

Analysis of Asset Health – an Approach to Monitoring and Diagnostics for Medium Voltage Circuit Breakers

by

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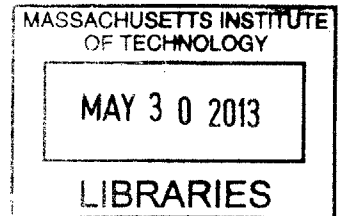
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ABSTRACT

The Medium Voltage Electric Industry is a very conservative and risk adverse sector that has undergone very little change in the past 30 years when compared to other technologically dependent activities; this reality is rapidly shifting.

The advent of cost-effective and reliable telecommunications, coupled with the drastic price decrease of wireless communication and sensing technologies, are steering the industry towards an information based era that is generically known as smart-grid.

With an emphasis on medium voltage circuit breakers, the purpose of this thesis was to identify sensor technology and analytics that will allow electric utilities in North America—primarily the United States—to assess the health of their equipment and utilize this information for maintenance operational decisions.

The main areas of research included in this work were the market context for medium voltage circuit breaker Monitoring & Diagnostics solutions, the financial justification for such applications, and the technical merit of multiple sensor technologies and associated analytics.

The findings of this research helped support the development of an advanced Monitoring and Diagnostics kit currently deployed at a customer site as part of a pilot demonstration program. The prototype system provides real-time monitoring and trending information for six reactor-switching 15 kV circuit breakers.

The completion of this thesis, and successful development of the advanced Monitoring and Diagnostics kit, was the result of the collaborative effort of a small interdisciplinary team assembled to identify smart-grid opportunities in the medium voltage space. This work took place at ABB's Medium Voltage Headquarters in the United States.

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

ABB – Asea Brown Boveri

AC – Alternating Current

A/D – Analog to Digital

AMI – Advanced Metering Infrastructure

ANSI – American National Standards Institute

CB – Circuit Breaker

CIGRE – International Council on Large Electric Systems (*translated from French*)

CVR – conservation voltage reduction

DC – Direct Current

DOE – Department of Energy

FDIR – Fault Detection, Isolation, and Restoration

HV – High Voltage

IEEE – Institute of Electrical and Electronics Engineers

IEC – International Electromechanical Commission

ISO – Independent System Operator

IC – Integrated Circuit

IT – Information Technology

M&A – Mergers and Acquisitions

M&D – Monitoring and Diagnostics

MV – Medium Voltage

NA – North America

NPV – Net Present Value

NRC – U.S. Nuclear Regulatory Commission

O&M – Operations and Maintenance

OT – Operation Technology

ROI – Return on Investment

RTD - Resistance Temperature Detector

RTO – Regional Transmission Operator

SAW – Surface Acoustic Wave

SCADA – Supervisory Control and Data Acquisition

T&D – Transmission and Distribution

USD – United States Dollar

1 SMART-GRID, WHAT IT IS AND ITS SIGNIFICANCE

1.1 Introduction

The concept of Smart-grid has been evolving for at least 20 years and is yet to be fully defined in literature, policy, and technological specifications. In essence, a smart-grid is an electric transmission and distribution (T&D) network managed through the analysis and synthesis of massive amounts of information.

Although existing electric grids hold the capability of generating some information through existing *supervisory control and data acquisition systems* (SCADA), current architectures have limited information flow bandwidth and/or the flexibility to incorporate additional information that might be useful to an electric utility operator. Thus the importance of Smart-grid—Smart-grid envisions enhanced data acquisition systems, data transmission and storage technology, and the use of computing power and analytics to help manage electric grid operations.

Moreover, from an economic standpoint, smart-grid offers the promise of enabling more efficient and reliable dispatch and routing of electricity. Utilities will have enhanced real-time monitoring of their networks and will thus be able to reduce system energy losses with the adoption of *conservation voltage reduction* (CVR) and *fault detection, isolation, and restoration* (FDIR) technology. Utilities will also have the ability to transition away from time-based maintenance schemes and deploy data-intensive monitoring and diagnostic approaches to manage their assets.

Along with the economics, smart-grid also envisions the capability to effectively incorporate renewable sources (e.g., wind, solar) and manage their inherent intermittency; this capacity to adapt is a critical technological enabler if renewable resources are to become significant contributors in the electric generation mix. The same enabling argument exists for electric vehicles, distributed generation (e.g., residential solar panels), energy storage, and advanced electric grid ancillary services (e.g., demand response).

Additionally, on the consumer's side, as smart metering becomes pervasive and tariff structures better reflect the "*true cost*" of electricity, utility customers will have the ability to shift loads away from peak prices and allow for an overall more efficient use of electric generation capabilities.

In the same way that Smart-grid is an enormous technological undertaking, it is also an equally important financial and policy challenge. As with any infrastructure upgrade, the cost of developing and deploying smart-grid will require billions, and be subject to a complex political-regulatory landscape; the utility space is risk adverse and not accustomed to the rapid pace with which technology for the sector has evolved.

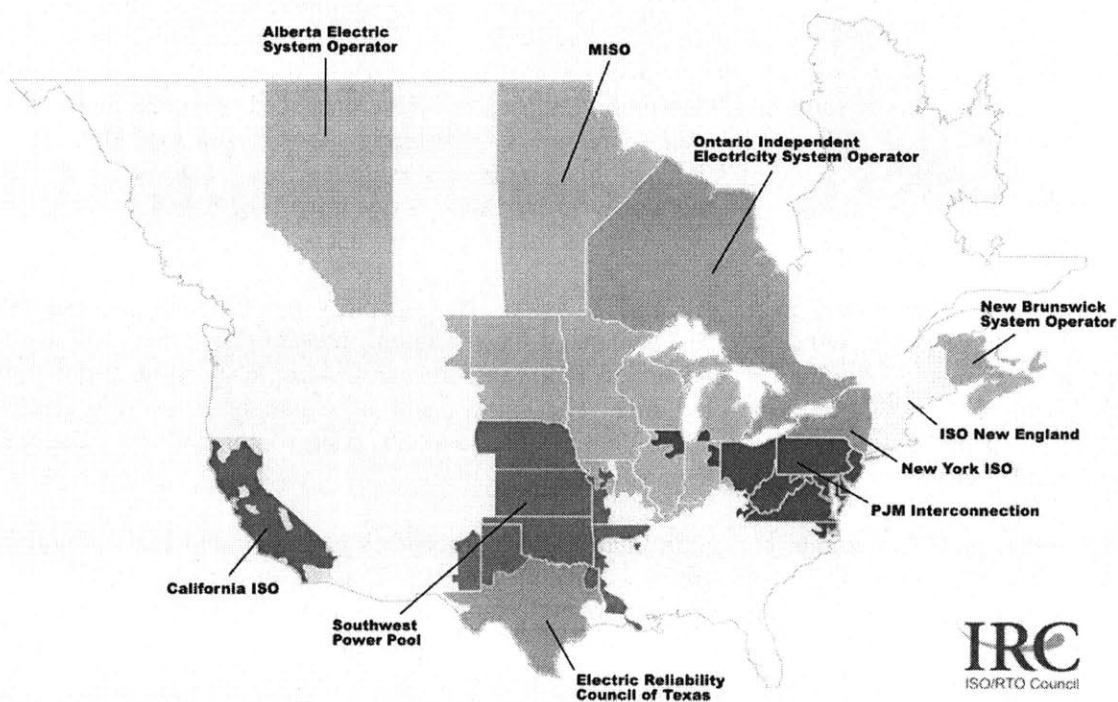
Consequently, smart-grid will be distinct across the electric utility spectrum and will be reflective of the technological needs and capabilities, policies, and financial means of the distinct territories in which utilities operate.

To sum up, in 2003 The National Academy of Engineering announced that *Electrification* was the most significant engineering achievement of the 20th century. Therefore, in a world evermore reliant on electricity, smart-grid is the 21st century evolution—the next chapter—in what is an amazingly exciting, and daunting, challenge.

1.2 Context of Smart-Grid in the United States

The electric sector in the United States serves 143 million residential, commercial, and industrial customers through more than 6 million miles of transmission and distribution lines owned and/or managed by more than 3,000 entities that range from investor owned companies to cooperative enterprises [1].

But the United States, unlike other developed nations, does not have a unified national electricity policy as regulation occurs at the state, as well as the federal level. Partly because of this fragmented regulatory landscape between federal and state authorities, the U.S. is composed of vertically integrated utilities, cooperative utilities, and organized wholesale electricity markets operated by Independent Transmission Organizations (ISOs) or Regional Transmission Organizations (RTOs) as seen in Figure 1-1.



Source: ISO/RTO Council, <http://www.isorto.org>. Copyright © ISO/RTO Council, all rights reserved.

Figure 1-1: North American Regions with Organized Electricity Markets

The lack of a shared policy, over time, has resulted in the adoption of distinct engineering standards and equipment management practices that are at times anchored in rules of thumb dating back to an era where computing power was not available to adequately plan for an optimal system. Over time, and partly due to the lack of communication that exists amongst utilities, these standards and practices have evolved in a disjoint fashion with the most serious disconnect existing in the distribution arena.

The Federal Government understands the need for modernization. During the Bush administration, the U.S. Congress put forth the *Energy Independence and Security Act* of 2007, which identifies the modernization of the grid as a directive for the country and instructs the

Department of Energy (DOE) to issue a report on the status of smart-grid deployment. During the Obama administration, the *American Recovery and Reinvestment Act* of 2009 directed \$4.5 billion to the DOE for modernization of the electric grid and increases grants for the *Smart Grid Investment Program* from 20% to 50% [2].

