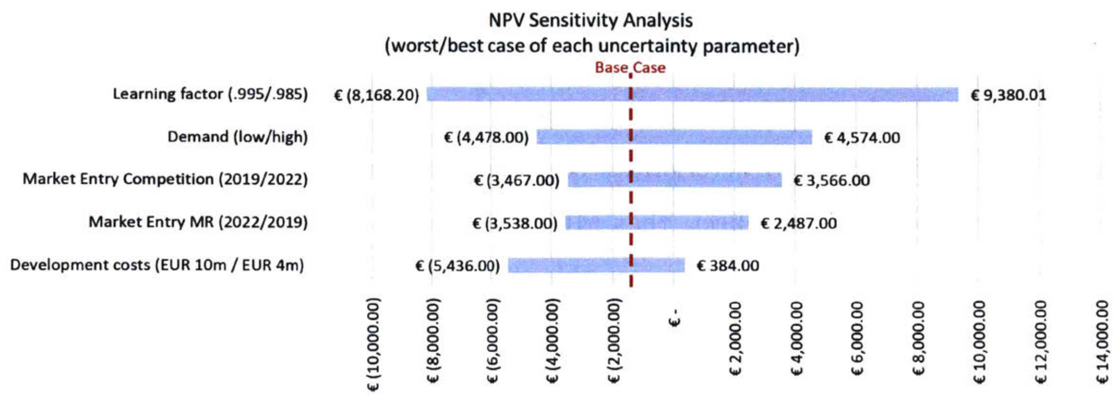

Figure 6-9: NPV sensitivity analysis (units: kEUR)

Source of uncertainty	Base parameter	NPV Base case	Unfavorable development	Favorable development	NPV low	NPV high
Development Costs (EUR 10,000k / EUR 4,000k)	€ 6,000.00	€ (1,408.00)	€ 10,000.00	€ 4,000.00	€ (5,436.00)	€ 384.00
Market Entry MR (2022/2019) [year]	2020	€ (1,408.00)	2022	2019	€ (3,538.00)	€ 2,487.00
Market Entry Competition (2019/2022) [year]	2020	€ (1,408.00)	2019	2022	€ (3,467.00)	€ 3,566.00
Demand (low/high) [units]	1100	€ (1,408.00)	500	2000	€ (4,478.00)	€ 4,574.00
Learning Factor (.995/.985) [unitless]	0.99	€ (1,408.00)	0.995	0.985	€ (8,168.20)	€ 9,380.01

Figure 6-10: Table for NPV sensitivity analysis (units: kEUR)

that the learning factor has the largest impact on the performance of the project and that profitability is highly sensitive to small changes in the learning factor: with a 5% unit cost improvement from the current level after 1600 manufactured units ($LF = 0.995$) the NPV is deeply negative, but with a 15% unit cost improvement ($LF = 0.985$) the UPFC becomes a big success (figure 6-9). The high degree of sensitivity of the NPV to a change in learning factor results from the fact, that the current product cost is very close to the feasible market price and hence, small changes can push the NPV in either negative or positive territory. In fact, since the product cost is slightly above market price, a product cost reduction is necessary in the first place, to make the project economically feasible. Due to the fact, that the current BOM cost structure foresees 70% of the product to be sourced, it is, however, unlikely to assume product cost reduction of more than the targeted 10% will be achieved. For this reason the learning factor will be fixed at $LF = 0.99$ for the development of further scenarios.

Following the learning factor, demand is the second uncertainty affecting the business case of the project (figure 6-9). This did not really come as a surprise, since the two scenarios (high/low) cover a very broad range from an extremely pessimistic to a more than optimistic outlook for the new product.

Much more interesting is the comparison between the uncertainties around market entry of MR and the competition, which will directly impacting MR's market share. We can observe, that if the competition enters the market just one year before MR (competition enters in 2019), the project NPV for MR deteriorates considerably compared to the base scenario. This is to be attributed to the effect, that MR would need to "win back" market share from the competition. Of course, we only see this effect, because the first-mover effect, and hence this specific market-share development, has been "built into" the model. However, it exemplifies the substantial impact a possible FMA could have on the project.

The same effect is visible if we look at MR's market entry. Being able to enter the market only one year before the competition (MR market entry in '19, competition in '20) would make the UPFC economically viable according to the model (NPV = EUR 2.48m).

Another observation we can make is, that if MR is ready with the development of the product only in time for a market entry in 2020, but competition enters even later in 2022, the project becomes viable with an NPV of EUR 3.56 million. This is a better NPV compared to the case in which MR enters in 2019 and competition in 2020. In this model it is hence more beneficial to enter before the competition than entering early: the latter will only yield the upsides from a few additional sales in early years, whereas an entry before the competition secures long term first-mover benefits.

Last, and as expected, a reduction of the development cost from EUR 6m to EUR 4m will considerably improve the NPV of the project compared to the base case, and in the model setup yield a positive NPV of EUR 384k.

6.9 Analysis including uncertainty

Now we want to see how the NPV of the project will change after we apply uncertainty to the model and change some of the parameters.

First, we will randomize which demand curve is used for the project, according to the following probabilities: The probabilities for this simulation are not based on market research, but are based on the experience that extreme scenarios are less likely to occur than average

Demand scenario	Cumulative demand (m)	Probability
high	2000 units	25%
average	1100 units	50%
low	500 units	25%

Table 6.1: Probabilities of demand scenarios

ones.

The project now yields a NPV of EUR -0.65m. The result is higher (less negative) than the NPV for the deterministic base case but still negative. In the base case including uncertainty MR can take full advantage of the upside of the high demand scenario, since we assumed no capacity restrictions, but is also hit by losses of a low demand scenario. The NPV is less bad than in the deterministic base case, because the upside of the hight demand scenario is slightly better than the downside of a low demand scenario.

Because we introduce three very distinct scenarios with specific probabilities and the NPV is the average over all 2000 random trials we talk about an Expected NPV or ENPV: in reality only one of the three scenarios is going to materialize, and we will get either the high NPV (in the high scenario) and average or a low NPV (and in fact negative both average and low scenarios). This is something we need to keep in mind when taking the decision whether to go ahead or not with the project. The cumulative density function (CDF) of this base case with demand uncertainty visualizes the three NPV steps very well: in 25% of the cases our NPV will be below EUR -4.7m, in 75% of the cases below EUR -1.7m and in 100% of the cases below EUR 4.5m.

6.9.1 Analyses of alternative scenarios

Let's take the base case with demand uncertainty as our new base case and see if we can improve it and reach a positive ENPV. We remember from the sensitivity analysis that MR will be able to capture a FMA in form of higher market share if it enters the market before our competition. If we set MR's market entry to 2019, and leave the competition entering the market in 2020, the ENPV jumps to EUR 3.8m. This is attributed to the fact, that the additional market share will provide a strong upside in a high demand scenario. However, it will not help us to hedge the losses in a low demand scenario.

Similarly, our ENPV will substantially decrease if we enter the market in 2020 but our competitors already in year 2019 and hence capture the FMA. Figures 6-12 and 6-13 illustrate

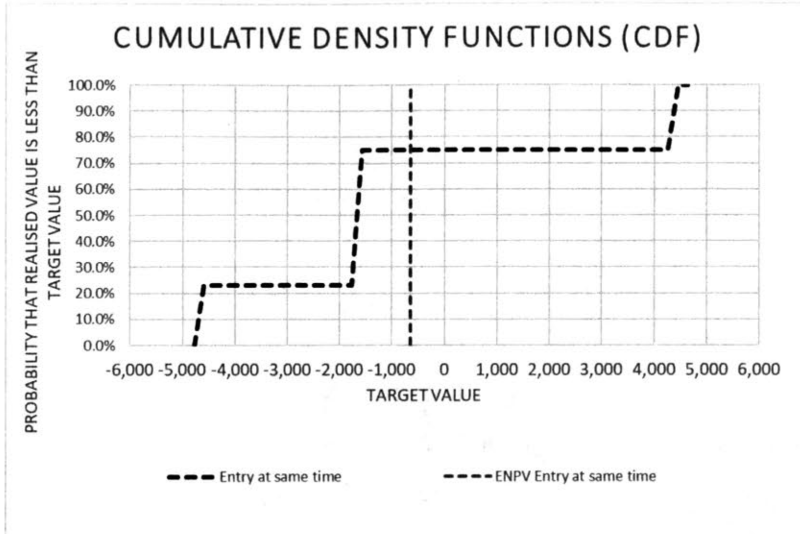

Figure 6-11: CDF of base case with demand uncertainty (Target value units in kEUR)

how the three scenarios compare to each other.

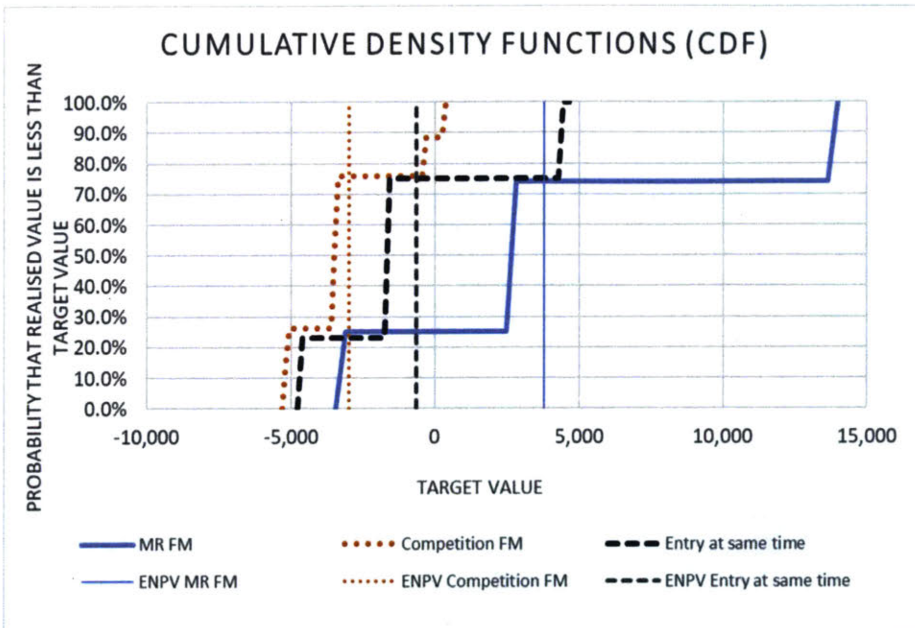

Figure 6-12: CDFs and ENPV comparison of different marekt entry points (Target value units in kEUR)

	MR first-mover	Competition first-mover	Entry at same time
ENPV	**€ 3,796.71**	**€ (2,982.81)**	**€ (647.23)**

Figure 6-13: ENPV comparison of different marekt entry points

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Chapter 7

Conclusions of Part I

The analysis of possible market reactions and the case study of a UPFC concept has provided arguments for supporting the following statements:

1. If MR were to enter the PE-market with a product for the medium-voltage distribution grid, the risk of experiencing retaliation from customer of their OLTC product line is regarded as low.

2. Equally, the risk of experiencing retaliation from suppliers for their OLTC product line is regarded as low.

3. Based on the market characteristics of slow pace of technology and market evolution there is a good chance that the player entering the market for power regulation and control equipment for the medium-voltage distribution grid with a PE-based product first, will benefit from a first mover advantage.

4. The PE-based products will have a substantially lower in-house development and manufacturing potential for MR than the product of the current OLTC product line.

5. Costs for PE-based products are still too high for commercial applications.

6. A clear value proposition/use case still has to be developed in order to attract commercial customers.

7. Concerns regarding reliability of PE-based products may inhibit their adoption by commercial customers

From statements 1, and 2 we can suggest, that MR should pursue the development of PE based products. The development of new capabilities in a technology which is regarded to play an important role in future energy infrastructure can help MR to expand their strong position as trusted partner in the power industry. Furthermore it tackles one of MR's most pressing questions: what if electromechanical transformers and OLTCs become obsolete? Statement 3 suggests that a considerable effort should be made to enter the market before the competition. In order to do so, MR should focus on identifying ways to accelerate their product development. This requires at least two things:

1. Allocation of sufficient resources for the development of target products, such as SST or UPFC.
2. The organization developing the new products needs to be empowered to take quick decisions.

In order to fulfill the first requirement MR would probably need to increase their upfront investment in the project, which would mean an increment of the development cost position in the ENPV model. In the case study we can simulate this by assuming MR would invest EUR 8m instead of the required EUR 6m and enter the market a year earlier. The ENPV would be positive at EUR 2.0m and hence substantially better than in the base case. However, in the case of a low demand scenario, the product would not be profitable and MR would have to consider whether to abandon the project. The CDFs and ENPV with an EUR 8m upfront investment are summarized in figures 7-1 and 7-2.