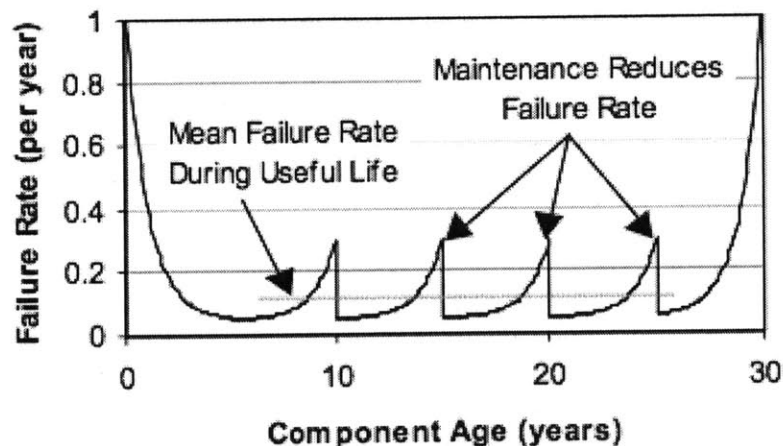
Although the federal directives and availability of funds are steps in the right direction, they are not enough because the nation's smart-grid efforts are still uncoordinated and geographically disperse. Examples of this abound and can be found in the troubled and localized adoption and deployment of advanced metering infrastructure (AMI), the distinct regulatory and market approaches with which demand response and distributed generation are managed, and the different campaigns designed to engage utility customers, amongst others.

From an economic standpoint, the need for smart-grid is paramount if one considers that increasingly scarce energy resources conflict with U.S. expected electricity demand growth. By 2050, EPRI estimates that the average electric bill could reach 400% if smart-grid technologies are not deployed; whereas, with the adoption of smart-grid the projected increase is 50% [3].

1.2.1 Reliability and an Ageing Infrastructure

In 2011, the McDonnell Consulting Group published a report [4] showing that 53% of the top 100 utilities in North America rank ensuring reliability of their ageing assets as a top strategic priority, and 94% consider it one of their top three priorities. The report, unlike surveys conducted in the past, brings the problem of an ageing infrastructure to the forefront because the cost of maintaining existing assets, in order to deliver expected reliability, is becoming more expensive.

The ageing electrical infrastructure problem in the U.S. is not new, and has been expected and documented in literature for the past twenty years. The main problem with old equipment is that it is three to ten times more likely to fail than newer equipment, and the onset of increased failure rates typically follows an exponential trajectory as seen in Figure 1-2.



Source: Brown, R., *Electric power distribution reliability*, 2009

Figure 1-2: Sawtooth Bathtub Failure Rate Curve

The higher load factors that the U.S. system has observed in the past 30-40 years¹ further exacerbate the issue. These higher loads are a consequence of the lack of investment that has failed to keep up with demand growth, and are directly responsible for an acceleration of the ageing phenomenon. On top of this, through the 1990s, many de-regulated utilities saw budgetary reductions of 25%-35%, which impacted maintenance operations—and thus worsened the ageing infrastructure problem [5].

The level of investment required to modernize the existing U.S. electric grid is prohibitively expensive if the system is to perform with the same reliability as in the past. Rather than increasing the frequency of time-based maintenance intervals to mitigate the ageing infrastructure problem, smart-grid offers the possibility of implementing condition based maintenance schemes as a means of extending the life of existing equipment.

1.2.2 Technological Challenge

The technological foundation required to put in place smart-grid: viable sensors, widespread telecommunications, and the availability of storage and computing power, are all readily available as evidenced by systems already utilized in industrial/manufacturing settings. The main challenge is not the technology itself, but rather the design and integration of smart-grid as a system.

In order for smart-grid to be successful, clear specifications need to be defined so that all interfacing parties are capable of designing components—sensors, telecommunications, and software—in such a way that they *plug-and-play*. In the United States, in line with the lack of a decisive electric sector policy, there has not been a serious effort to define interface standards and overall system architecture for the system².

A major hurdle to piecing smart-grid together in the U.S. is the *siloing* that characterizes the industry. Information sharing amongst utilities is not pervasive given that each serves distinct territories and more than likely operates in separate regulatory environments. Moreover, even within utilities, transmission and distribution planning are viewed as “*Church and State*” and this divide is even reflected in the organizational structures of electrical equipment vendors, which in turn places an additional hurdle for the much-needed systems integration capability required.

Another barrier for smart-grid is the pressure of time imposed by the fact that utilities will need to replace 46% of skilled technician positions by 2015 because of retirement or attrition [6]. Smart-grid, with the potential of utilizing information to streamline operations, is essential in order to bridge this imminent workforce gap. This gap becomes even wider if one realizes that an ageing grid requires more effort to maintain: the challenge is to deploy smart-grid in a short period.

Along the way, smart-grid will provide vast amounts of information, which in itself will be an immense challenge to manage. Ultimately, the way in which we store, analyze, and extract value from the grid will be a reflection of the degree of consensus achieved throughout the industry in what is clearly a highly complex system design and integration challenge.

¹ Average electrical feeder loading in metropolitan areas increased 50% between 1965-2000 [5].

² Cyber-security, a key element of the grid given its national security aspect, is the focus of much attention and concern when discussing requirement definitions.

1.2.3 Financial and Policy Challenge

The lack of standards, silos, and the complexity presented by interests involved in de-regulated territories, are all elements of risk to the development and adoption of multi-billion dollar modernization investments. These elements, in the midst of the traditionally risk adverse electric sector, explain the slow pace that has characterized smart-grid deployment in the U.S.

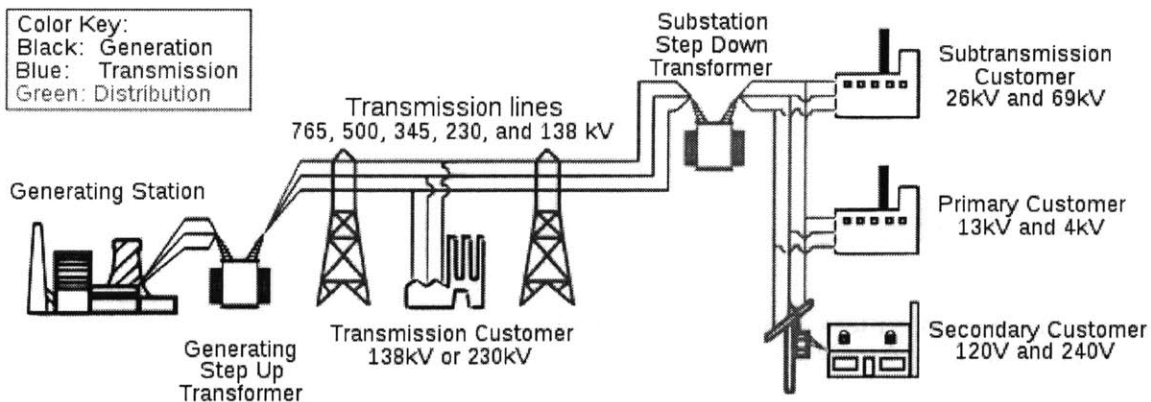
The fragmented utility landscape of the United States has the unintended consequence of creating an environment in which the business case for distinct smart-grid applications is difficult to make as each region's operational realities are distinct and/or are yet to be defined (e.g., monetization of frequency regulation). With utilities subject to distinct operational and regulatory constraints, achieving production economies of scale with inter-operable systems is harder to achieve.

Nevertheless, the societal benefits of smart-grid are clear. As noted previously, EPRI estimates that smart-grid will help maintain electricity economically viable through 2050, with utility bills increasing by 50% (versus the alternative of 400% without smart-grid) [3]. And in the more immediate future, McKinsey's 2010 report on smart-grid [7] estimates that a successful deployment of smart-grid could generate savings of \$130 billion annually by the end of the decade.

Smart-grid development finds itself at the intersection of a technical, financial, and policy problem that is currently in gridlock. As it stands, development will continue to be organically driven and slow paced unless the enactment of strong federal policy defining market mechanisms and incentives comes to fruition alongside clearly outlined smart-grid standards and interface definitions.

1.3 Project Motivation and Goal

The justification for Monitoring & Diagnostics (M&D) schemes in the utility sector is well understood in the generation and transmission—high voltage (HV) space (Figure 1-3) where assets and equipment failure outage costs are valued in millions (USD). As such, equipment in this space (e.g., HV transformers) has had M&D solutions for over 10 years.



Source: U.S.-Canada Power System Outage Task Force, *Final Report on the August 14, 2003, Blackout in the United States and Canada: Causes and Recommendations*, April 2004.

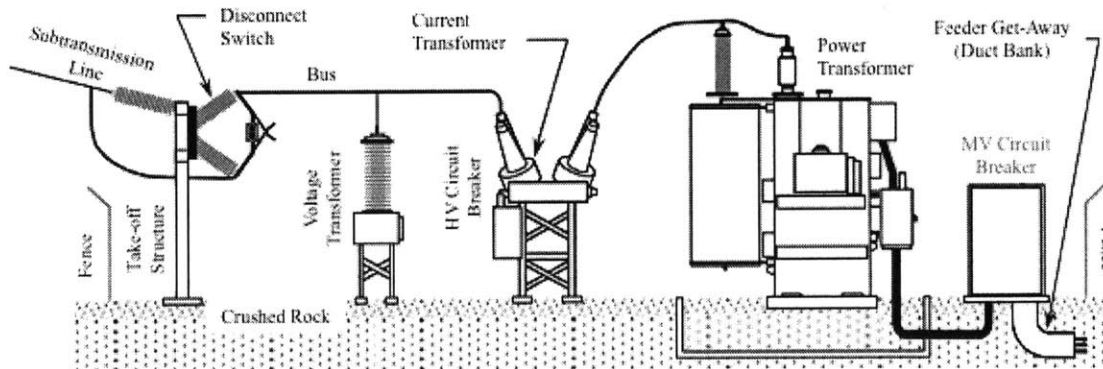
Figure 1-3: Electric Generation, Transmission, and Distribution Infrastructure

The underlying principle is for M&D to provide advance warning of impending failures and/or reduce problem diagnosis times in order to restore service as quickly as possible, and thus minimize the financial penalties to the utility incurred during an unplanned outage. This decreased likelihood of incurring outage penalties is the main driver for investment in M&D technologies.