The second requirement is more of organizational than of financial nature. The new venture should have the chance to either succeed or fail fast and hence should be separated from the OLTC core business and have a direct reporting line to top management. One possibility would be to create an own business unit or own legal entity for the new power electronics business. Besides quicker decisions, this option would also ensure more transparency of the performance of the power electronics business, since both negative or positive developments will not be "hidden" by the performance of the larger core business. This would enable decision makers to either support the business with new resources in case of early success, or limit losses by terminating the venture in case of a negative development (e.g. due to low demand). Since the new business unit would not have own production capacity, it must get it from MR's core business. This could be realized with a rent agreement for production

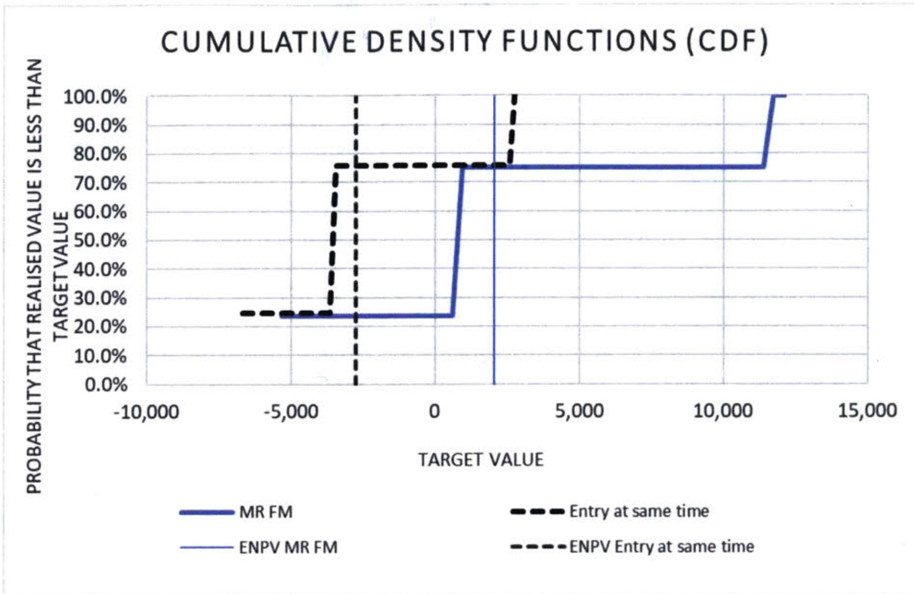


Figure 7-1: CDF of entering market early and EUR 8m upfront investment (Target value units in kEUR)

	MR first-mover	Entry at same time
ENPV	**€ 2,045.88**	**€ (2,749.71)**

Figure 7-2: ENPV of entering market early and EUR 8m upfront investment

space and equipment or utilize MR as contract manufacturer. In either way it ads a further cost element to the new business, which then need to be included in the NPV calculations. The low in-house development and manufacturing share of the envisioned PE-product will put more focus on the procurement capabilities of the company. A dedicated procurement organization or category management team with strong experience in the power electronics sector will be required to keep direct costs low, especially due to the expected low product volume. The low volume is also a reason why a considerable effort should be made to modularize the design of the PE-products and use as many "re-usable" components as possible for different applications in order to maximize volume. The IGBT cell, if selected for in-house development, should be designed in such way, that it can be used for different voltage levels by connecting several identical IGBT cells with each other.

During the project it became also clear, that the use case/value proposition for a PE-product for medium-voltage distribution grid applications still has to be defined. It is hence required, that sales and marketing focus on the identification of and the engagement with potential customers in order to define the use case and narrow down demand scenarios. A dedicated sales resource in the current power electronics competence group will be required to make progress on this important task.

It seems like differentiation and a competitive edge are more likely to originate from application design and less from manufacturing and built quality of the product. Hence, investments should be targeted at expanding and building capabilities in design engineering for power electronics and software engineering for application design. This could enable additional product functionality such as remote access and control of the device, better integration of products in existing grid and power plant infrastructure, and data acquisition from sensors for the development of additional services like preventive maintenance.

The concerns regarding reliability of PE-products and high direct costs due to over-engineering can be addressed by integrating failure mode and effects analysis (FMEA) and reliability engineering from the very beginning of the product design process. Part II of this report will outline the most important steps and showcase the application of the methodologies on a current system.

Figure 7-3 summarizes the recommendations of part I.

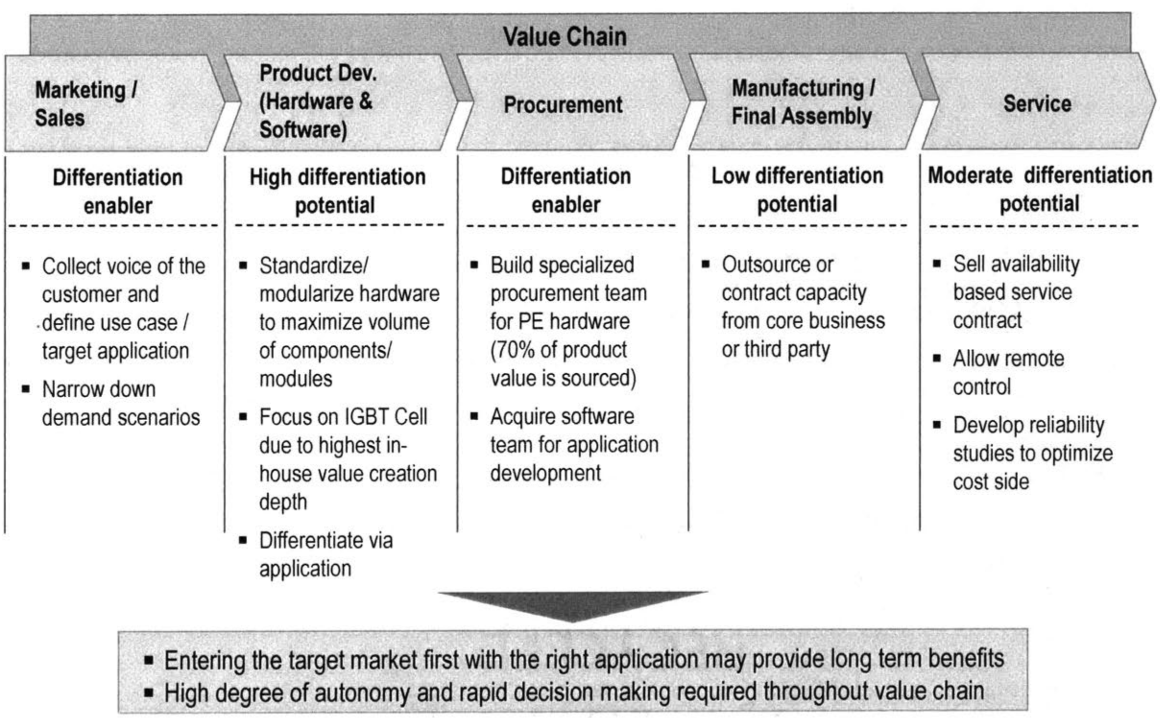


Figure 7-3: Summary of recommendations along the value chain

Part II

Failure Mode, Effects and Reliability Analysis of a Static VAR Compensator

As discussed in the previous part, two of the main challenges of establishing PE-based products as an alternative to the current electromechanical products are the costs of the new technology and concerns regarding its reliability. Failure Mode and Effects Analysis (FMEA) in conjunction with reliability engineering techniques may offer a way to tackle both of these challenges.

We want to show how the application of Failure Mode and Effect Analysis (FMEA) enables the quick development of top-level reliability models of the system which will help to keep product costs on target while still meeting the reliability requirements imposed by a customer or application. The underlying idea is to avoid over-engineered and hence too costly solutions by gaining a better understanding about how each system component affects the overall system reliability. In the same way insufficiently reliable components can be identified as well. Furthermore operations manager will face a trade-off when planning their maintenance strategy: which spare parts shall be kept on site (and paid inventory holding costs for) in order to maintain an optimal level of system availability?

We will show how to set up and perform the Failure Mode and Effects Analysis, which outputs are required to build the reliability model and how to use the latter to compute key reliability metrics and to identify cost optimization potential. The process will be showcased on a static VAR compensator which is currently being developed as a one off project by MR. Nevertheless the process can be universally applied to every other system and hence also to a future UPFC or SST.

Chapter 8

Static VAR Compensator System Description

The System under investigation is a static VAR compensator (SVC) which is currently being developed by MR to support an electric steel plant to meet its power quality standards during operations.

Steel plants with arc furnaces have a randomly varying power demand that can swing multiple hundreds of MW in short time intervals (30-90 minutes). The effects of this load change may be noticed in lights, PCs, and TVs: voltage and frequency will change and result in a change of light intensity. In addition, the arcs in each furnace of the mill can result in an imbalanced load that leads to undesired harmonic oscillations creating what one may call "dirty" power. This load connected to the grid can affect other customers connected to the grid [34]. SVCs are among the devices used to restore power quality, specifically by compensating the lack of reactive power in the grid and by filtering harmonics.

The SVC in this study is designed to ensure the compliance with European Norm IEC 50160 (reactive power, harmonics) at the point of common coupling of an electric steel plant similar to the one depicted in figure 8-1. It can provide reactive power compensation in a range of with a range of 30 MVAr (capacitive) to 10 MVAr (inductive). It

Electric steel plants operate around the clock with predefined maintenance intervals. In order to avoid penalty payments to the utility company when not meeting the power quality requirements at the point of common coupling it is critical that the reactive power compensation unit works reliably. Compliance with power quality requirements is measured with

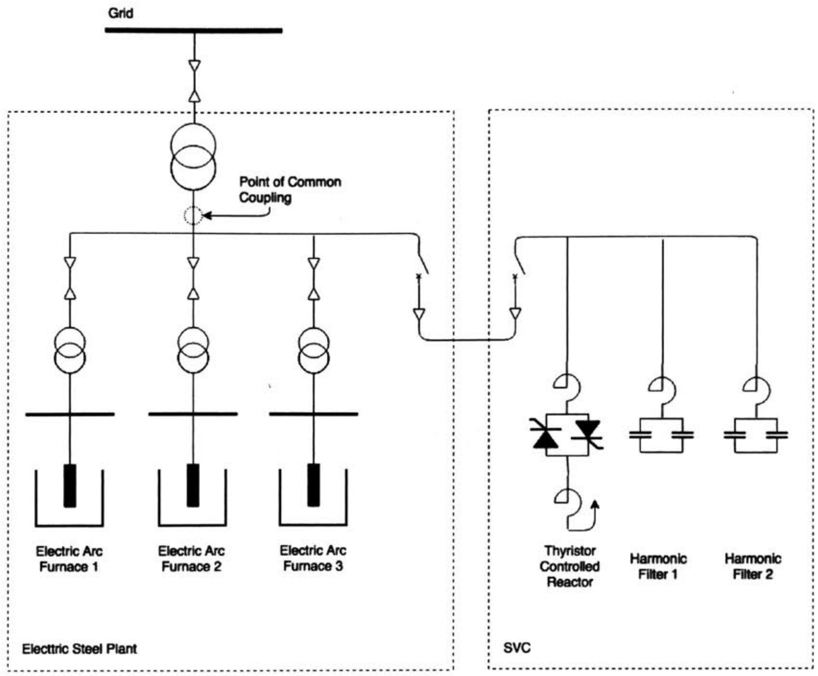


Figure 8-1: Schematic of electric steel plant and SVC

the "power factor" $\cos\varphi$, which needs to be between -0.9 and 0.9 in this case. To meet this criteria the SVC "injects" reactive power (either capacitive or inductive) into the circuit by converting active power.

Chapter 9

Design FMEA of Static VAR Compensator

In this chapter we will walk through the Design FMEA of the SVC introduced in section 8. For each step we will briefly summarize the lessons learned in order to help improve the next iteration of the FMEA.

9.1 FMEA Steps and Preconditions

From beginning to end there are eight steps to be conducted to complete one FMEA cycle according to Stamatis, 2003 [27] (remember that as the product develops a new FMEA cycle should be conducted.):

1. Select the team and brainstorm
2. Map functional block diagram and/or process flowchart
3. Prioritize
4. Collect data
5. Analyze data
6. Generate results
7. Confirm/evaluate/measure

8. Repeat

The single steps up to step six will be detailed in the next section and exemplified on basis of the actual SVC. Step seven and eight could not be performed within the time horizon of this project.

It is important to acknowledge that the FMEA is a technique that requires time to be performed properly. There is certainly a learning curve, but if done seriously it is not something a team can rush through. It hence is essential, that the effort is factored into the project budget and fully supported by management. After all, continuous improvement is first and foremost a culture and mindset which, in order to be effective and beneficial, needs to be ingrained into all hierarchy levels of an organization.

9.2 Step 1: Select the Team and Brainstorm

The selection of the right team is critical for the success of the FMEA. The team must be cross-functional and multi-disciplined and the team members must be willing to contribute [27]. It is important that subject matter experts (SME) are well represented in the team. The FMEA requires to think through complex systems and an understanding of their functional interconnections, e.g. how components, sub-modules, and modules work and interact with each other. In most cases, and definitely in this project, this is something only experienced (systems-) engineers can do. The other important function required is a FMEA facilitator with a good working understanding of the FMEA methodology. The facilitator does not necessarily need to have deep knowledge of the system, design, process, or service being analyzed, however it certainly is beneficial if one facilitator can conceptualize the system and understand the technical basics. The facilitator needs to make sure that the team of SMEs are familiar with the FMEA process. If the team is new to the process it is suggested that an introductory explanation about the FMEA methodology, its outputs and benefits is conducted out before the first working session.

During the working sessions, the facilitator needs to take care of guiding the team and ensuring steady progression. During this project we found that special attention has to be given to:

Focus on the objective: keep the objective of the FMEA in mind, and remind the team about it if activities and discussions are running of track.

Do not get lost in details: make sure the discussion stays at the agreed level of detail and that no time is wasted discussing in-depth technical details.

After the team has been established, the brainstorm session is intended to prioritize the opportunities of improvement and to set the direction of the FMEA [27]. This could be e.g. which of the four types of FMEA to perform or whether to focus on specific modules/components of the product or specific known failures.
The FMEA team assembled for the analysis of the SVC was very small. It comprised only three people, the head of product management for medium voltage power quality systems, an experienced systems engineer and FMEA facilitator, and the author (with some previous FMEA experience). For the purpose of this project, the mapping of a path from FMEA to a reliability model for MR's power quality products, the resources provided were sufficient. Within this step the team decided to focus the design FMEA on the functionality of the SVC to compensate inductive reactive power, and not on the entire set of functionalities of the SVC. The drivers for this decision were the limited time available for the project (it was on-top work on the day to day business) and the intention of the company to first evaluate potential benefits of the FMEA before rolling out the FMEA on a larger scale. It had also been decided that the FMEA shall be finalized in four to five sessions of about five to six hours each, a framework sufficient for completing one FMEA cycle.

9.2.1 Step 1 Lessons Learned

- More than one subject matter expert is recommended to perform a thorough FMEA. Ideally three to four should be involved in order to ensure correctness, completeness, and to distribute responsibility. Too few subject matter experts open up the risk that the FMEA will not be sufficiently thorough and that key failure modes may not be uncovered. Also, mistakes, which definitely can happen when establishing the functional interconnections, may not be caught.

- Ideally, one FMEA cycle is carried out in a block of consecutive days. This helps to keep the team focused and prevents that the team has to become familiar with the product again in each session. If this is not possible, effort should be made to minimize the the number of days elapsed between each session.

9.3 Step 2: Map functional block diagram

This step is required to create a common understanding of the system among the team members. It will also generate the output required to build the reliability model, specifically the reliability block diagram (RBD) of the system. The reliability block diagram will be based on the functional block diagram:

Functional Block Diagram: shows the major elements of the system and creates understanding how those elements affect the system itself or the other external systems [27].

In executing this step one can start from top to bottom, by identifying the top-level functions of the system or product and then break down each function several levels, until the most basic function is mapped. It should be noted at this point, that functions may coincide with a physical entity (such as a module or component), but do not necessarily need to.

In this project the team started to map out the main functions of the SVC. The functions should be expressed with at least one object and a verb and be as concise as possible. At this level four functions where identified:

- 1. compensate reactive power
- 2. reduce flicker
- 3. compensate harmonics
- 4. balance operating current

As defined in step one, we will focus on the function *compensate reactive power* from here on. In order to compensate reactive power over the entire range of 30 MVAr (capacitive) to 10 MVAr (inductive) it is necessary that the system is able to perform the functions *1.1 compensate inductive reactive power* and *1.2 compensate capacitive reactive power*. This method to break down functions one by one will lead to the functional block diagram depicted in figure 9-1. As we can see, the decomposition of a basic function can become quite granular. It is up to the team to find the balance between adding or omitting another layer of granularity.

We will also assign all the functions to physical components of the current SVC design.

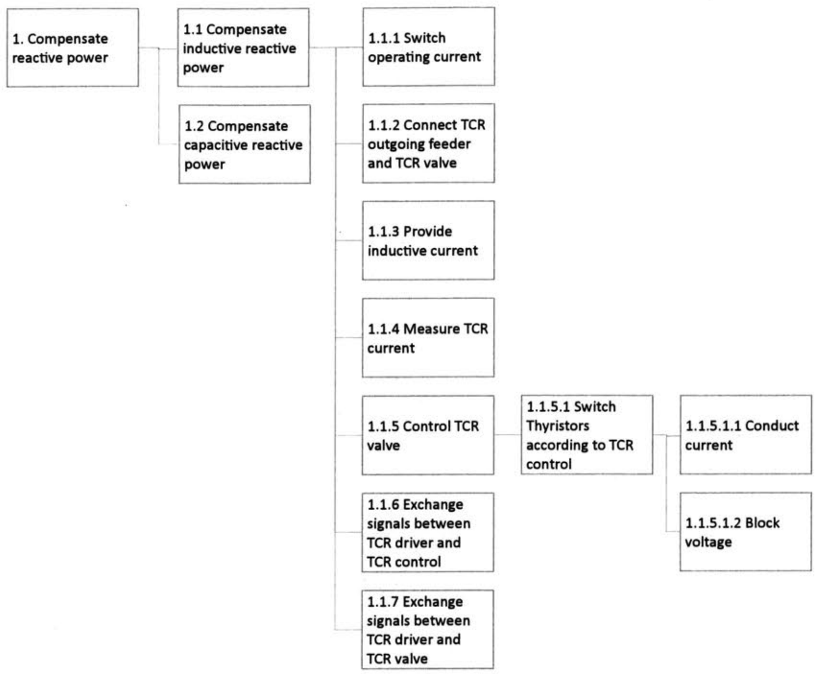


Figure 9-1: Functional block diagram of the function "compensate reactive power"

This is necessary for the extraction of the reliability block diagram later on, since we need to know which components or modules are involved in providing a certain function. The result is illustrated in figure 9-2.

Next, we determine potential failure modes for the functions. A failure mode is a loss of a design function [27]. If we take for example *1.1 Compensate inductive reactive power* then a failure mode is *1.1FM1 No compensation of inductive reactive power.* But what if inductive reactive power is being compensated but just not at the right level? This gives us a second failure mode: *1.1FM2 wrong compensation of reactive power.* This clearly shows that a function cannot only fail in one way, but in many (9-3). The right question to ask to identify possible failure modes of a function is "How could this system , design, component, subsystem, or process fail?".

The identification of failure modes needs to be done for all functions contributing to the main function *1.1 Compensate inductive reactive power* and hence for all functions listed in figure 9-2. The result is summarized in figure 9-4. In this figure the functions are grouped according to the physical entities they reside. Functions contributing to function *1.1 Compensate inductive reactive power* are highlighted in **bold** and their failure modes in ***bold***

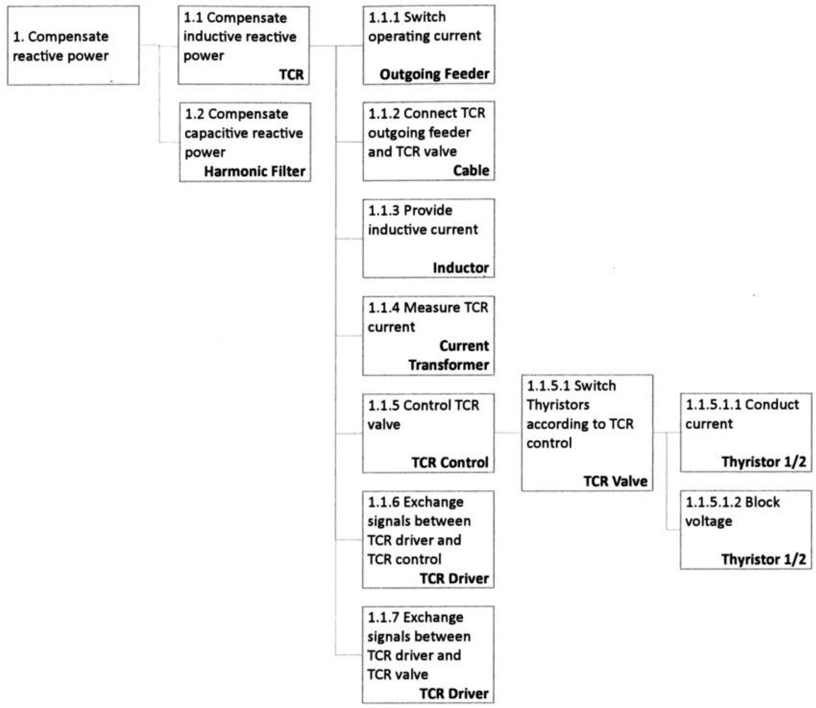


Figure 9-2: Physical components involved in providing the function "compensate reactive power"

and italic. Functions not directly related to function *1.1* are not emphasized. Considering we are currently only analyzing one function, the breakdown in contributing functions and failure modes generates an already quite complex network of interconnections. Therefore it is highly advised to use a software package to document the FMEA which automatically enumerates the functions/failure modes and keeps track of the interconnections.

9.3.1 Step 2 Lessons Learned

- It is challenging to focus on the functions without connecting them to physical entities. However, this is especially important at the beginning of a product development project in order to not limit the solution space (for providing a certain function) too early.

- The use of a FMEA software is highly recommended since the management of the complexity becomes very challenging in a regular spreadsheet program.

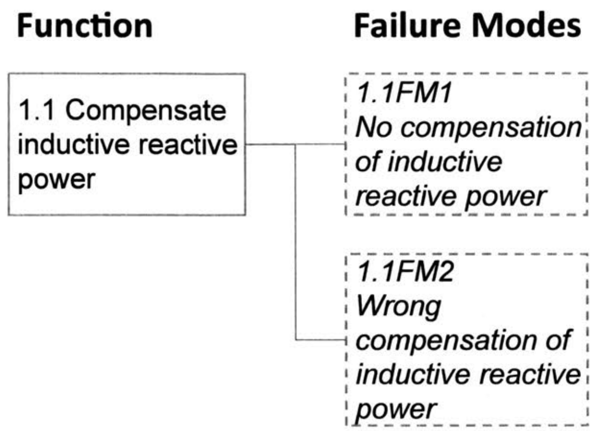


Figure 9-3: Failure modes of "1.1 Compensate inductive reactive power"

9.4 Step 3: Prioritize

If not done already, this step is to prioritize and structure the further analysis after getting the insights from the decomposition of system functions. We have done that already by focusing on one specific function.

9.5 Step 4: Collect Data

In the data collection step the FMEA form sheet is compiled with the identified functions and failure modes to prepare for the analysis step. The format of the FMEA form can vary, however contains certain standard elements. These are according to Stamatis, 2003 [27]:

Process function Description of the process function under investigation

Potential failure mode Description of a potential failure mode of the function under investigation

Potential effect of failure Description of the effect of a function failing with a specific failure mode. The effect will usually impact a system level above the level of the function under investigation.

Severity (S) Rating indicating the seriousness of the effect of a potential failure mode. Usually on a scale from 1 to 10, where 10 is indicating the most serious effect (e.g. loss of human life)

TCR	
1.1	**Compensate inductive reactive power**
1.1FM1	***No compensation of inductive reactive power***
1.1FM2	***Wrong compensation of inductive reactive power***

Outgoing Feeder	
1.1.1	**Switch operating current**
1.1.1FM1	***No switching of operating current***
	Switch off fault current
	No switching of of fault current

Cable	
1.1.2	**Connect TCR outgoing feeder to TCR valve**
1.1.2FM1	***No connection between outgoing feeder and valve***

Inductor	
1.1.3	**Provide inductive current**
1.1.3FM1	***Inductive current not provided***

Current Transformer	
1.1.4	**Measure TCR current**
1.1.4FM1	***No measurement TCR current***
1.1.4FM2	***Wrong measurement TCR current***

TCR Control	
	Measure voltage, grid current, load current
	No measurement voltage
	No measurement current
	Check status TCR driver
	Not able to check status TCR driver
1.1.5	**Control TCR valve**
1.1.5FM1	***No control of TCR valve***
1.1.5FM2	***Wrong control of TCR valve***

TCR driver	
1.1.6	**Exchange signals between TCR driver and TCR control**
1.1.6FM1	***No signal exchange between TCR driver and TCR control***
1.1.7	**Exchange signals between TCR driver and TCR valve**
1.1.7FM1	***No exchange of signals between TCR driver and TCR valve***
	Provide feeback when thyristor is operational
	Provide feeback although thyristor is not operational

TCR valve	
1.1.5.1	**Switch thyristors according to TCR control**
1.1.5.1FM1	***Thyristors not switched accroding to TCR control***
	Monitor thyristor voltage
	Thyristor voltage not monitored

Thyristor	
1.1.5.1.1	**Conduct current**
1.1.5.1.1FM1	***Current not conducted***
1.1.5.1.2	**Block voltage**
1.1.5.1.2FM1	***Voltage not blocked***

Figure 9-4: Functions and their failure modes organized by physical entities

Potential causes of failure Description of events which cause the function under investigation to fail. It is important to differentiate between symptoms and root cause. Only the latter really matters and may require application of techniques such as "5-times-Why" in order to be identified.

Occurence Rating indicating the estimated number of failures that could occur for a given cause on a scale form 1 to 10, where 10 is indicating the highest occurrence. Occurrence data can be obtained through experiments, data sheets of components (e.g. failures in time or FIT ratings), or reliability mathematics

Detection method Description of method, test or existing control for detecting a certain failure in the design or part.

Detection (D) Rating corresponding to the likelihood that the proposed design controls will detect a specific root cause of a failure mode before the part is released for production. Also on a scale from 1 to 10, where 10 is indicating that detection is very unlikely.

Risk Priority Number (RPN) Product of severity (S), occurrence (O), and detection (D):

$$RPN = S \cdot O \cdot D \tag{9.1}$$

The higher the RPN, the higher the priority of the failure. The RPN gives the team a clear indication in which sequence to tackle the different failures. It is up to the organization to define which RPN rating requires action, e.g. an RPN rating below 50 may fulfill customer expectations in one circumstance but not in another.

Recommended action Recommended next steps to tackle the failure under investigation. This could be a specific action and/or also further studying.

The pre-compiled FMEA form for our function *1.1* is visualized in figure 9-5.