Within the distribution medium voltage (MV) space (Figure 1-3), where equipment is valued in the thousands, geographic reach of disruptions is much more limited, and outage costs are significantly lower, the financial case to invest in M&D has been non-existent given the comparatively elevated costs associated with sensing equipment, telecommunications, data storage, and computing capability, versus cost of the asset protected.

This paradigm, however, is rapidly shifting given the advent of cost-effective and reliable telecommunications, and the drastic cost decrease of computing power and sensing technologies. The widespread and economical availability of these technologies is steering the MV space towards exploring M&D solutions in what is a smart-grid application that can help streamline O&M operations and alleviate the problems associated with an ageing distribution network and skilled workforce shortage.

This project explores sensor technology and analytics that enable M&D schemes for medium voltage circuit breakers (Fig. 1-4) and justifies the selected technology, system integration, and monitoring analytics from both a technical and financial standpoint. The project's hypothesis is that it is possible to develop cost-effective M&D schemes for MV circuit breakers and switchgear equipment for the utility market.



Source: Brown, R., *Electric power distribution reliability*, 2009

Figure 1-4: Typical Substation Components and Layout

Research for this project took place on site at ABB's Power Products Medium Voltage (PPMV) headquarters in the United States. Developed for, and included herein, is a customized M&D system for a fleet of reactor switching circuit breakers³ currently deployed at a customer site as part of a demonstration pilot. The documented design methodology and end results serve as a case study of M&D development for medium voltage circuit breakers.

³ Reactor bank switching is a practice utilized by utilities to compensate for reactive power in the grid.

The market opportunity for medium voltage circuit breaker M&D, a subset of the \$8 billion USD benefit McKinsey sees in M&D [7], is significant as there are more than 60,000 distribution substations in the United States [8] averaging 2-3 MV circuit breakers each. Furthermore, many of these substations lack even the most basic SCADA capability⁴, and thus the operational impact smart-grid M&D applications is substantial [9].

1.4 Research Methodology

The project’s evolution, findings, and implementation are part of the collaborative effort of a small *Accelerated Proof of Concept Team* assembled to identify smart-grid opportunities in the medium voltage space. As the project’s objective is to ultimately develop an advanced circuit breaker M&D functional prototype, the development effort follows a simple product development flow consisting of the following gates (Figure 1-5):

Problem Understanding: This gate focuses on understanding essential medium voltage circuit breaker systems and operation, failure modes and reliability, and the equipment’s associated costs when viewed from the customer’s perspective.

Concept Design: With the objective of increasing equipment reliability and decreasing customer costs, research will evaluate the merit of distinct sensing technologies and propose an analytical framework for the down-selected sensors. The end task for this gate will be the integration of sensors, communications, data aggregation, and analytics.

Concept Validation: Lab testing will validate system design before piloting the advanced prototype at a customer location. This gate will also identify and document system design decisions dependent on field data analysis—future work and areas of research.

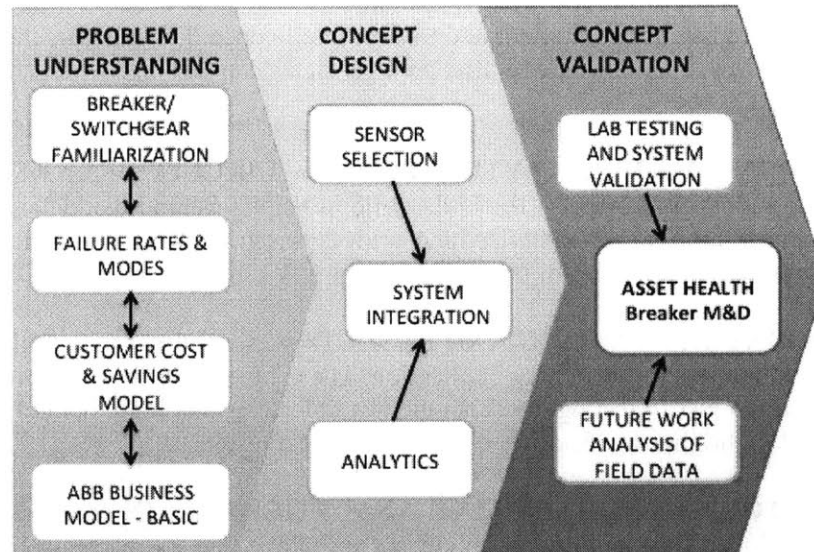


Figure 1-5: Medium Voltage Circuit Breaker M&D Research and Design Gates

⁴ PG&E, one of the most progressive utilities and the third largest in the United States, has a fleet of 724 distribution substations of which only 50% have SCADA capability.

1.5 Thesis Outline

The thesis proceeds as follows:

Chapter 1, SMART-GRID, WHAT IT IS AND ITS SIGNIFICANCE introduces smart-grid in the context of its technological and policy challenges, as well as potential economic benefits. Emphasis is drawn on the ageing infrastructure problem faced by electric utilities in the United States and the opportunities that exist for monitoring and diagnostics solutions. The chapter describes the project's motivation, goal, methodology, and this thesis outline.

Chapter 2, ABB NORTH AMERICA & SMART-GRID provides a brief historical background on the company as well as its management and operating structure in North America. Additionally, it places the thesis project in the context of the company's recent smart-grid strategy.

Chapter 3, RELIABILITY OF MEDIUM VOLTAGE CIRCUIT BREAKERS gives an overview of reliability for MV breakers in the U.S. by piecing together information available from the German MV distribution system, the U.S. Nuclear Generation sector, and the IEEE. The lack of information on equipment failure rates frames the discussion and justifies the work presented.

Chapter 4, MEDIUM VOLTAGE CIRCUIT BREAKER FAILURE MODES looks into the leading equipment failure mechanisms. Here too, as with Ch. 3, a collage of information is the result of piecing together reports from the German MV distribution system, the U.S. Nuclear Generation sector, CIGRE, and the IEEE.

Chapter 5, THE BUSINESS CASE FOR MV CIRCUIT BREAKER M&D presents the business case for M&D applications for both circuit breaker manufacturers and their utility customers. For OEMs, a transition towards service models marks the need for M&D as a means to provide insight into customer equipment and market intelligence. For utilities, the justification is based on a simple *Cost & Savings* model that predicts significant savings when considering the findings of Ch. 3 and Ch. 4.

Chapter 6, EXISTING M&D ANALYTICS FOR MV CIRCUIT BREAKERS gives an overview of existing work in the space, the underlying principles behind magnetic coil profiling and interrupter thermal monitoring analytics, and utilizes this framework to justify the selected sensing technologies and overall system integration of the MV circuit breaker M&D kit.

Chapter 7, LABORATORY TESTING AND RESULTS presents the results utilized to design the M&D analytics for a reactor switching application. The chapter describes the prior knowledge and information used to justify testing, presents the test objectives and logic behind the design of the experiment, and highlights key findings obtained from test results.

Chapter 8, REACTOR SWITCHING—M&D ANALYTICS DESIGN provides an overview of the analytics developed for a pilot program currently deployed on six reactor-switching circuit breakers. The focus of the chapter is on the distinct levels of protection designed for monitoring mechanical operations.

Chapter 9, SUMMARY AND CONCLUSIONS provides an overview of the project and brings together the most significant findings and results.

2 ABB NORTH AMERICA & SMART-GRID

This chapter provides a general overview of the corporate structure of ABB with emphasis on its Medium Voltage operations in North America, and presents the key competitive and cultural challenges facing the company as it begins developing M&D solutions. The objective of the chapter is to provide a context of the operating environment surrounding the research conducted.

2.1 ABB Corporate Background

Headquartered in Zurich, Asea Brown Boveri, Ltd. (ABB) is formed in 1988 when ASEA AB (est. 1883) of Sweden and BBC Brown Boveri (est. 1891) of Switzerland combine their electrical engineering and equipment businesses.

Since its inception, the company has had a history of acquisitions that has allowed it to establish itself as one of the largest engineering conglomerates with operations in over 100 countries. In conjunction with its acquisition strategy, beginning in the 2000s, and with the objective of refocusing on core competencies, the company initiated a consolidation process (still ongoing) that began with the divestiture of its nuclear and conventional power generation businesses.

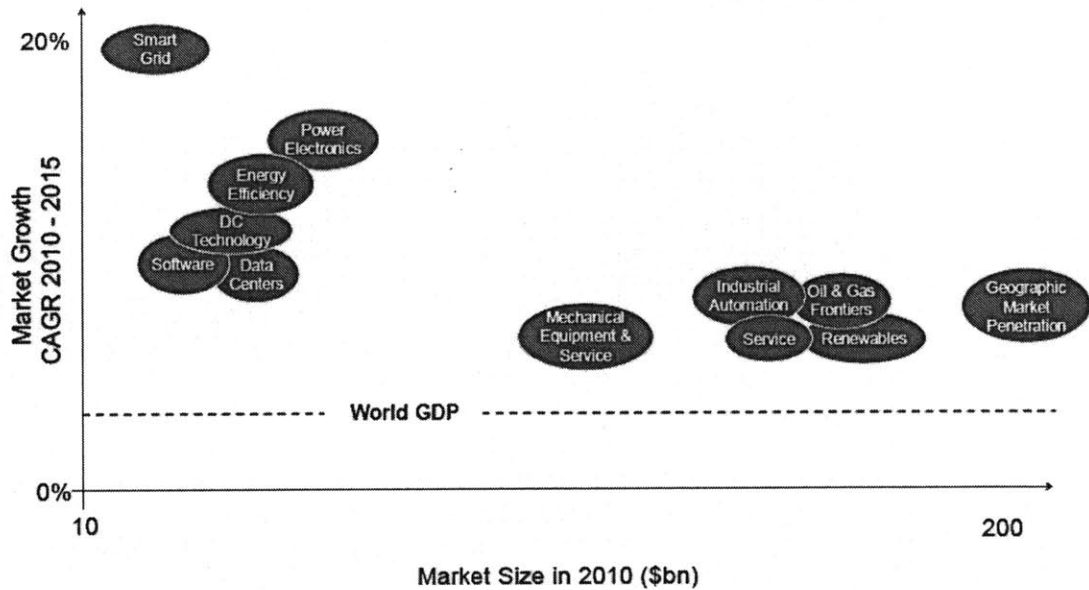
In 2006, after consolidating its remaining businesses into two areas, *Power Technologies* and *Automation Technologies*, ABB restructured its operations into five divisions (Figure 2-2): *Power Products*, *Power Systems*, *Automation Products*, *Process Automation*, and *Robotics*. ABB's acquisition and consolidation strategy continues to this day.