Design function #	Design function	Potential failure mode #	Potential failure mode	Potential effects of failure	Severity (S)	Potential causes of failure	Occurrence (O)	Detection method	Detection (D)	RPN	Recommended action
1.1	Provide inductive reactive power	1.1FM1	No compensation of inductive reactive power							0	
		1.1FM2	Wrong compensation of inductive reactive power							0	

Figure 9-5: FMEA form for function "1.1 Compensate inductive reactive power"

Furthermore the team collected failure data on the subcomponents which make up the thyristor controlled reactor. These are: the outgoing feeder, cables, inductor, current transformer, TCR control, TCR driver, and TCR valve. Due to the proprietary nature of this data, this report will only show exemplary data which does not reflect reality. However, it will still be sufficient to illustrate the process. The data is shown as mean time between failures (MTBF), which is expressed in years and failures in time (FIT), which is expressed as a rate in terms of occurrences over 1 billion (10^9) hours. The data will be explained in more detail in the next part of this report.

Component	MTBF [years]	FIT [1/10^9 h]
Cable	150	761
Inductor	80	1427
TCR control	57	2003
TCR driver	50	2283
TCR valve	761	150
Current transformer	80	1427
Outgoing feeder	100	1142

Figure 9-6: Reliability data for TCR components (exemplary data only, does not reflect reality)

9.5.1 Step 4 Lessons Learned

- The definition of the ratings for severity, occurrence and detection can be a small project in itself, since it needs to be aligned and approved with upper/top management and across various functions (engineering, production, sales, service). If not already defined, enough time and resources need to be allocated to this fundamental step of setting up a robust FMEA framework.

- FIT-ratings of components are not as easy to retrieve as one may think. Often a specific request needs to be stated to the manufacturer of the component.

9.6 Step 5: Analyze Data

With the analysis step we want to get the necessary information to fill in the blank fields of the FMEA form. This step requires again deep understanding of the system and the functional interconnections and hence it is necessary that subject matter experts are participating.

First, we identify the effect of the specific function failing with a specific failure mode. From figure 9-1 we can see that function *1.1* is required to support function *1 Compensate reactive power*. Hence, the potential failure mode *1.1FM1 No compensation of inductive power* may have as potential effect *Insufficient compensation of reactive power*. From this example we can see, that the failure mode of one function on a certain system level is a potential cause of failure on a higher system level. This relationship is illustrated in figure 9-7.

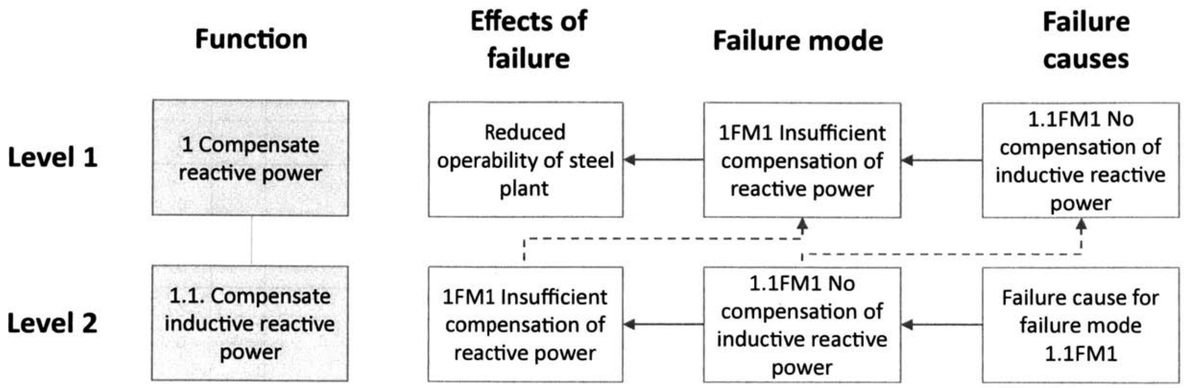


Figure 9-7: Relationship between failure causes, modes, and effects

Having identified a potential effect of the failure mode, we need to quantify its severity rating S on a scale from 1 to 10. The rating system is company specific and in our case we will use one based on partner company specifications. Alongside we introduce the tables for the ratings for occurrence (O) and detectability (D).

The severity of the failure effect *Reduced operability of steel plant* has been rated at a level of 6, and hence medium. If the TCR is defect the range of reactive power which can be compensated will be limited, but the steel plant can still work. The steel plant could incur additional costs, if the repair or exchange of spare parts would take too long. These would originate from failing to meet the "power factor" $\cos\varphi$ requirements at the point of common coupling.

The second failure mode from figure 9-5 *Wrong compensation of inductive reactive power* can also cause the effect *Reduced operability of steel plant.* Also here, the severity is rating is 6 since the potential effect of failure is the same as before.

The next step in the analysis is the identification of potential causes of the failure modes. The team has identified seven potential causes for *1.1FM1* and five potential causes for *1.1FM2* and recorded them in the FMEA form 9-8.

However, looking at the causes, most of them do not seem to be the root causes. If we take for instance failure mode *1.1.2FM1 No connection between outgoing feeder and valve* we would still be able to ask *"why is there no connection between outgoing feeder and valve?"*. For this question at least two answers could be identified:

Design function #	Design function	Potential failure mode #	Potential failure mode	Potential effects of failure	Severity (S)	Potential causes of failure #	Potential causes of failure	Occurrence (O)	Detection method	Detection (D)	RPN	Recommended action
1.1	Provide inductive reactive power	1.1FM1	No compensation of inductive reactive power	Reduced operability of steel plant	6	1.1.2FM1	No connection between outgoing feeder and valve	1		2	12	
					6	1.1.3FM1	Inductive current not provided				0	
					6	1.1.4FM1	No measurement TCR current				0	
					6	1.1.5FM1	No control of TCR valve				0	
					6	1.1.5.1.1FM1	Current not conducted				0	
					6	1.1.5.1.2FM1	Voltage not blocked				0	
					6	1.1.7FM1	No exchange of signals between TCR driver and TCR valve				0	
		1.1FM2	Wrong compensation of inductive reactive power	Reduced operability of steel plant	6	1.1.4FM2	Wrong measurement TCR current				0	
					6	1.1.5FM2	Wrong control of TCR valve				0	
					6	1.1.5.1FM1	Thyristors not switched accroding to TCR control				0	
					6	1.1.6FM1	No signal exchange between TCR driver and TCR control				0	
					6	1.1.7FM1	No exchange of signals between TCR				0	

Figure 9-8: Potential effects and causes of failure

1. cable is defect

2. cable is not connected

Hence, these are the actual root causes and need to be replaced in the FMEA form. We apply the same procedure to the other failure causes and identify potential root causes as shown in the table in figure 9-9.The table now also includes the detection method for each of the identified failure causes, which have been identified by the subject matter expert. This concludes step five.

Design function #	Design function	Potential failure mode #	Potential failure mode	Potential effects of failure	Severity (S)	Potential causes of failure #	Potential causes of failure	Identified root cause of failure #	Identified root cause of failure	Occurrence (O)	Detection method	Detection (D)	RPN	Recommended action
1.1	Provide inductive reactive power	1.1FM1	No compensation of inductive reactive power	Reduced operability of steel plant		1.1.2FM1	No connection between outgoing feeder and valve	1.1.2FM1RC1	Cable is defect		Inspection	4	0	
								1.1.2FM1RC2	Cable is not connected		Inspection	4	0	
						1.1.3FM1	Inductive current not provided	1.1.3FM1RC1	Inductor is defect		Inspection	4	0	
						1.1.4FM1	No measurement TCR current	1.1.4FM1RC1	Current transformer defect		Inspection	4	0	
						1.1.5FM1	No control of TCR valve	1.1.5FM1RC1	TCR Control defect		Inspection	4	0	
								1.1.5FM1RC2	Bug in control software		Software Quality control process / Error code	3	0	
						1.1.5.1.1FM1	Current not conducted	1.1.5.1.1FM1RC1	Thyristor 1/2 defect		Active monitoring of thyristor status via TCR driver	2	0	
						1.1.5.1.2FM1	Voltage not blocked	1.1.5.1.2FM1RC1	Thyristor 1/2 defect		Active monitoring of thyristor status via TCR driver	2	0	
						1.1.7FM1	No exchange of signals between TCR driver and TCR valve	1.1.7FM1RC1	Faulty connection between TCR driver and TCR valve		Inspection	4	0	

Figure 9-9: Potential root causes of failures and their detection methods

9.6.1 Step 5 Lessons Learned

- The process to identify the root causes is time consuming and can lead to debates on principles. Before getting stuck, it is better to stop, move on to the next item, and then come back.

9.7 Step 6: Generate Results

The *result* step includes the calculation of the risk priority number (RPN). For this, we first need to quantify occurrence and detection ratings. Technically, also the assessment of the severity could be included in this step. In our case, we already completed it in step five.

For the failure causes which indicate a defect component the rating has been determined via the FIT-rating of the component from figure 9-6 and its corresponding rating from figure C-2. For causes where no data was available, e.g. *Bug in control software*, the opinion of subject matter experts has been used.

The detection rating of the different failure modes has been assigned according to figure C-3. We observe, that many failure causes can only be clearly identified via an on site inspection, and hence obtain only a rating of four.

The last step is the calculation of the risk priority number (RPN). As mentioned earlier this is the multiplication of severity, occurrence and detectability. The RPN is indicating which failure modes should be tackled first, starting with the ones with a high RPN. A company can determine for themselves which rating triggers an action, and which rating can still be deemed as good enough. Stamatis, 2003 [27] mentions that a rating below 50 may be considered still acceptable, but causes with a higher RPN rating should be tackled.

Design function #	Design function	Potential failure mode #	Potential failure mode	Potential effects of failure	Severity (S)	Potential causes of failure #	Potential causes of failure	Identified root cause of failure #	Identified root cause of failure	Occurrence (O)	Detection method	Detection (D)	RPN	Recommended action
1.1	Provide inductive reactive power	1.1FM1	No compensation of inductive reactive power	Reduced operability of steel plant	6	1.1.2FM1	No connection between outgoing feeder and valve	1.1.2FM1RC1	Cable is defect	2	Inspection	4	48	
					6			1.1.2FM1RC2	Cable is not connected	1	Inspection	4	24	
					6	1.1.3FM1	Inductive current not provided	1.1.3FM1RC1	Inductor is defect	3	Inspection	4	72	
					6	1.1.4FM1	No measurement TCR current	1.1.4FM1RC1	Current transformer defect	3	Inspection	4	72	
					6	1.1.5FM1	No control of TCR valve	1.1.5FM1RC1	TCR Control defect	3	Inspection	4	72	
					6			1.1.5FM1RC2	Bug in control software	3	Software Quality control process / Error code	3	54	
					6	1.1.5.1.1FM1	Current not conducted	1.1.5.1.1FM1RC1	Thyristor 1/2 defect	2	Active monitoring of thyristor status via TCR driver	2	24	
					6	1.1.5.1.2FM1	Voltage not blocked	1.1.5.1.2FM1RC1	Thyristor 1/2 defect	2	Active monitoring of thyristor status via TCR driver	2	24	
					6	1.1.7FM1	No exchange of signals between TCR driver and TCR valve	1.1.7FM1RC1	Faulty connection between TCR driver and TCR valve	2	Inspection	4	48	

Figure 9-10: Potential root causes of failures with occurrence and detection rating

For the potential failure causes identified for the failure mode *1.1FM1 No compensation of inductive power* this would mean, that four root causes may require attention. These are:

- *1.1.3FM1RC1 Inductor is defect*
- *1.1.4FM1RC1 Current transformer defect*
- *1.1.5FM1RC2 TCR control defect*
- *1.1.5FM1RC2 Bug in control software*

9.7.1 Step 6 Lessons Learned

- A one unit change in one of the three ratings can change whether a root cause is significant or not. Since this outcome will decide over future work, tie up resources and ultimately directly impact the customer, the rating needs to be managed very carefully. Hence, it should be as objective and quantifiable as possible in order for the team to be able to make fact based decisions and leave as little room for interpretation as possible.

9.8 Benefits of the FMEA

This has been the first time that an FMEA has been performed on a product of MR's Power Quality (PQ) portfolio. Although the FMEA methodology is applied in other business units, e.g. in their on load tap changer (OLTC) business, it had not been deployed in the PQ unit. The reason behind this is the believe that, for the one off projects of the PQ unit, the time and resource investment required to perform an FMEA may not be justifiable.
While it is difficult to assess if the investment in undertaking an FMEA may pay off in financial terms for the aforementioned type of projects, the team has gained beneficial insights from this FMEA, and is convinced that more benefits will emerge if the methodology is applied regularly. The insights gained are:

Opportunity for continuous improvement: while each project may be different in its details, the product architecture may be shared (to a certain extend) with previous projects. A static VAR compensator will generally perform the same functions and hence rely on one or more common architectural elements such as modules. An FMEA from a previous project could hence serve as template and starting point for a new project and accelerate its development. At the same time the improvements could be prioritized based on the RPN ratings of the previous project and in such way kick off a continuous improvement process which is methodologically improving the customer experience with each project.

Basis for troubleshooting procedures: the FMEA, even if only available at a higher product level, can be a very valuable tool for reactive maintenance/ troubleshooting. Based on the observed effect (of failure), the FMEA can help to narrow down the search space for the identification of the root cause. This will speed up the repair and hence improve availability of the system.

Enhancement of system understanding: the process to perform the FMEA enhances and aligns the understanding of the system among the engineering team. This can have a beneficial effect for subsequent projects since the team is better informed about capabilities, strengths and weaknesses of their product architectures.