The company's strategy through 2015 is to continue the consolidation process of today's still highly decentralized conglomerate into a more centralized organization, meanwhile ensuring that a connection to country and regional customers, and market realities, remains strong. From a product development and portfolio offering the company's focus is to:

- Penetrate emerging markets.
- Develop industries expected to grow faster than world GDP (Figure 2-1).
- Address mature market opportunities (e.g., infrastructure renovation).
- Integrate Operational Technology (OT) and Information Technology (IT)⁵.
- Continue M&A strategy to fill in gaps in product portfolio offering.
- Stimulate *Disruptive Innovation*: business models, products, and services.

In 2011, the company had sales of \$37.99 billion (USD), a net income of \$3.17 billion, assets of \$39.65 billion, and a market value of \$47.77 billion. ABB has close to 145,000 employees.

⁵ The case of smart-grid.



Source: *Overview of ABB's 2014 strategy*, <http://www.abb-betterworld.com/en/>, [http://www02.abb.com/global/abbzh/abbzh259.nsf/0/c3098a179f5b83bdc125793a00339e27/\\$file/ABB+CMD+1+-+Joe+Hogan.pdf](http://www02.abb.com/global/abbzh/abbzh259.nsf/0/c3098a179f5b83bdc125793a00339e27/$file/ABB+CMD+1+-+Joe+Hogan.pdf)

Figure 2-1: ABB 2015 Strategy - 12 Growth Areas

2.2 ABB North America Power Products Medium Voltage (PPMV)

The products that ABB offers the T&D market are the focus of its *Power Products Division* that is composed of three subdivisions (Figure 2-2): *Transformer Products*, *High Voltage Products & Systems*, and *Medium Voltage Products & Systems*. Each sub organization is comprised of a global office tasked with strategic decision-making and country/regional offices responsible for execution. Within both offices, the organization is matrix-structured into product lines (e.g., circuit breaker) and functions (e.g., marketing).

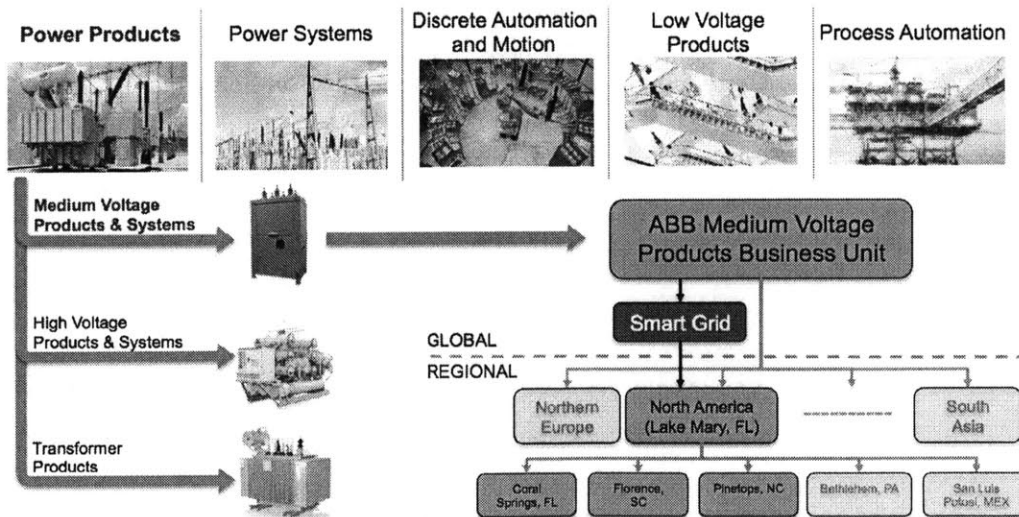
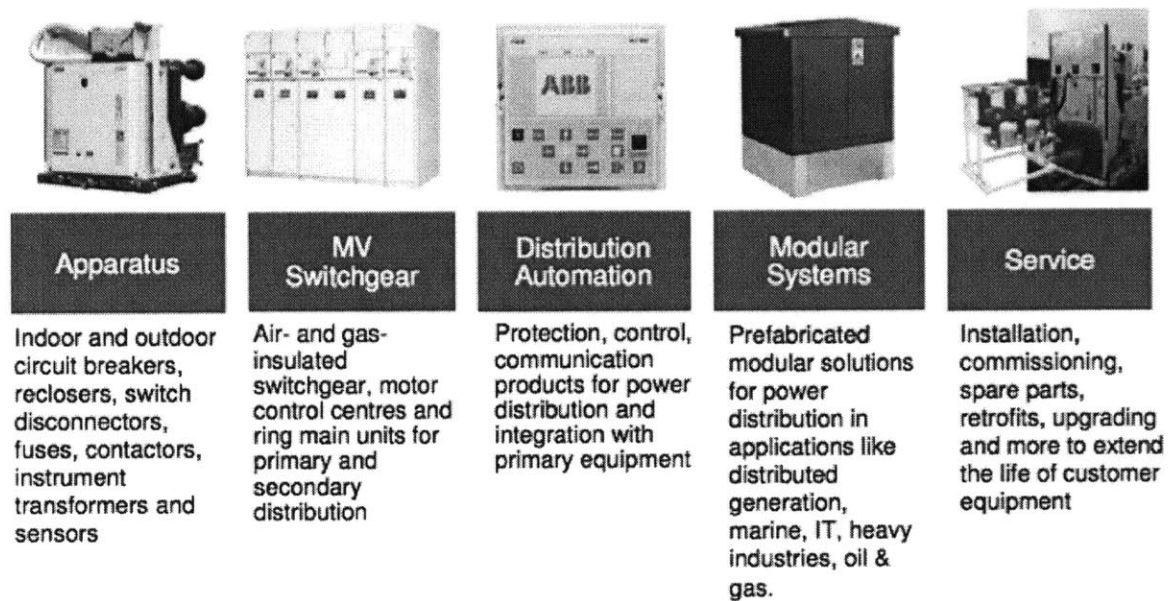


Figure 2-2: ABB's Divisional Structure and North America PPMV Smart-Grid

2.2.1 ABB PPMV NA Product Portfolio

In North America, ABB’s Power Products Medium Voltage (PPMV) head office is located in Lake Mary (FL) and includes operations in Coral Springs (FL), Bethlehem (PA), Pinetops (NC), Florence (SC), San Luis Potosí, Mexico, Dorval (Quebec), Calgary (BC), and Brampton (Ontario). Its products offering (Figure 2-3) mainly serves the United States, Mexico, Canada and other Latin American countries that follow standards set forth by the *American National Standards Institute* (ANSI).



Source: *ABB Medium Voltage Products*, ABB.com, [http://www02.abb.com/global/abbzh/abbzh259.nsf/bf177942f19f4a98c1257148003b7a0a/0614867da50216a7c1257508003315d9/\\$FILE/081120+JP+Morgan+Medium+Voltage+Presentation.pdf](http://www02.abb.com/global/abbzh/abbzh259.nsf/bf177942f19f4a98c1257148003b7a0a/0614867da50216a7c1257508003315d9/$FILE/081120+JP+Morgan+Medium+Voltage+Presentation.pdf)

Figure 2-3: ABB PPMV Product Offering

2.2.2 ABB PPMV NA Utility Sales Channel

The sales channels for PPMV NA’s products to the utility sector are complex and highly dependent on the unique relationship that ABB has with each utility customer. For the most part, the utility sector maintains a predominantly product-direct business model with maintenance operations contracted out to third parties, or performed by the utilities themselves.

Although a simplification of the complex interactions involved in utility sales, Figure 2-4 depicts the main interactions between ABB’s sales and engineering support teams with utility customers and ABB’s competition, as well as third party service providers. Worth noting is the restricted access to utility substation equipment: this limits the information available regarding equipment reliability, hinders marketing intelligence, and explains the need for close ties between ABB field personnel and utility customers.

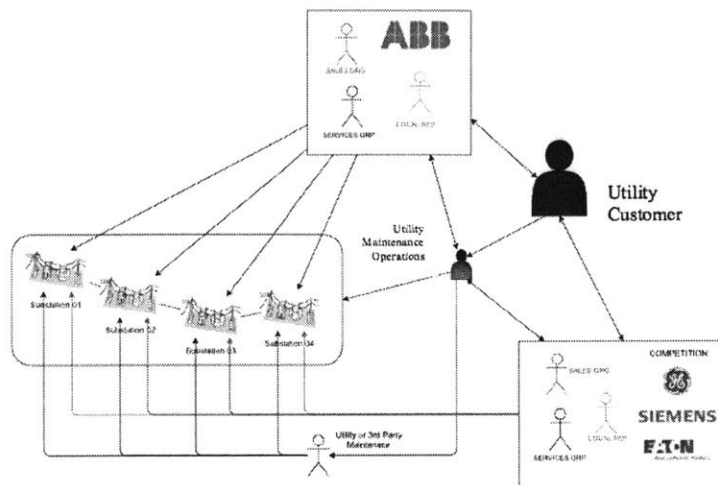


Figure 2-4: ABB, Competition, and Utility Customer Simplified Interaction Diagram

2.2.3 ABB PPMV NA R&D and Product Design Capabilities

ABB’s PPMV NA Division leverages both local and international R&D capabilities to meet the company’s product development needs in the ANSI market. These R&D resources are capable of developing custom products and/or adapting existing technologies to meet market needs.