Chapter 10

Reliability Analysis of Static VAR Compensator

For operators of complex equipment, be it mechanical, electrical or electromechanical, equipment availability and understanding of the time required for maintenance and repair becomes fundamental. In case of the SVC, equipment downtime could potentially mean, that the steel plant cannot operate and as a consequence loses revenues and profits. Besides the financial impact, operators want also to understand how safe the equipment is, and which threat it imposes to people and the environment, if it fails.

10.1 Scope of Reliability Analysis within the Project

Within this project we would like to find out how to use the insights from the FMEA to gain a first understanding of the *reliability* and *availability* of our system, specifically the thyristor controlled reactor of the SVC. This additional understanding shall provide value to the partner company by enabling them uncover both design weaknesses (reliability below customer requirements) and cost saving opportunities (reliability above customer requirements) as well as having a tool to define an optimal spare part strategy. To reach that point we will follow the six-step process outlined in Birolini, 2017 [35]:

1. Definition of the required function and of its associated mission profile.

2. Derivation of the corresponding reliability block diagram (RBD).

3. Determination of the operating conditions for each element of the RBD.

4. Determination of the failure rate for each item of the RBD.

5. Calculation of the reliability for each item of the RBD.

6. Calculation of the system reliability.

10.2 Required Function

The required function specifies the item's or system's task whose reliability we want to assess. If the item or system is able to perform the task according to specified requirements, we regard the item or system as available. If not, it defines failure. This is analogue to the definition of failure we have used for the FMEA in 9.3: failure is the loss of a design function [27].

In our case the required function is *1.1 Compensate inductive power* as specified during the FMEA and depicted in 9-3. We now need to identify which physical components are involved in providing and sustaining that function in order to define the reliability block diagram (RBD) for this function. This has basically already been investigated in the failure cause analysis performed during the FMEA.

10.3 Reliability Block Diagram (RBD)

The reliability block diagram RBD connects all the physical entities needed to provide the required function being investigated. As specified by Birolini, 2017 [35] the RBD answers the question: *Which elements of the item under consideration are necessary for the fulfillment of the required function and which can fail without affecting it?* The elements which are necessary for the required function are connected in series, while elements which can fail with no effect on the required function are connected in parallel or not included at all in the diagram.

Looking at the required function *1.1 Provide inductive reactive power*, we have identified that the component providing this function, the *thyristor controlled reactor*, is build up from the following components:

1. Cable

2. Inductor

3. Control
4. TCR driver
5. TCR valve (incl. the two thyristors)
6. TCR control
7. Current transformer
8. Outgoing feeder

We now have to evaluate which of these components are essential to the function (the function cannot be sustained if the components fails). The FMEA has shown that all the components need to be operational in order to sustain the required function. This is visualized in the functional tree of the TCR in figure 10-1. We can hence can sketch the

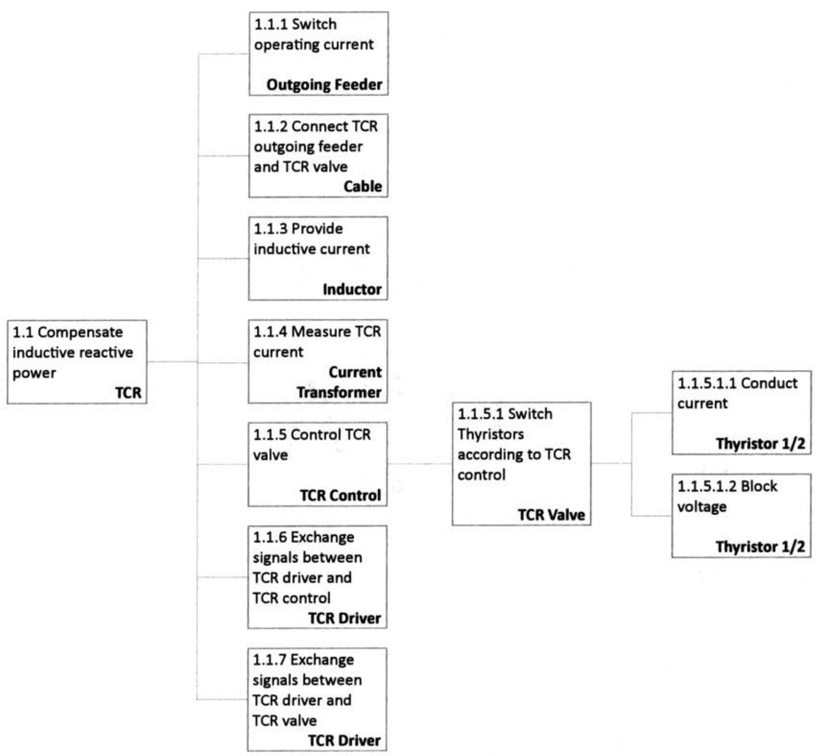


Figure 10-1: Basis for RBD: function tree from FMEA including logical connectors

reliability block diagram of the function *1.1 Provide inductive reactive power* by connecting all the essential components in series as depicted in figure 10-2 Purely in series connected elements are the simplest form of a reliability block diagram. Also, the calculation of their reliability, as we will see later, is quite straight-forward. However, since they essentially

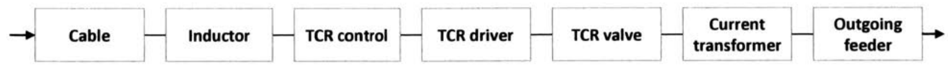


Figure 10-2: Reliability block diagram for the function *1.1 Provide inductive reactive power*

work according to the *weakest-link-principle*, in which the least reliable element commands to a large extend the reliability of the entire system, they are pretty useful to evaluate the system's *worst case scenario.* The capability to define a lower bound for the system reliability shows to be very useful in an actual business context as we have seen during the work on this project.
We further notice that the two thyristors do not appear in the reliability block diagram. This is due to the fact that we are given the reliability data (MTTF/FIT values) for the entire TCR valve, which includes the thyristors. If that data was not given we had to evaluate the thyristors separately. The reliability block diagram would then be similar to the one represented in figure 10-3 whit the thyristors connected in parallel, to reflect their *1-out-of-2 redundancy* (also referred as *n-1 criteria*, whit n=2). This means, that in order to support the required function, at least one of the two thyristors needs to be functional.

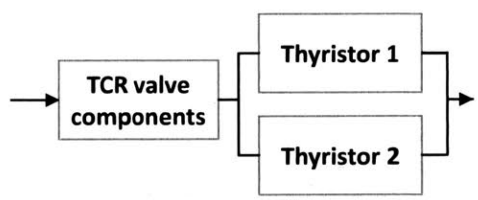


Figure 10-3: Reliability block diagram for TCR valve

Figure 10-4 shows some of the most common RBDs and their corresponding reliability functions R_S.

10.4 Operating Conditions at Component Level

For a correct evaluation of the system reliability its operating conditions, such as temperature, humidity, and pressure need to be taken into consideration. Specifically electrical components are sensitive towards ambient temperature which could result in a higher failure rate and shorter lifetime as depicted in the *bathtub curve* in figure 4-13. For the purpose

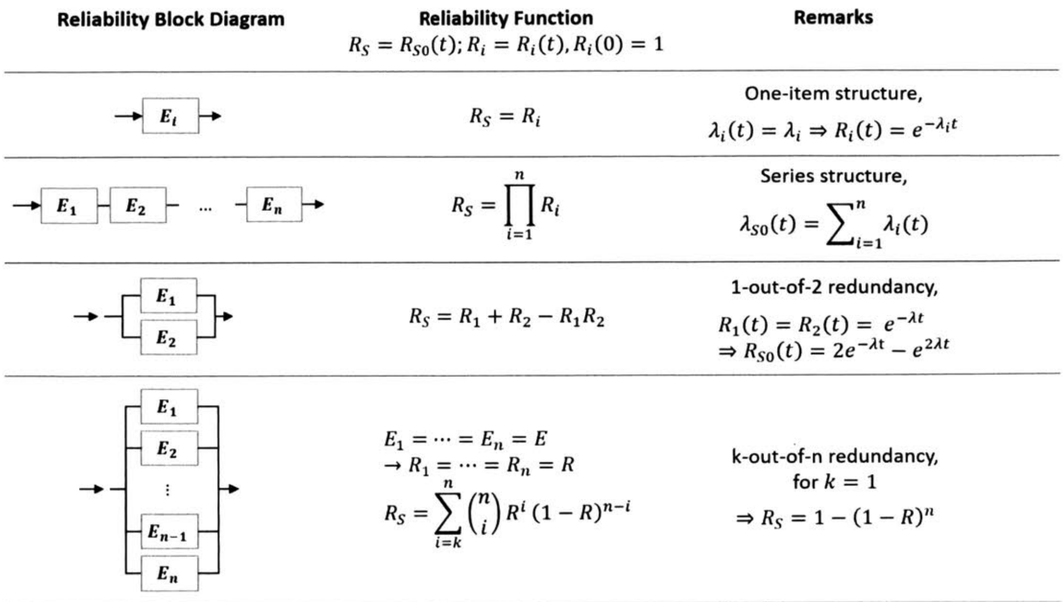


Figure 10-4: Reliability block diagram for basic structures according to Birolini, 2017 [35]

of this project we assume that the operating conditions of the SVC and hence of the TCR are within what is considered *normal working conditions* by the manufacturer.

10.5 Failure Rates for each Element of the RBD

For the reliability calculations we assume constant failure rate during the useful life and hence

$$\lambda(t) = \lambda$$

This assumption simplifies calculations since item failures can then be described by a homogeneous *Poisson* process with rate λ:

$$R_i(t) = e^{-\lambda_i t} \rightarrow R_i = e^{-\lambda_i} \qquad \text{(for a one-item structure)} \qquad (10.1)$$

The failure rates for the individual components can be obtained either via field data if population is large enough to be statistically significant and operating conditions are well known, through accelerated reliability tests, from failure rate handbooks such as MIL-HDBK-217F [36] if component is an established electronic or electromechanical component, or via inquiry at the original equipment manufacturer. Failure rates are most commonly supplied in either FIT-rates or $MTTF/MTBF$-data. As already mentioned FIT-rates are describing failures in time and usually indicates how many failures can be expected over a period of 10^9 hrs. $MTTF/MTBF$ data are often supplied in a unit of years $[a]$ or hours $[h]$. The conversion between FIT and $MTTF/MBTF$ is straight forward (for FIT expressed in $[1/10^9 h]$ and $MTTF$ expressed in years $[a]$):

$$FIT = \frac{10^9}{MTTF \cdot 365 \cdot 24} \tag{10.2}$$

$$MTTF = \frac{10^9}{FIT \cdot 365 \cdot 24} \tag{10.3}$$

For the calculations in this report the (disguised) data from table 9-6 will be used.

Note: Should working conditions be outside the regime of *normal working conditions*, correction factors π_i, such as π_T (temperature), π_E (environmental), or π_Q (quality) need to be applied to failure rate values [35], e.g.:

$$\lambda = \lambda_0 \pi_T \pi_E \pi_Q \tag{10.4}$$

10.6 Calculation for Each Element of the RBD

Next, we calculate the reliability function for each single item in the RBD. Specifically we are interested in obtaining R_i over the course of one year. We assume each item is *non-repairable*, which means it needs to be exchanged with a new or refurbished item if broken. We recall equation 10.1 and obtain with the FIT values from table 9-6 item reliabilities R_i summarized in table 10-5. *Note*: to obtain R_i for one year we need to normalize λ_i to one year. E.g. the reliability of the cable R_{cable} is hence calculated as follows $R_{cable} = e^{-\frac{761}{10^9} \cdot 365 \cdot 24}$. In this

Item	No. of items [#]	Redundancy	item MTTF [a]	item FIT λ [1/10^9]	R_i item reliability (over 1 year) [%]
Cable	*1*	*no*	*150*	*761*	99.33%
Inductor	*1*	*no*	*80*	*1427*	98.75%
TCR control	*1*	*no*	*57*	*2003*	98.25%
TCR driver	*1*	*no*	*50*	*2283*	98.00%
TCR valve	*1*	*no*	*761*	*150*	99.87%
Current transformer	*1*	*no*	*80*	*1427*	98.75%
Outgoing feeder	*1*	*no*	*100*	*1142*	99.00%

Figure 10-5: Item reliabilities R_i over one year expressed in %

case the calculation is very simple, since there is no redundancy for any of our items. If we had redundancy, we would need to compute a cumulative reliability for the combined redundant item. Let's assume we have two TCR controllers of which one out of two needs to be operational in order for the TCR to perform its function. Then we are talking about a *one out of two* redundancy, which we can model as shown below. We know that there are three different states under which the TCR can operate:

Table 10.1: 1 out of 2 redundancy: possible states under which TCR can operate

State no.	Status controller 1	Status controller 2
1	ok	defect
2	defect	ok
3	ok	ok

The item reliability $R_{controller}$ of 0.9825 is basically the probability of the item being operational at any given time throughout a year. Hence, the probability of the item being non operational Q_i can be expressed as:

$$Q_i = 1 - R_1 \tag{10.5}$$

For the controller we obtain $Q_{controller} = 0.0175$. Now we can compute the probability of case occurring:

Table 10.2: 1 out of 2 redundancy: probability of operational states

State no.	Status controller 1	Status controller 2	Probability P
1	ok	defect	$P = 0.9825 \cdot 0.0175 = 0.0172$
2	defect	ok	$P = 0.0175 \cdot 0.9825 = 0.0172$
3	ok	ok	$P = 0.9825 \cdot 0.9825 = 0.9653$

The combined probability of at least one controller working is then simply the sum of the probabilities of each case. This way we get the reliability for a redundant controller configuration R_S:

$$R_S = 0.0172 + 0.0172 + 0.9653 = 0.9997$$

As expected, the reliability of the redundant configuration is higher as the one of the single element. We can get to the same result by applying the formula for *k out of n redundancy* from table 10-4:

$$R_S = \sum_{i=k}^{n} \binom{n}{i} R^i (1-R)^{n-i} \tag{10.6}$$

In our case with $k = 1$ and $n = 2$ this yields:

$$R_S = 2e^{-\lambda} - e^{-2\lambda} \qquad \text{with } \lambda = 2003 \cdot 10^{-9} \cdot 365 \cdot 24$$

10.7 Calculation of System Reliability

Now that we have the reliability for each single element we can calculate the reliability for the entire system. In a system where we have only elements connected in series the system reliability is simply the product of each item reliability, following the chain rule from probability theory:

$$R_S = \prod_{i=1}^{n} R_i = 0.9221$$

Next, we are interested in getting to know what is the mean time to failure of the system $MTTF_S$. For this, we first need the FIT value for the system λ_S. This is simply the sum of the item-FIT values λ_i times the quantity of each item n_i (which is 1 for each of the items in our system):

$$\lambda_S = \sum \lambda_i \cdot n_i = 9192$$

With equation 4.6 we obtain the mean time to failure of our system expressed in years [a]:

$$MTTF_S = 12.42 \; [a]$$

This figure itself is just telling us, that statistically the TCR will experience a failure on average after 12.42 years, however it could experience that same failure just after installation or after only 24.82 years. For practical purposes it is much more interesting to understand how long it will take to repair the system once it fails and hence be able to quantify which (financial) losses the system operator is likely to occur. For this purpose we have already introduced the terms *Mean Time to Repair (MTTR)* and *availability*. The relationship between MTTR, MTTF and availability can be expressed as follows:

$$Availability_S = 1 - MTTR_S / MTTF_S \tag{10.7}$$

The calculation of MTTR requires us to have an understanding of how long a replacement of a defect component takes if it is readily available (e.g. a spare part on site or item is repairable) or how long it will take to source, install and test a spare part. As stated earlier, we assume that the items are not repairable and need to be replaced. For our system we look at the spare part situation summarized in table 10-6:

The decision has been made to stock one replacement from each item which is falling into

1	2	3	4	5	7	8	9	10	11	12	13	14
Item	No. of items [#]	Redundancy [yes/ no]	item MTTF *MTTF_i* [a]	item FIT *λ_i* [1/10^9]	Item reliability (over 1 year) *R_i* [%]	Replacement time *t_rep_i* [h]	spare parts on site *p_i* [#]	inventory cost per year ($10/day) *c_inv_i* [$]	leadtime delivery spare parts [weeks]	leadtime delivery spare parts *t_del_i* [h]	weight *w_i* [-]	expected item downtime *t_down_i* [h]
Cable	*1*	*no*	*150*	*761*	99.33%	48	1	$ 3,650.00	2	0	0.083	48.00
Inductor	*1*	*no*	*80*	*1427*	98.75%	48	1	$ 3,650.00	2	0	0.155	48.00
TCR control	*1*	*no*	*57*	*2003*	98.25%	16	0	$ -	4	672	0.218	688.00
TCR driver	*1*	*no*	*50*	*2283*	98.00%	16	0	$ -	16	2688	0.248	2704.00
TCR valve	*1*	*no*	*761*	*150*	99.87%	40	0	$ -	4	672	0.016	712.00
Current transformer	*1*	*no*	*80*	*1427*	98.75%	24	0	$ -	2	336	0.155	360.00
Outgoing feeder	*1*	*no*	*100*	*1142*	99.00%	24	0	$ -	4	672	0.124	696.00
Totals					**92.21%**			**$ 7,300.00**		**Mean Time To Repair [h]**		**986.85**

Figure 10-6: MTTR: item data required to calculate expected system downtime

category three or higher of the *occurrence rating* (see appendix C-2). We hence stock one spare inductor, one TCR control, one TCR driver, one current transformer and one outgoing feeder on site. The remaining items need to be sourced and will incur the lead time t_{del_i} specified in column *12*. We note that for this simplified example the lead time for items stocked on site is zero and installation time for both sourced and on-site items is zero. MTTR is the weighted sum of the expected downtime of each item of the system:

$$MTTR_S = \sum_{i=1}^{n} w_i \cdot t_{down_i} \tag{10.8}$$

The weights w_i are the ratio of individual item FIT rate λ_i and system FIT rate λ_S:

$$w_i = \lambda_i / \lambda_S$$

The *expected item downtime* t_{down_i} is expressed as the product of the sum of *replacement time* t_{rep_i} (col. *8*) and, if any, *leadtime delivery spare part* t_{del_i}:

$$t_{down_i} = t_{rep_i} + t_{del_i}$$

With this approach we obtain a $MTTR_S = 65.03\ hrs$ and with the equation 10.7 a system availability of $Availability_S = 99.94\%$. The MTTR figure is telling us, that once the system fails (which we know will fail on average after 12.42 years), we require an average of 65.03 hrs to set it back in operation based on the selected spare part strategy.

This point concludes the general reliability assessment of our system. However, the obtained figures seem a bit abstract and do not provide clear recommendations for action. Hence, in the next chapter we want to evaluate how we can use the reliability analysis to improve business operations and customer satisfaction.

Chapter 11

Optimization of Operations based on Output of Reliability Analysis

The reliability analysis provided us with three key insights:

1. An understanding of the *weakest link* in the system, the item or module with the lowest reliability (MTTF/FIT-rate)
2. A quantification of the expected downtime of the system (MTTR)
3. A quantification of the technical availability of the system (MTTF and MTTR)

We can use these insights to optimize the design so that customer expectations are met in terms of availability and (operational) cost. This section will illustrate how the reliability analysis of the TCR can be used to minimize its MTTR and hence reduce lost revenue and improve profits for customer with a smart spare part selection.

We know that at some point one or more components of our system are going to fail. Statistically this will happen on average every 12.42 years ($= MTTF$). Downtime of the system equals lost revenue and lost profit. An operations manager hence needs to think about how to minimize that downtime. Availability of spare parts and a quick replacement of the defect component are an essential part of this task. However, in most cases it will be a trade-off between keeping a full set of spare parts on site, which would minimize downtime but at the same time generate substantial inventory holding costs, and stocking replacements for only those components which are most likely to fail and this way limit inventory holding costs. At this point the problem turns into an optimization problem which seeks to minimize total costs.

To illustrate this we will go back to the case in the previous section. We assumed that the operations manager stocks spare parts for items with failure rates of 1140 FIT and above (category 3 and above in table C-2). We assume further that items stocked on site will incur yearly inventory holding costs of 10% of their purchasing cost. At the same time we expect this configuration to be subject to a downtime of 5.24 hrs per year. This results if we sum the probability of failure within one year (which corresponds to $1 - R_i$) of each item and multiply it with their weighted expected downtime over the entire lifetime:

$$T_{down1Y_i} = \sum_{i=0}^{n} (1 - R_i) \cdot w_i \cdot t_{downLT_i}$$

Under the assumptions that the steel plant generates revenue of \$100 per hour when operational, and that the company operates at a margin of 20%, the incurred cost due to downtime sums to \$104.73 per year. Together with the inventory holding cost of \$1,750 the total cost, and hence lost profit, is \$1854.73. Table 11-1 summarizes the baseline case.

Let's remember that the theoretical availability of this system is 99.94%. Although a high

1	3	10	11	12	13	14	15
Item	**spare parts on site** *p_i* **[#]**	**item cost** *c_i* **[$]**	**item holding cost/year (10% of item cost)** *c_inv_i* **[$]**	**leadtime delivery spare parts** *t_del_i* **[h]**	**weight** *w_i* **[-]**	**expected item downtime over lifetime** *t_downLT_i* **[h]**	**expected item downtime over 1 year** *t_down1Y_i* **[h]**
Cable	0	$ 100.00	$ -	336	0.083	384.00	2.56
Inductor	1	$ 500.00	$ 50.00	0	0.155	48.00	0.60
TCR control	1	$ 5,000.00	$ 500.00	0	0.218	16.00	0.28
TCR driver	1	$ 10,000.00	$ 1,000.00	0	0.248	16.00	0.32
TCR valve	0	$ 5,000.00	$ -	672	0.016	712.00	0.94
Current transformer	1	$ 1,000.00	$ 100.00	0	0.155	24.00	0.30
Outgoing feeder	1	$ 1,000.00	$ 100.00	0	0.124	24.00	0.24
		Totals	**$ 1,750.00**		**MTTR**	**65.03**	**5.24**
						Expected downtime costs/year	**$ 1,854.73**

Figure 11-1: Expected costs of downtime for baseline case

system availability of well above 99% is certainly good, it might be suboptimal, since it comes at too high a cost. We can easily evaluate if this is the case by running a simple optimization. The objective function Z we want to minimize is the *total expected downtime cost/year*, which is the sum of the inventory holding cost for one year C_{inv1Y} and the expected cost due to system downtime for one year C_{down1Y}:

$$Z = min(C_{down_{total}})$$

$$\text{where } C_{down_{total}} = C_{inv1Y} + C_{down1Y}$$

$$\text{and } C_{inv1Y} = \sum_{i=1}^{n} p_i \cdot c_i \cdot 10\%$$

$$\text{and } C_{down1Y} = T_{down1Y} \cdot \$20/hr$$

The decision variables are the number of spare parts p_i stocked on site (column 3 in 11-1). For simplicity we allow for each component either 0 or 1 replacement on site. This will be our only constraint:

$$p_i \in [0, 1]$$

Since the model is linear we can solve it with the *Simplex* algorithm as available in e.g. Microsoft Excel™.

The optimization finds a new spare part configuration which reduces total downtime costs by 17% or $315. The difference to the baseline case is that we will not stock a spare TCR control or current transformer, but a cable. These choices will reduce our total system availability from 99.94% to 99.78% and expected downtime will increase from 5.24 hrs to 18.99 hrs but the reduction in inventory holding cost will outweigh that increase. Table 11-2 compares the two cases.

Spare part strategies			
	Baseline	Optimal	Delta
system availability	99.94%	99.78%	0%
mean down time [hours]	5.24	18.99	
revenue/hr	$ 100.00	$ 100.00	
lost revenue	$ 523.63	$ 1,898.58	
profit margin	20%	20%	
lost profit due to downtime	$ 104.73	$ 379.72	263%
inventory holding cost	$ 1,750.00	$ 1,160.00	-34%
net downtime costs	**$ 1,854.73**	**$ 1,539.72**	**-17%**
Spare parts inventory on site			
Cable	0	1	1
Inductor	1	1	0
TCR control	1	0	-1
TCR driver	1	1	0
TCR valve	0	0	0
Current transformer	1	0	-1
Outgoing feeder	1	1	0
Cost savings due to improved spare parts strategy			**$ 315.01**

Figure 11-2: Comparison between baseline and optimal spare part strategy

Chapter 12

Conclusions of Part II

The calculations with the model have shown, that having a better understanding of the system's reliability can reduce operational costs which are directly impacting the bottom line. Furthermore, this option is available even if the system is already commissioned, since the function tree, failure tree and reliability models can be all created after the system has already been commissioned. To a certain extend, this has also been the case in this work. During the project we have seen, that it is fairly easy, also for an unexperienced team in the field, to extract the required information to build a first reliability model of the system, and even these models can generate customer value:

- Customer can be provided with the expected reliability of the system, which has a reassuring effect, even if the product comes from a manufacturer known for high quality.
- Customer can be advised pro-actively on spare part strategies and hence on the optimization of their OPEX.
- If the reliability analysis is done in conjunction with the FMEA during the product design phase, the system manufacturer can identify over-engineered components by comparing their FIT rates with the FIT rates of other components in the system. This way potential cost saving opportunities can be captured. Same applies to components with too low FIT rates/too weak components.

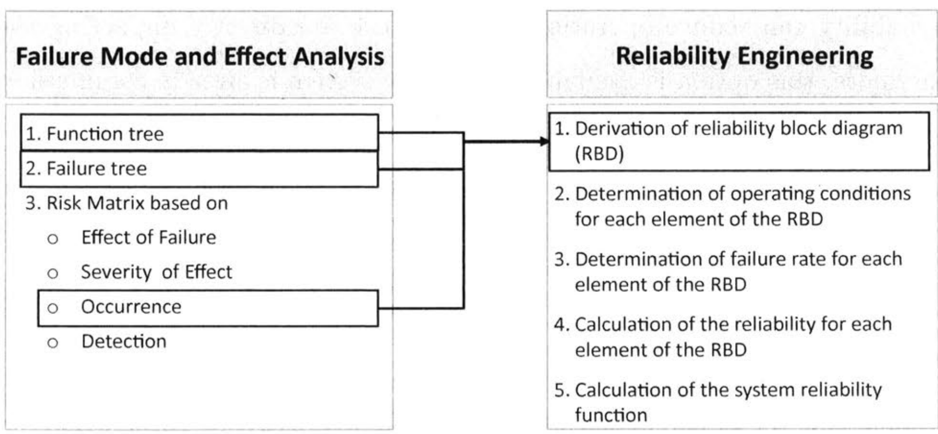


Figure 12-1: Main steps of FMEA and reliability analysis and their connection

Chapter 13

Thesis Summary and Future Work

13.1 Thesis Summary

The thesis research was started with the goal to investigate the following two topics and formulate recommendations on how to approach them.