From a smart-grid perspective, ABB has invested heavily in a *Smart Grid Center of Excellence* to develop and showcase end-end solutions intended for the ANSI market. The intention is to provide ABB rapid product design capability, leverage technology developed in the U.S. and Europe, and address the rapid and uncertain U.S. and Global smart-grid market.

On the M&A front, ABB closed three important deals that fill gaps in IT, telecommunications technology, as well as the company’s market presence in the medium/low voltage space:

- **Ventyx** — is a software provider to asset-intensive businesses (e.g., electric utilities) offering asset and workforce management solution (acquired 2010).
- **Tropos Networks** — is a smart-grid communications technology company (acquired 2012).
- **Thomas and Betts** — is a medium/low voltage electrical component manufacturing company focused on cables, connectors, and other distribution related products (acquired 2012).

2.3 ABB North America’s Smart-Grid Efforts

The capability for ABB to develop tailored products for the U.S. smart-grid market is critical as Europe and the United States have distinct smart-grid deployment priorities⁶. An example of this is Europe’s current focus on renewable integration architectures, whereas the United States has focused on Conservation Voltage Reduction (CVR) and Fault Detection Isolation and Restoration (FDIR) technologies [10].

⁶ The main driver behind these differences is the distinct grid architectures in North America and Europe.

This strategy falls in line with the efforts of ABB's main competitors (i.e., GE, Schneider Electric) who themselves have created dedicated centers in the U.S. and/or Canada and are actively involved in policy and discussions for the elaboration of standards.

The challenge for ABB is to develop a consistent product offering across its three Power Product subdivisions (Figure 2-2). The integration of ABB's legacy products with its recently acquired telecommunications and IT capabilities (*Tropos Networks, Ventyx*) will require strong coordination and governance across organizational boundaries.

As a mitigating factor to the systems integration challenge described above, ABB PPMV NA put in place a small *Accelerated Proof of Concept and Product Development Team* tasked with identifying market opportunities and fast development projects. The team's objective was to develop advanced working prototypes aimed at validating market requirements, evaluating market potential, and providing demonstration/learning platforms for future detailed design engineering, R&D, and market research.

Justification for an *Accelerated Proof of Concept Team* is that of disruptive innovation and stems from the positive—and documented—results obtained when carefully selected teams are allowed to operate with flexibility and free of large overhead activities [11]. It is in the context of this *Accelerated Proof of Concept Team* that the advanced circuit breaker M&D functional prototype, here documented, is developed.

3 RELIABILITY OF MEDIUM VOLTAGE CIRCUIT BREAKERS

Chapter 3 starts with a brief history on circuit breaker technology and follows with an overview of failure rates observed in equipment utilized in the MV space. Reliability information is an essential component when determining the financial viability of any M&D effort.

3.1 Circuit Breaker Technology and Operation Basics

Circuit breakers exist for distinct current and voltage ratings spanning the entire low-high voltage spectrum. The operating principle of a circuit breaker is no different from a residential light switch as its design allows for switching capability; its main objective however is to provide critical protection from overload or short circuit failures by interrupting fault currents within milliseconds.

Fault detection and switching control of circuit breakers is typically performed by an automatic relay system capable of detecting the abovementioned fault conditions. Relay systems typically reside in the equipment's low voltage compartment and are electrically isolated from the circuit breaker's protected circuit in order to enhance overall system safety and reliability. Present day relay systems found in utility and industrial settings also have the ability of receiving remote switching instructions—this gives operators enhanced grid control and coordination ability.

During the interruption of current in any switch-like device, as the device's contacts begin to separate, an electric plasma arc will form between the two electrodes (Figure 3-1). The means utilized to control the quenching of the arc are critical in circuit breaker engineering and grow in complexity as the intended design rating of the equipment increases (i.e., higher voltage and/or current).

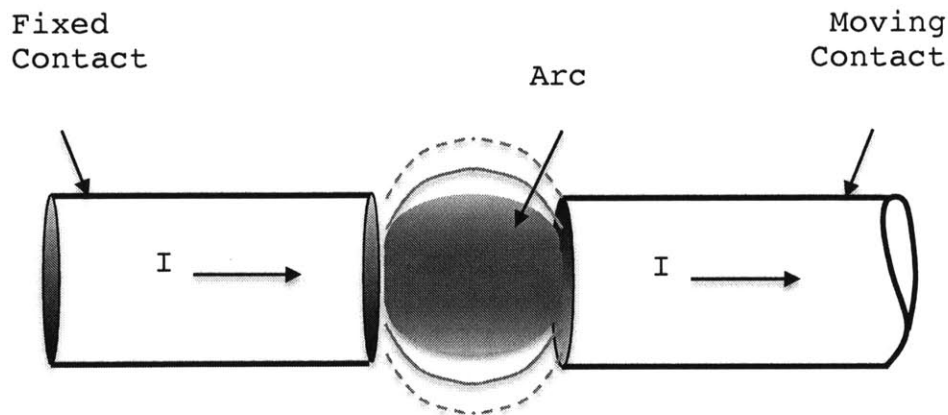


Figure 3-1: Arc Formation during Separation of Live Electric Contacts

Alongside the current and voltage ratings, the technology (or medium) utilized to extinguish the plasma arc is also a circuit breaker classification criterion. During the first half of the twentieth century, in the mid-high voltage realm (4 kV and above), circuit breakers relied on oil-filled tanks as a quenching medium. This technology, however, was prone to fires, and the need for alternatives was clear.

By the 1940s, the use of compressed air as a means to “blow out” the arc was an attractive substitute to oil-filled tanks. By the 1960s, the use of inert gas—sulfur hexafluoride (SF₆)—became extremely popular given it lacked the need for external compression machinery and was less expensive to operate. In the mid 1970s, the vacuum circuit breaker appears on stage and quickly becomes the technology of choice for the MV space (4 kV-35 kV).

In vacuum circuit breakers, as the live electric contacts separate, the metal electrodes begin to evaporate and it is this metal vapor that provides the medium for arc formation. Through careful design of the vacuum chamber, the arc extinguishes when the vaporized metal re-condenses on the electrodes and walls of the interruption chamber [12].

From an operations standpoint, vacuum interrupter technology offers higher reliability and requires significantly less maintenance than its compressed air and SF₆ counterparts. As a rule, vacuum circuit breakers should be inspected at least once a year or every 2000 operations, whichever occurs earlier [13].

The research presented in this paper focuses, for the most part, on vacuum circuit breakers. The general approach, however, is easily extendable to SF₆ breakers and other protection equipment.

3.2 Medium Voltage Circuit Breaker Reliability – Industry Guidelines

Circuit breaker failures happen whenever the equipment fails to achieve its commanded state (i.e., open or closed), or transitions occur outside the timing specifications required to avoid damaging interconnected assets (e.g., transformers) and the circuit breaker itself.

Although it might come as a surprise, the medium voltage space for circuit breakers and other apparatus lacks detailed information that would allow for a serious, present day, analysis of circuit breaker or apparatus reliability. In the case of the United States, the vast the number of utilities providing service, coupled with a regulatory and political environment that stifles information sharing, are partly to blame for the imperfect, incomplete, and outdated reliability MV datasets.

This shortcoming in information is recognized, and entities such as the IEEE have conducted countrywide surveys and data collection efforts in order to gain a better understanding on equipment reliability and failure modes. Far from perfect, the results from these efforts are published in the IEEE’s 493 report [14] in what has come to be regarded as a standard resource across the industry.

Last published in 2007, the IEEE’s 493 report sheds valuable information that has been an adequate proxy in distribution planning. However, the same is not true in the context of smart-grid M&D applications:

- Reliability numbers are based on data collected from 1971-1991.
- Failure mode information dates from surveys conducted in 1974 and 1985.
- Dynamic database for further interrogation does not exist—only printed format.
- High uncertainty given data sampling limitations and distinct operational realities.
- Information fails to capture impact of ageing infrastructure.

The latest reliability information for MV circuit breakers printed in the IEEE’s 493 report shows an expected yearly failure rate of **3.3%**. This value, although on the high end, is partially in agreement with other published guidelines, which place substation circuit breaker failure rates anywhere from a **0.1-3.0%** range—these values, though, are offered as “*rules of thumb*” [15].

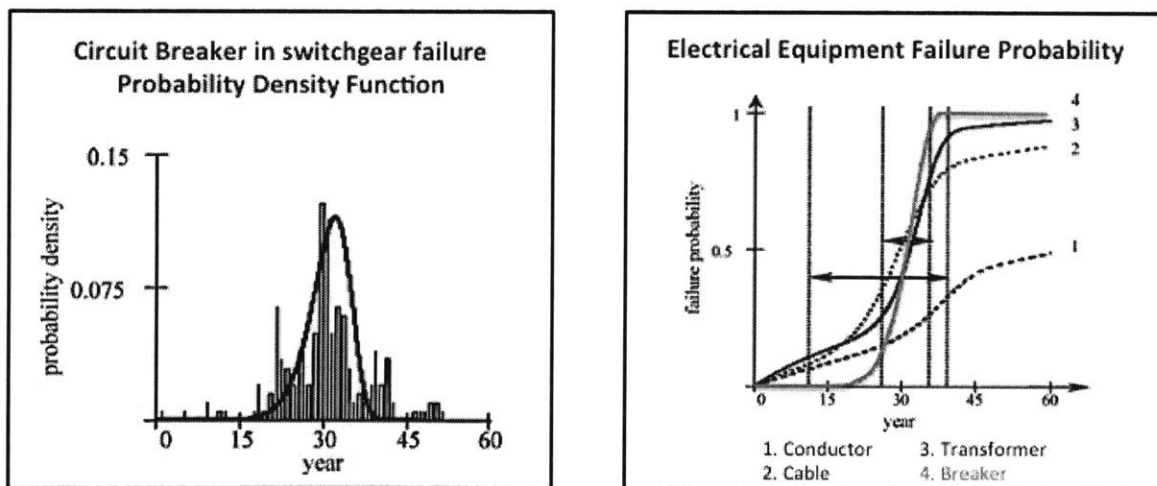
3.3 The Impact of Ageing on Reliability

3.3.1 The German Experience

Although there are many differences between the electric grids of the U.S. and Germany⁷, both nations have a high penetration of vacuum and SF₆ circuit breakers, and both share the same underlying operation principles requiring rapid equipment functioning as a means of minimizing network damage. While an apples-to-apples comparison of the equipment in both countries is not possible, Germany’s experience with ageing assets provides insight into what could happen in the United States.