1. Power electronics are based on semiconductor components which require scale to be manufactured economically. Further, the development and manufacturing of PE-based systems require a different labor skill set than electromechanical products. Which level of vertical integration for specific PE-based products would make economic and strategic sense for MR? Should MR build a similarly high degree of vertical integration as in its OLTC business?

2. The technology shift from electro-mechanical devices towards power electronics enables MR to develop products, such as solid state transformers, which may make traditional transformer technology obsolete in the long term. This imposes the risk of cannibalization of own products, such as the OLTCs, and direct competition to the transformers manufactured by current customers. Additionally it may raise competition with current suppliers, who are already active in the PE space. How can these risks be evaluated and mitigated?

In chapter 5 *Market Reaction* the second point has been addressed. It has been found, that MR is unlikely to suffer retaliation from current customers or current suppliers if entering the market for PE-based products for power regulation and control. MR's main asset which is providing the safety against retaliation is its strong brand, best in class product quality and innovative business model for its most important product line, the OLTCs. Based on this finding the research suggests that MR should enter the PE-space. In light of the ongoing decentralization of electricity grids, and the resulting increasing technical requirements for power regulation and control equipment, there is a risk that the current electromechanical products may be displaced by PE-based products in the mid- to long-term future. Hence, it becomes important for MR to build up the necessary capabilities to master the new technology early enough, in order to secure its status as a strong and innovative partner of the industry also in case this technology shift should occur.

The case study of a possible PE product, a UPFC, in chapter 6 *Case Study: Unified Power Flow Controller* has addressed the first point. The analysis of the simplified BOM of the UPFC has indicated that MR would have to source approximately 70% of the required components from external supplier and only manufacture 30% in-house. This may not be the strategically ideal split, but it acknowledges the currently available in-house capabilities. To increase the in-house share, MR would need to invest first in building up the necessary engineering competencies.

The 70/30-split represents a substantial shift from MR's current status of a highly vertically integrated manufacturer towards a potential system integrator. In the PE-value chain the sourcing function would, hence, own most of the product cost and carry more responsibility for the overall financial success of the project. To succeed in this new role, the sourcing function must be integrated in the product development process from the very beginning, have the technical ability to source complex products (as opposed to raw materials and half-finished goods), and demonstrate strong competencies in managing system requirement specifications with and between suppliers. The analysis of the current BOM also indicates that a reduction of the variable costs of the UPFC is required in order to make the product economically viable.

The case study has further analyzed the possible effects of a first mover advantage on the UPFC business case. Literature research has found indication, that a first mover in the specific market for power regulation and control equipment for the medium-voltage distribution grid is likely to be able to benefit from its status. The suggestion resulting from the thesis research is hence, that MR accelerates the development of the PE-technology, and enters the market with the right application before its competitors.

The FMEA of a static VAR compensator in chapter 9 *Design FMEA of Static VAR Compen-*

sator and the subsequent reliability analysis in chapter 10 *Reliability Analysis of Static VAR Compensator* showcase the application of engineering methods which can support the development of the envisioned PE-product with focus on product cost and reliability. The FMEA has found to be valuable to enhance the general understanding of the system's functions and represents an effective method to quantify whether functions meet customer requirements. This transparency is helpful for concentrating efforts to deliver only functions which customers care about and this way help to contain product costs.
Based on the function tree developed within the FMEA, reliability engineering provides a deeper insight in design-weaknesses and expected service and maintenance needs of the system. This is helpful to analyze design trade-offs between highly reliable, but likely costly solutions, and designs which will still meet customer requirements but also offer cost saving potential. Before all, reliability engineering helps the product development team to build in reliability where needed and avoid over-engineering or weaknesses in the system design.
Chapter 11 *Optimization of Operations based on Output of Reliability Analysis* further demonstrates how reliability engineering can be applied to optimize the spare part strategy for a given system.
Based on these findings it is suggested that MR adopts FMEA and reliability engineering for the development of the envisioned PE-product, especially because the success of the product is likely to be sensitive to its variable unit cost and its technical reliability.

13.2 Future Work

The following topics have not been addressed within the time-frame of the thesis research and hence offer avenues for future work:

1. Perform an in-depth market research to get a better understanding of critical applications for PE-based products and their respective demand. The short and long term market potential and use case for PE-based products such as UPFC and SST seems not yet clearly defined. This would help MR to focus the product development efforts on a system which taps a real customer need. It will also help assess whether the organization has all competencies on board, which are required to succeed in this endeavor.

2. Investigate success factors of souring functions in companies which are considered

system integrators. Examples for such companies are automobile or airplane manufacturers but also MR's own customers, the transformer manufacturers. This will be valuable knowledge to MR for the setup and organization of its own sourcing function in light of a possible enhanced scope.

3. Validate both the presented FMEA and reliability analysis with empirical field data from an existing system and update the FMEA documentation and the reliability model with the findings. The validation is ideally carried out with a system for which ample data on failures, downtime and spare part consumption exists. Possible sources for such data are service reports or system error logs, ideally accessible through a database. The validated models can then be used as foundation for the development of the successor system and hence help accelerate the development process.
   It is suggested to first master well the modeling and analysis with more basic methods and models, such as the serial-parallel structures adopted in this research, before more sophisticated approaches to reliability analysis with methods such as Markov or semi-Markov processes (Owens, 2014 [37], Taylor, 2015 [38]) are applied. This statement is made from a practical point of view: it may be quite difficult to explain a more complex model to stakeholders with different technical knowledge, especially if further assumptions have to be made, such as required for the probabilities for the (state) transition matrices for Markov or semi-Markov processes.

Appendix A

List of Abbreviations

AC Alternating Current

ABC Activity Based Costing

DC Direct Current

ENPV Expected Net Present Value

FIT Failures In Time

FMA First Mover Advantage

FMEA Failure Mode and Effects Analysis

IGBT Insulated Gate Bipolar Transistors

LFT Line Frequency Transformer

MDT Mean Down Time

MMC Modular Multilevel Converter

MTBF Mean Time Between Failures

MTTF Mean Time To Failure

MTTR Mean Time To Repair

NPV Net Present Value

OEM Original Equipment Manufacturer

OLTC On Load Tap Changer

PE Power Electronics

PF Power Factor

RPN Risk Priority Number

SME Subject Matter Expert

SST Solid State Transformer

SVC Static Var Compensator

TCR Thyristor Controlled Reactor

UPFC Unified Power Flow Controller

VAR Volt Ampere Reactive

Appendix B

Figures

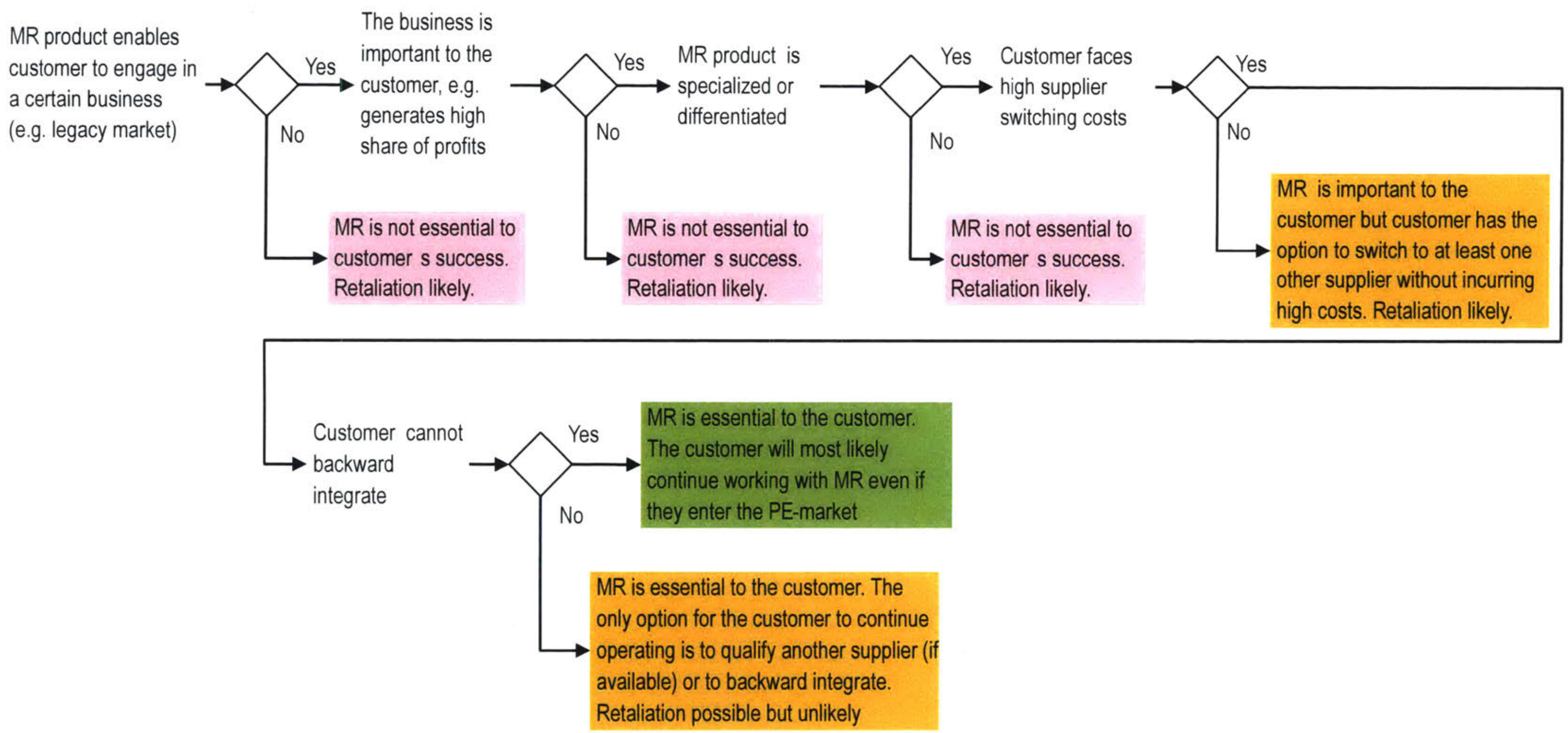
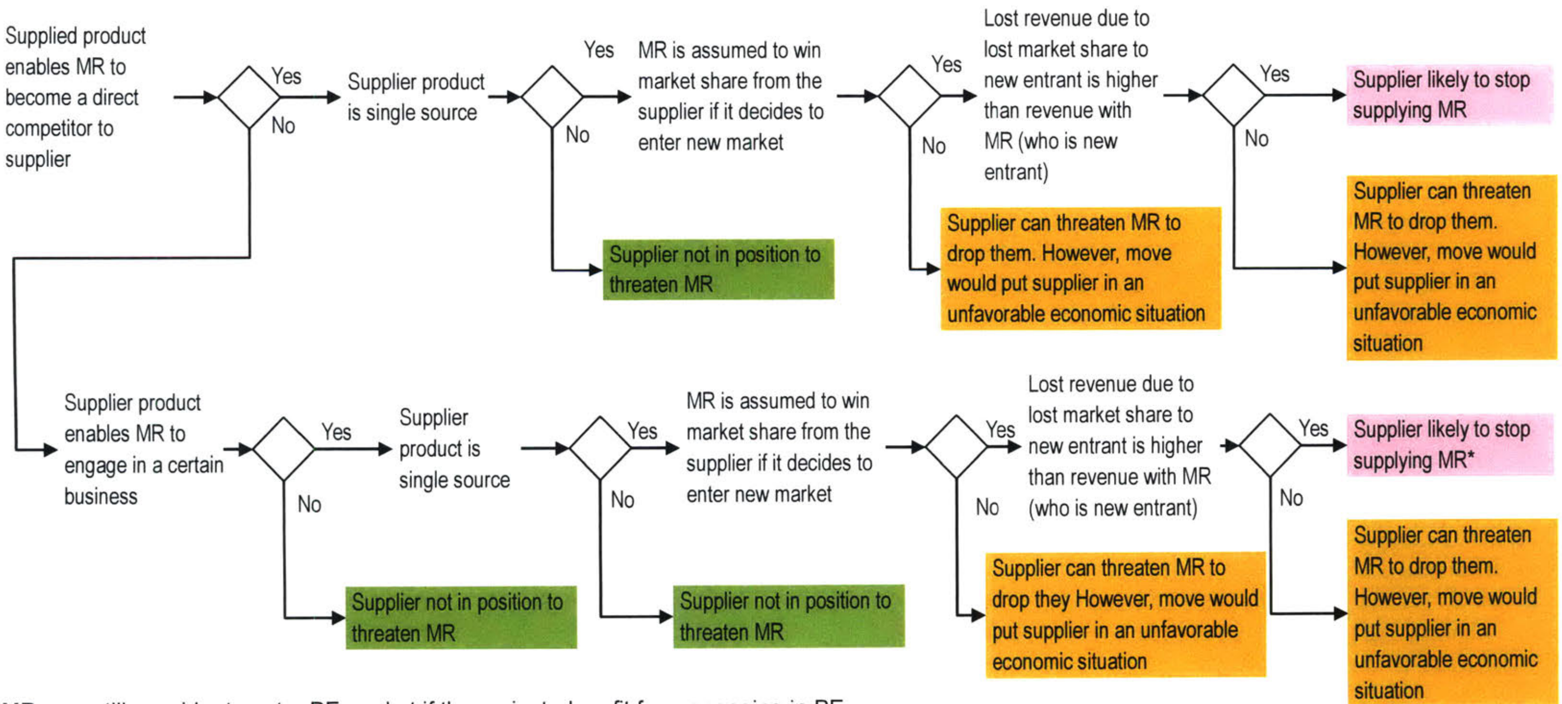


Figure B-1: Flow chart for the assessment of buyer retaliation



* MR may still consider to enter PE market if the projected profit from engaging in PE market is higher than the projected profit of the legacy/current business.

Figure B-2: Flow chart for the assessment of supplier retaliation

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Appendix C

Tables

Severity (S)		
Rating	**Name**	**Impact**
1	minimal	Customer does not notice failure
2,3	minor	Only a few customers notice impact
4,5,6	medium	Loss of secondary functions, triggers customer dissatisfaction
7,8	severe	Loss of main function / large financial impact for customer
9,10	critical	Safety hazard such as fire, explosion, electric schock

Figure C-1: Severity rating for effect of failure mode

Occurrence (O)		
Rating	**Name**	**MTTF (FIT)**
1	almost never / unrealistic	>1000 a (<114 FIT)
2	once every 100 years	>100 a (<1,140 FIT)
3	once every 10 years	>10 a (<11,420 FIT)
4,5,6	once per year	>1 a (<114,420 FIT)
7,8	once per week	>168 hrs (<6m FIT)
9,10	once per shift	>8 hrs (<125m FIT)

Figure C-2: Occurrence rating of failure mode

Detectability (D)		
Rating	**Name**	**Detection probability during operation**
1	very high	electrical diagnosis function >99%
2	high	electrical diagnosis function 90% - 99%
3	high	electrical diagnosis function 60% - 90%
4	medium	detectable with yearly inspection (e.g. checkpoint on checklist)
5	medium	detectable on inspection at 3 years interval (e.g. checkpoint on checklist)
6	medium	detectable on inspection at 7 years interval (e.g. checkpoint on checklist)
7,8	low	Detectable only at commissioning
9,10	very low	No mechanism in place to detect

Figure C-3: Detectability rating of failure mode

Parent ID	Child ID	Test configura tion	Qty per subasse mbly	BOM qty
200_L1_UPFC	203_L2_Circuit Breaker	buy	2	2
200_L1_UPFC	204_L2_Contactor	buy	3	3
200_L1_UPFC	205_L2_Cooling	buy	2	2
200_L1_UPFC	209_L2_Current Measurement	buy	9	9
200_L1_UPFC	211_L2_Disconnector	buy	6	6
200_L1_UPFC	241_L2_Phase Leg Reactors	buy	12	12
200_L1_UPFC	250_L2_Surge Arresters	buy	9	9
200_L1_UPFC	251_L2_Voltage Measurement	buy	6	6
200_L1_UPFC	202_L2_Bypass Unit	buy	3	3
200_L1_UPFC	212_L2_Filters	buy	1	1
200_L1_UPFC	248_L2_Series Transformer	buy	3	3
200_L1_UPFC	249_L2_Shunt Transformer	buy	3	3
200_L1_UPFC	217_L2_MM Converter	make	2	2
200_L1_UPFC	242_L2_Pre Charging Unit	make	2	2
200_L1_UPFC	210_L2_Discharging and Earthing Unit	make	2	2
200_L1_UPFC	201_L2_Application Controller	make/buy	1	1
217_L2_MM Converter	234_L3_Cell Insulator	buy	120	240
217_L2_MM Converter	248_L3_PEBB Insulator	buy	120	240
217_L2_MM Converter	249_L3_Insulation Barrier	buy	33	66
217_L2_MM Converter	251_L3_Protection Controller	buy	1	2
217_L2_MM Converter	252_L3_AC Bushings	buy	9	18
217_L2_MM Converter	253_L3_DC Bushings	buy	6	12
217_L2_MM Converter	238_L3_MMC Cabinet	buy	4	8
217_L2_MM Converter	219_L3_IGBT Cell	make/buy	60	120
217_L2_MM Converter	239_L3_Chain Link Controller	make/buy	1	2
217_L2_MM Converter	250_L3_MMC Controller	make/buy	1	2
219_L3_IGBT Cell	220_L4_Capacitors	buy	2	240
219_L3_IGBT Cell	224_L4_Current Measurement	buy	1	120
219_L3_IGBT Cell	225_L4_Voltage Measurement	buy	1	120
219_L3_IGBT Cell	228_L4_Snubber Capacitor	buy	4	480
219_L3_IGBT Cell	229_L4_Discharging Resistor	buy	2	240
219_L3_IGBT Cell	232_L4_Fiber Optic Cables	buy	16	1920
219_L3_IGBT Cell	233_L4_IGBT	buy	4	480
219_L3_IGBT Cell	221_L4_Cooling Unit	make/buy	1	120
219_L3_IGBT Cell	222_L4_Power Supply	make/buy	1	120
219_L3_IGBT Cell	223_L4_Gate Driver	make/buy	4	480
219_L3_IGBT Cell	226_L4_Cell Bypass Unit	make/buy	1	120
219_L3_IGBT Cell	227_L4_Cell Control Circuit	make/buy	1	120
219_L3_IGBT Cell	230_L4_Busbar set	make/buy	1	120
219_L3_IGBT Cell	231_L4_Mechanical Frame	make/buy	1	120
242_L2_Pre Charging Unit	243_L3_Connector	buy	1	2
242_L2_Pre Charging Unit	244_L3_Contactor	buy	3	6
242_L2_Pre Charging Unit	245_L3_Disconnector	buy	1	2
242_L2_Pre Charging Unit	247_L3_Charging Resitstors	buy	6	12
242_L2_Pre Charging Unit	246_L3_Transformer	make/buy	1	2
	200_L1_UPFC	make/buy	1	1
			Total	**5601**

Figure C-4: BOM structure and item count of UPFC used in case study

Bibliography

[1] M. Brain and D. Ross, "How Power Grids Work," Apr. 2000. [Online]. Available: https://science.howstuffworks.com/environmental/energy/power.htm

[2] S. W. Blume, *Electric Power System Basics for the Nonelectrical Professional*, 2nd ed. Hoboken, New Jersey: Wiley-IEEE Press, Dec. 2016.

[3] L. Bird, M. Milligan, and D. Lew, "Integrating Variable Renewable Energy: Challenges and Solutions," Tech. Rep. NREL/TP-6A20-60451, 1097911, Sep. 2013. [Online]. Available: http://www.osti.gov/servlets/purl/1097911/

[4] P. Scherz and S. Monk, *Practical Electronics for Inventors, Fourth Edition*, 4th ed. McGraw-Hill Education TAB, Apr. 2016.

[5] D. R. Adapa, "The Role of Power Electronics in the Future Smart Electric Grid," *EPRI - Electric Power Research Institute*, p. 53, 2011. [Online]. Available: https://ewh.ieee.org/r6/scv/pels/archive/Role%20of%20Power%20Electronics%20in%20Future%20SMART%20Electric%20Grid.pdf

[6] D. Dohnal, *On-Load Tap-Changers for Power Transformers.* Maschinenfabrik Reinhausen. [Online]. Available: https://cds-frost-com.libproxy.mit.edu/p/58319/#!/ppt/c?id=MB0F-01-00-00-00&fq=%22smart%20transformer%22

[7] "Global Transformer Market," Frost & Sullivan, Industry Research Analysis MB0F, May 2016.

[8] I. Staff, "Forward Integration," Nov. 2003. [Online]. Available: https://www.investopedia.com/terms/f/forwardintegration.asp

[9] M. E. Porter, *Competitive Advantage: Creating and Sustaining Superior Performance*, 1st ed. New York: Free Press, Jun. 1998.

[10] M. Kannegiesser, *Value Chain Management in the Chemical Industry: Global Value Chain Planning of Commodities*, 2008th ed. Heidelberg: Physica, Sep. 2008.

[11] H. Tchale and J. Keyser, "Quantitative Value Chain Analysis : An Application to Malawi," World Bank, Policy Research working paper no. WPS 5242, 2010. [Online]. Available: https://openknowledge.worldbank.org/handle/10986/3730License: CCBY3.0IGO

[12] International Conference on Value Chain Management, H. Jodlbauer, J. Olhager, and R. Schonberger, *Modelling value selected papers of the 1st International Conference on Value Chain Management, May 4th-5th, 2011, University of Applied Sciences in Upper*

Austria, School of Management, Steyr, Austria. Heidelberg; New York: Physica-Verlag, 2012, oCLC: 773192745. [Online]. Available: http://site.ebrary.com/id/10523791

[13] R. Kaplan, "Time-Driven Activity-Based Costing," Jul. 2006. [Online]. Available: http://hbswk.hbs.edu/item/time-driven-activity-based-costing

[14] M. E. Porter, "The Five Competitive Forces that Shape Strategy," *Harvard Business Review*, vol. 86, no. 1, pp. 78–93, 2008, oCLC: 264022440.

[15] ——, *Competitive Strategy: Techniques for Analyzing Industries and Competitors*, 1st ed. Free Press, Jun. 2008.

[16] M. B. Lieberman and D. B. Montgomery, "First-Mover Advantages," *Strategic Management Journal; Chicago*, vol. 9, p. 41, 1988. [Online]. Available: https://search.proquest.com/docview/224996706/abstract/63CA07D837E40A9PQ/1

[17] R. S. Pindyck, "Entry and Reaction to Entry," in *Lecture Notes for 15.013 Industrial Economics for Strategic Decisions.* Sloan School of Management, MIT, Jul. 2017.

[18] C. Markides and L. Sosa, "Pioneering and First Mover Advantages: The Importance of Business Models," *Long Range Planning*, vol. 46, no. 4-5, pp. 325–334, Aug. 2013. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0024630113000319

[19] S. Blank, "Steve Blank Why Pioneers Have Arrows In Their Backs," Oct. 2010. [Online]. Available: https://steveblank.com/2010/10/04/why-pioneers-are-the-ones-with-the-arrows-in-their-backs/

[20] F. Suarez and G. Lanzolla, "The Half-Truth of First-Mover Advantage," Apr. 2005. [Online]. Available: https://hbr.org/2005/04/the-half-truth-of-first-mover-advantage

[21] F. M. Bass, "A New Product Growth for Model Consumer Durables," *Management Science*, vol. 50, no. 12, pp. 1825–1832, 2004. [Online]. Available: http://www.jstor.org/stable/30046153

[22] G. E. Fruchter, "Forecasting the Sales of New Products and the Bass Model," Bar-Ilan University, 2000. [Online]. Available: https://faculty.biu.ac.il/~fruchtg/

[23] S. Beckman and D. Rosenfield, *Operations Strategy: Competing in the 21st Century*, 1st ed. Boston: McGraw-Hill/Irwin, May 2007.

[24] A. K. Dixit and R. S. Pindyck, *Investment under Uncertainty*, first printing edition ed. Princeton, N.J: Princeton University Press, Jan. 1994.

[25] E. Grimson and J. Guttag, "Introduction to Computational Thinking and Data Science," 2016. [Online]. Available: https://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-0002-introduction-to-computational-thinking-and-data-science-fall-2016/

[26] T. P. Omdahl, *Reliability, availability, and maintainability dictionary.* ASQC Quality Press.

[27] D. H. Stamatis, *Failure mode and effect analysis: FMEA from theory to execution.* Milwaukee, Wisc.: ASQ Quality Press, 2003, oCLC: 51810625.

[28] "AC power," Dec. 2017, page Version ID: 817281622. [Online]. Available: https://en.wikipedia.org/w/index.php?title=AC_power&oldid=817281622

[29] W. v. d. Merwe and T. Mouton, "Solid-state transformer topology selection," in *2009 IEEE International Conference on Industrial Technology*, Feb. 2009, pp. 1–6.

[30] A. Shri, "A Solid-State Transformer for Interconnection between the Medium- and the Low-Voltage Grid:," Ph.D. dissertation, Delft University of Technology, 2013. [Online]. Available: http://oatd.org/oatd/record?record=oai%5C%3Atudelft.nl%5C%3Auuid%5C%3A3bb366d5-6f87-4636-a4a3-0245269125f5

[31] "Are Solid-State Transformers Ready for Prime Time?" Aug. 2017. [Online]. Available: http://www.powerelectronics.com/alternative-energy/are-solid-state-transformers-ready-prime-time

[32] U. Kaltenborn, "PAG Solid State Anwendungen," Feb. 2014.

[33] H.-W. Juan, "Sourcing strategy for power electronics derived from modular product structure," Thesis, Massachusetts Institute of Technology, 2017. [Online]. Available: http://dspace.mit.edu/handle/1721.1/111918

[34] R. Austria, "Steel Mill in the Neighborhood | Pterra Consulting." [Online]. Available: http://www.pterra.com/steel-mill-in-the-neighborhood/

[35] A. Birolini, *Reliability Engineering: Theory and Practice*, 8th ed. New York, NY: Springer, May 2017.

[36] *Military Handbook (MIL)-HDBK-217, Revision F.* DOD, Dec. 1991.

[37] A. C. Owens, "Quantitative probabilistic modeling of environmental control and life support System resilience for long-duration human spaceflight," Thesis, Massachusetts Institute of Technology, 2014. [Online]. Available: http://dspace.mit.edu/handle/1721.1/93770

[38] B. W. Taylor, *Introduction To Management Science*, 12th ed. Pearson India, 2015.