Results from a study performed under contract from the *National Research Council of Germany* found that 36% of all failures verified in medium voltage substations were due to circuit breaker misoperation, and 90% of these were due to material fatigue (cyclic load) ageing [16].

The study, with data provided by *Research Institute for Electric System and Power Economy* (Manheim, DE), sheds light on the drastic failure rate increase that circuit breakers observed as the equipment reached the 25-year age mark. Likewise, similar trends are observable in other MV electrical equipment included in the study (Fig. 3-2).



Source: © 2007 IEEE. Reprinted, with permission, from Zhang, X. (et al.), *Estimation of the Lifetime of the Electrical Components in Dist. Networks*, IEEE Transactions on Power Delivery, Vol. 22, No 1, Jan 2007

Figure 3-2: Lifetime Estimation of German MV Electrical Components

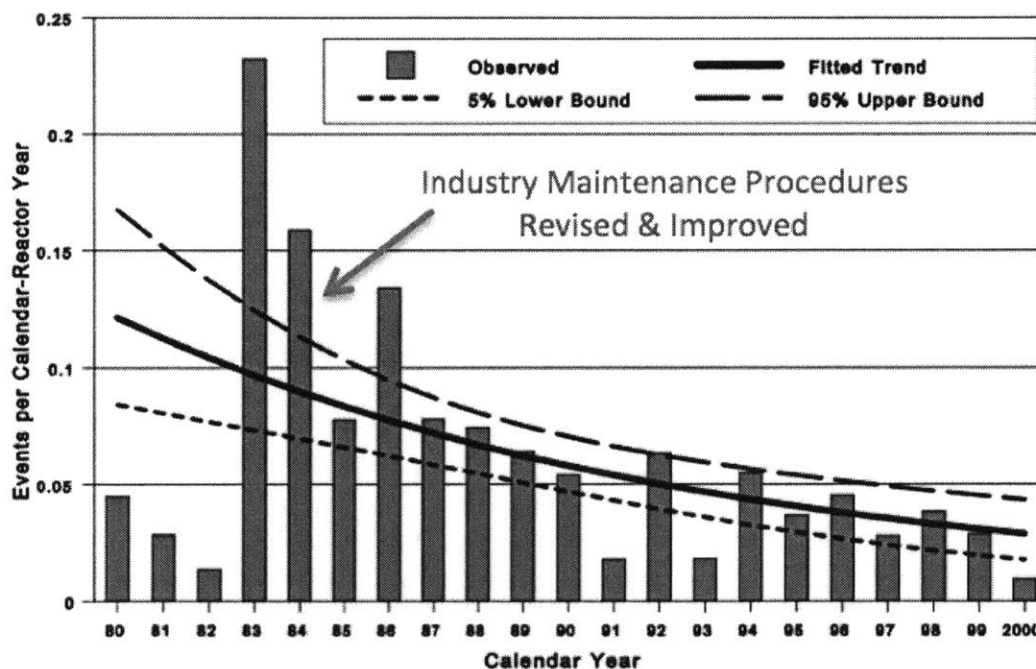
⁷ Examples: Europe’s network is underground and follows *International Electromechanical Commission* (IEC) protection standards versus the U.S. that is mostly above ground and follows ANSI guidelines.

3.3.2 Insights from the U.S. Nuclear Generation Sector

Analogous to the German and U.S. comparison, the Nuclear Generation sector in the United States also offers valuable insight into what could be in store for the U.S. MV circuit breaker fleet from a reliability perspective.

The Nuclear Regulatory Commission (NRC), after analyzing MV circuit breaker failure reports spanning from 1980 through 2000, found that 62% of partial failures spotted during routine maintenance were due to mechanical degradation (ageing breakdown). The data for the 4.16-6.9 kV circuit breaker fleet also found evidence that lubrication and dirt were the two leading equipment deterioration catalysts [17].

The NRC report provides some history on how analysis of this data led to a revision of maintenance operation practices after a spike in reported failure events was recorded in 1983 (Figure 3-3). The data available at the time allowed the Nuclear Generation sector to identify ageing as the main culprit behind the failure increase, and facilitated the design of improved testing and inspection practices that visibly decreased the number of recorded failures over the next 15 years.



Source: T. E., Rasmuson (et al.), *Common-Cause Failure Event Insights Circuit Breakers*, 2003

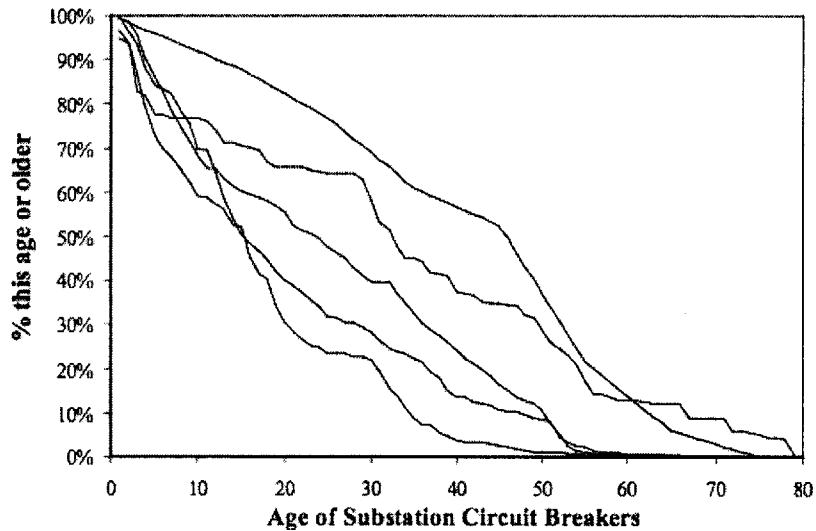
Figure 3-3: MV CB Failure Events with Fitted Trend and 90% Confidence Band

The sector's timely response, and the impact of the revised maintenance practices, would have been more difficult to achieve had the industry not had rigorous data collection and documentation practices. These results, although primitive and not based on real-time data, provide insight into the impact that M&D applications can have on reliability.

3.4 MV Circuit Breaker Survivability Simulation

A simple numerical simulation, understanding that reliability information for MV circuit breakers is imprecise, provides a means of testing distinct failure rate scenarios in order to better understand potential implications to a utility.

Based on available substation distribution circuit breaker survivability curves for 5 major U.S. utilities [15], the simulation's objective is to attain a reasonable approximation of the general equipment survivability trajectories observed in Figure 3-4.



Source: Brown, R., *Electric power distribution reliability*, 2009

Figure 3-4: MV Circuit Breaker Survivability Curves for Five Large U.S. Utilities

3.4.1 Survivability Simulation Inputs

The main inputs to the model are: a yearly MV breaker fleet growth (% units installed), and a *bathtub* failure rate model. A description of the model's variables as coded in Matlab (*in parenthesis*) follows. Reader can reference the Matlab code in Appendix A-10.1.

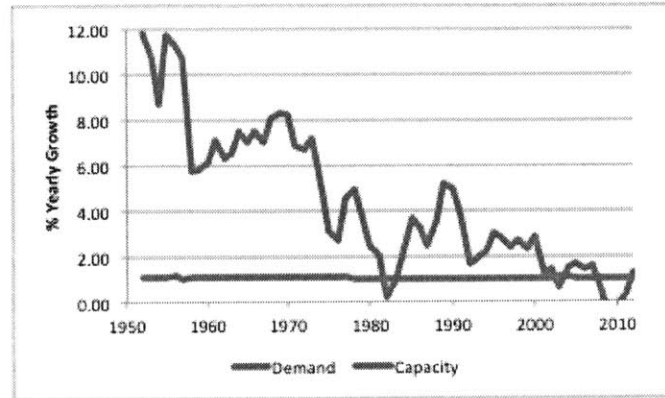
i) Fleet Growth Over Time (*growth*)

This parameter represents the average yearly growth observed in the MV circuit breaker fleet across all utility sites.

This parameter is set to a value of 0.01 based on the fact that installed capacity grew, in the United States, at an average pace of 1.0% annually from 1950 through 2012 [18]—the model assumes that circuit breaker population growth scales with the system's installed capacity⁸.

⁸ Nearly identical system capacity growth rates are reported by EPRI between 1988-2008 [19].

Figure 3-5 depicts U.S. growth observed for both electricity demand and electric generation capacity in the past 60 years. The disproportionate level of investment, when compared to growth in the system, is partly responsible for the advanced age of distribution assets.



Source: DOE/EIA, *Annual Energy Outlook 2012: With Projections to 2035*, 2012.

Figure 3-5: Growth Imbalance between Demand and System Capacity 1950-2012

ii) Bathtub Failure Rate Model Parameters

The variables below are utilized to describe the *bathtub* failure model used by the simulation. Figure 3-6 provides guidance on the meaning of each variable.

- Infant Mortality Yearly Failure Rate (*failRateZero*)
- Typical Failure Yearly Rate (*baseFailRate*)
- Failure Rate Yearly Increase (*failRateAdj*)
- Failure Rate Increase Year (*failShift*)

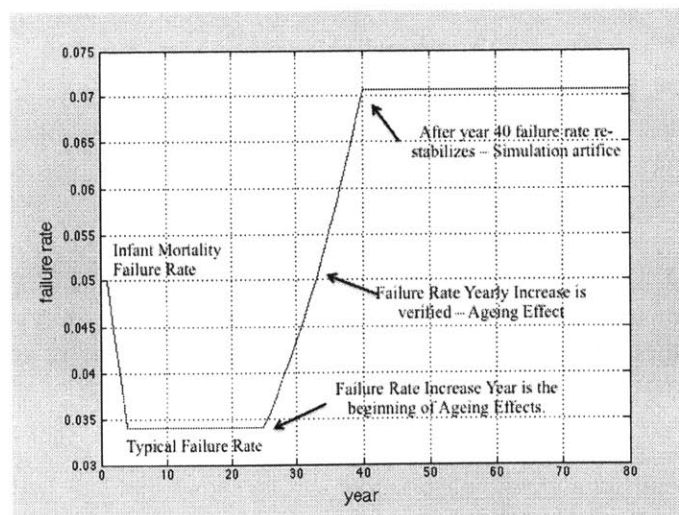


Figure 3-6: Survivability Simulation Bathtub Failure Rate Model

3.4.2 Survivability Simulation Results

Figure 3-7 depicts the simulation results for three distinct failure mode profiles. The plot to the far left shows the same information plotted in Figure 3-4, the middle chart presents the simulation results overlaid on top of the original data, and to the far right, the bathtub failure profiles utilized by the simulation:

- The plot in red is representative of a utility with sustained failure rates of 5.5% in which the equipment is most likely ill-maintained. Under the assumption that equipment is only replaced upon failure, the simulation shows a drastic onset of ageing with a yearly failure rate increase of 7.4%.
- The **blue** plot represents the average utility as described by the IEEE 493 report [14] with a typical yearly failure rate of 3.4%. Assuming still that all equipment is replaced after failure, the yearly failure rate increase that fits the “average” utility profile is 5.0%.
- Finally, the **black** plot represents the utility with the highest maintenance and operation standards (and costs) with a failure rate slightly below 2.0%. The simulation, in order to fit the data, places the yearly ageing increase at 9.5%; this value is not realistic as this utility’s equipment replacement policies will most likely remove a considerable fraction of aged equipment prior to failure.

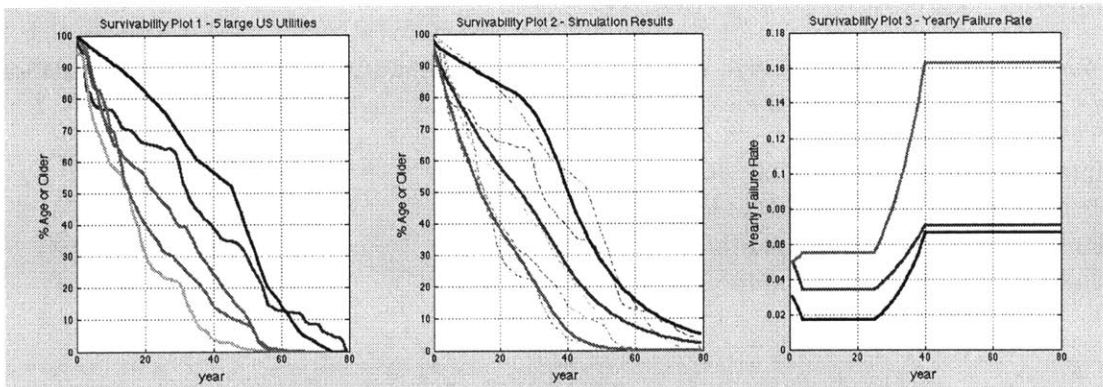


Figure 3-7: Survivability Simulation Results

3.4.3 Survivability—Simulation Insight

Eventhough the model has clear limitations, given the simplified assumptions for growth and textbook application of a bathtub failure model that fails to capture utility unique equipment replacement policies, the simulation fulfills the intent—within the scope of an *Accelerated Proof of Concept Team*—of gaining a better understanding of potential impacts of reliability on a utility fleet.

The simulation, with realistic and yet conservative inputs, shows that U.S. utility observed yearly failure rates are likely in the 2-5% range.

3.5 MV Circuit Breaker Reliability Summary

In the short-term, a clear understanding of failure rates observed by the U.S. MV circuit breaker fleet will lack a high degree of confidence, as data is outdated and incomplete.

Nevertheless, past-experience and educated inferences (Fig. 3-8) provide enough justification for MV circuit breaker M&D applications:

- Survivability simulations align well with IEEE 493 information.
- The case studies of Germany and the U.S. Nuclear Generation indicate that MV circuit breaker failure rates increase rapidly in ageing equipment.
- Failure rate exponential growth observed in ageing equipment fits well with survivability traces available for the industry.
- Data driven maintenance practices reduce MV circuit breaker failure rates. Data collected by the NRC supports this.

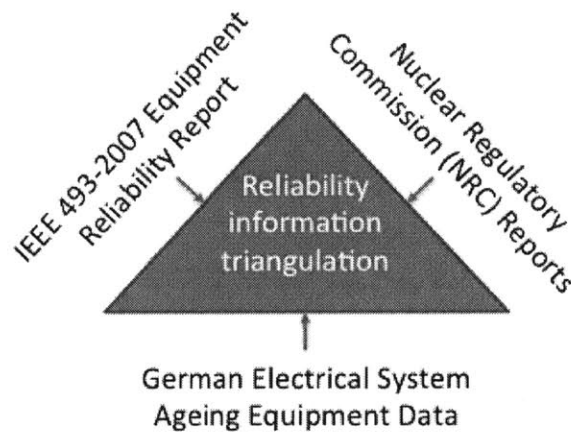


Figure 3-8: Reliability Information - Past Experience and Inferences

The MV Vacuum Circuit Breaker suspected yearly failure rate observed across the United States is in the **2-5%** range. These values are highly influenced by local environmental conditions, equipment use (i.e., loading), and maintenance practices. Equipment failure rates, as ageing begins to set-in, will increase significantly unless maintenance operations transition towards condition based practices (versus time based practices).

4 MEDIUM VOLTAGE CIRCUIT BREAKER FAILURE MODES

4.1 MV Circuit Breaker Failure Modes – Available Information

Whereas failure rates answer the question of how often equipment fails, failure modes describe how an individual component, assembly, or system can result in equipment misoperation. As with MV circuit breaker failure rates, it should come as no surprise that detailed failure mode datasets are also limited and outdated.

Despite this limitation, industry is notionally aware that gradual mechanical and/or electrical degradation of components are the leading contributors to failure. Along with this notion, however, there is ambiguity as to what factors initiate and/or contribute to deterioration.

4.1.1 IEEE 493 Report

The IEEE’s most recent data on MV circuit breaker failure modes dates from a survey conducted in 1985 looking into equipment installed prior to 1971 [14]. Results obtained from the survey were limited to a sample size of 2137 breakers in which only four failures happened. Table 4-1 shows the results from this survey.

Breaker Suspected Failure Responsibility	%	Breaker Failure Initiating Cause	%	Contributing Cause to Breaker Failure	%
Defective Component	25%	Transient Overvoltage	25%	Persistent Overload	25%
Operating Procedures	25%	Mechanical Breakdown	25%	Lubricant Loss or Deficiency	25%
Other	50%	Electrical Fault*	25%	Lack of Maintenance	25%
		Other	25%	Other	25%

*Not include insulation breakdown

Source: © 2007 IEEE. Reprinted, with permission, *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems*, IEEE Std 493-2007, June 2007

Table 4-1: IEEE 493 Failure Mode Summary for MV Circuit Breakers - 1985 Survey

As is to be expected, given the limited sample size and number of events recorded, the conclusions that could be drawn from the 1985 survey are distinct from the results obtained in 1974—the first survey conducted by the IEEE looking at MV circuit breaker failures.

Since 1971 (survey of '85), the U.S. MV circuit breaker fleet has evolved towards SF₆ and vacuum technology. As such, it is difficult to utilize the information from these sources other than as a means to support the notions already suspected by industry experts.

4.1.2 The German and U.S. Nuclear Generation Experiences

As described in Ch. 3.3.1 and Ch. 3.3.2, both German and U.S. Nuclear Generation medium voltage circuit breakers have observed an increase in failure rates driven by mechanical deterioration linked to ageing [16][17][20]. This information, other than identifying ageing as a culprit, sheds little insight into the actual components in the equipment that are prone to failure.

EPRI, in a report published in 2006 [20], looks at the leading ten failure modes present in MV circuit breakers in U.S. Nuclear Generation fleet for the years of 1996 through 2005. The report confirms that mechanical failures account for the majority of events recorded and that mechanical deterioration and ageing are prevalent.

Unlike other reports though, EPRI provides a rough breakdown of failure modes and how they relate to equipment manufacturers (Table 4-2). An important conclusion drawn from this information is that mechanical failure due to advanced age is the leading failure mode across most, if not all, OEM supplied MV circuit breakers.

Company	MECH %	CTRL %	ELECT & MISC %
ABB/ITE	35-61	15-37	0-28
Westinghouse	47-89	5-39	5-13
GE	39-91	0-39	0-23
Industry Fleet	40-81	6-38	1-22

Table 4-2: MV Failure Modes versus OEM

4.1.3 CIGRE Report on HV Circuit Breaker Reliability

The need for a better understanding of failure rates and failure modes is also existent in the HV circuit breaker space. In contrast to MV circuit breakers, where the typical cost of the equipment is \$20,000 (USD) with moderate outage costs, HV breaker and failure costs are in the millions.

Similar to the IEEE’s effort in the MV space, the International Council on Large Electric Systems (CIGRE) has dedicated significant effort into gathering reliability information for HV equipment covering several countries. The latest report, consisting of data collected between 1988 and 1991 for SF₆ circuit breakers (72 kV rating and above), shows that 70% of failures are mechanical in nature, 19% are due to auxiliary and/or control circuits, and 11% due to electric/interrupter breakdown [21].

Although mechanical failures are a highlight of the CIGRE report, extrapolating these and other CIGRE findings to MV equipment, a common pitfall across the industry, requires caution given that HV equipment is mechanically more complex and subject to more strenuous electrical failure modes (e.g., partial discharge)⁹.

4.2 IEEE Guide for the Selection of Monitoring for Circuit Breakers

The IEEE, alongside the efforts of CIGRE in the HV space, published a report [22] in which it describes the most common failure modes, and mitigating approaches, for equipment rated 1 kV or higher¹⁰.

⁹ In the industry, there are multiple definitions for what constitutes MV and HV. This multiplicity of definitions often times clouds the fidelity of reliability information.

¹⁰ Although ANSI would consider equipment rated for 1000 volts as low voltage, for the purposes of this report, 1000 volts is regarded as high voltage.

The intent of the report is for it to serve as a roadmap when designing or selecting an equipment-monitoring scheme or technology. Although integrated M&D applications, at the time of its publishing, were just beginning to be conceptualized for Transmission and Distribution, the report provides the essential framework and ideas that need to be considered—one of which is a thorough understanding of failure modes.

A significant portion of the report documents 60 possible failure modes typically observed in circuit breakers. The report provides information pertaining to the best-known monitoring technologies and/or practices for the time, and classifies each failure’s onset as gradual, sporadic, or dual. Considering that a central design objective for MV M&D applications is to capture the most number of gradual failures with the least number of sensors, this classification of failures is extremely useful when evaluating the merit of distinct sensor technologies.

Of the 60 failure modes presented, 54 apply to vacuum interrupters. Of these, 21 are gradual in nature, 16 can be either gradual or sporadic, and the remaining 17 are sporadic and do not have a viable means of detection. Table 4-3 presents the parameters that have the most impact from a monitoring perspective, as well as percentage of failure modes they mitigate.

Parameters Monitored	Gradual 21 Total Failures	Gradual and Sporadic Modes 16 Total Failures
Mechanical Operation Profiling	8 (38%)	5 (31%)
Temperature Trending	5 (24%)	2 (13%)
Primary Current Interruption (Relay)	1 (5%)	1 (6%)
System Current and Voltage (Relay)	1 (5%)	1 (6%)
Total →	15 (71%)	9 (56%)

Table 4-3: Failure Mode Mitigation Results for MV Vacuum Circuit Breakers

- *Mechanical Operation Profiling* – captures the information pertaining to the mechanical actuation of the device (i.e., speed, timing, force, etc.). The monitoring principle is to detect shifts in behavior that precede failure.
- *Temperature Trending* – its operating principle is to identify shifts in electrical resistance observed by the load carrying components of the equipment. As resistance increases—a sign of deterioration—the equipment will experience higher temperatures.
- *Existing Information* – the analysis found that some health monitoring parameters are already available in circuit breakers equipped with conventional relay systems. Current and voltage readings provide a means of verifying if fault currents and/or high loads are present in the equipment’s history. Likewise, a simple operations counter, standard to many circuit breakers, reflects the industry’s rudimentary, yet practical, approach to equipment ageing.

Although the analysis is insufficient to establish a relationship between individual failure modes and their contribution to observed failure rates, it does show that diagnosable failures for vacuum circuit breakers comprise **28-44%** of all documented modes. Furthermore, it shows that this diagnosis level is attainable by monitoring two parameters: mechanical operation and apparatus temperature—these parameters are the main contributors to equipment degradation.

Ultimately, what this analysis suggests is that 60-90% of failures observed in MV circuit breakers—gradual in nature—could potentially be diagnosable given the documented experiences of Germany (Ch. 3.3.1) and the U.S. Nuclear Generation Sector (Ch. 3.3.2). Realistically though, considering that a foolproof system is too ambitious and expensive, a failure rate reduction of 40-60% is a more credible and achievable target.

4.3 OEMs as a Source of Failure Mode Information

Unlike other capital-intensive technology driven sectors (e.g., airline industry) where OEMs maintain detailed reliability databases on the equipment they have sold, circuit breaker manufacturers serving the U.S. utility space¹¹ do not have access to such information.

As observed in Figure 2-4: ABB, Competition, and Utility Customer Simplified Interaction *Diagram*, on page 24, maintenance operations are the responsibility of utilities and/or contracted third parties. Because of this, and the fact that the majority of failures occur outside of warranty, OEMs have limited access to equipment in the field and are ill positioned to maintain detailed records that would allow them to identify components prone to failure.

The limited failure information that does exist for equipment covered by warranty is of little use as these events are “infant mortality” problems that have little resemblance with the bulk of ageing related failures observed by the equipment later in its life.

The analysis of spare parts as a means to estimate the failure rate of components, a known practice in other technology driven industries, also comes short as utilities will typically replace a failed circuit breaker with new equipment and repurpose failed gear when possible.

With the exception of internal accelerated testing and accident/incident investigations conducted by OEMs, the reality is that circuit breaker manufacturers do not have access to detailed reliability sources.

4.4 Existing Maintenance Practices – a Validation Source

Although reliability information is sparse, industry reports identify mechanical and thermal stresses as major contributors towards failure. Examination of existing test equipment and maintenance practices serves as a reaffirmation of this.

4.4.1 Circuit Breaker Time-Travel Analysis

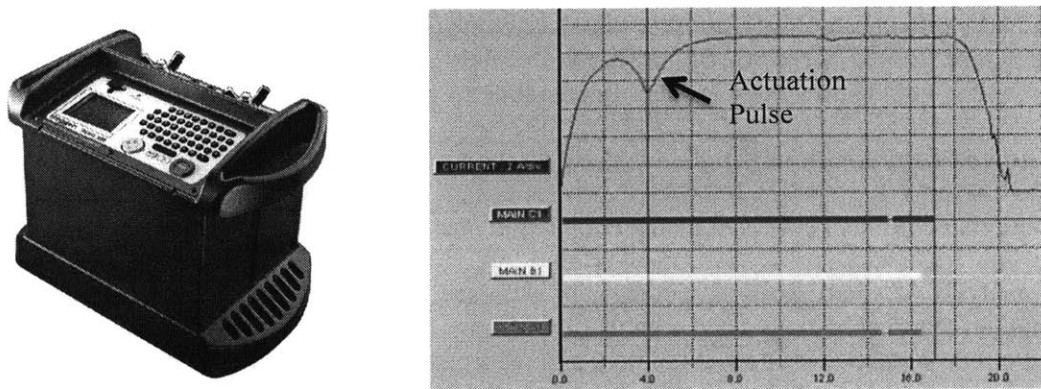
Mostly utilized for equipment rated at 34 kV and above [13], time-travel analysis, the analysis of the time the breaker contact takes to move from closed to open, is a means of verifying that a circuit breaker’s operating mechanism is healthy. The test equipment consists of a time-travel analyzer that is capable of producing charts that capture the actuator system’s characteristic

¹¹ ABB, Siemens, GE, Eaton, etc.

current (open and close coils), and provides timing information across all three breaker phases¹² for both OPEN and CLOSE switching operations.

Figure 4-1 shows an image of a widely used time-travel analyzer alongside the test unit's interrupter timing readouts (red, yellow, blue traces), and the circuit breaker's actuation pulse current (brown trace). This pulse, a 40-200-millisecond breaker-specific signal that can reach 50-150 Amperes, provides a measure of the total energy required to operate the circuit breaker. The signal also provides an indication of overall circuit breaker health, and gives qualified technicians valuable troubleshooting information while performing maintenance and repair work.

Chapter 6.2 provides an overview on circuit breaker actuation systems and presents work previously conducted describing how the abovementioned actuation pulse current can be utilized for M&D applications.



Source: http://www.megger.com/common/documents/CABA-Win_DS_en_V02.pdf

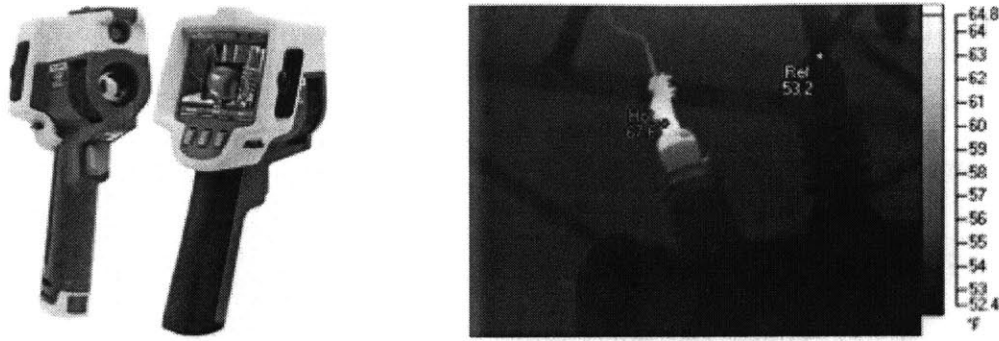
Figure 4-1: Time-Travel Analyzer with Actuation Coil Current Output Plot

4.4.2 Circuit Breaker Hot-Spot Testing

In electrical equipment, abnormally high temperatures are associated with an increase in conducting resistance. As infrared technology has become accessible, maintenance crews have adopted thermal imaging as a means of identifying these potentially hazardous hot-spots on the breaker contacts or electrical connections to the breaker.

Infrared technology, when applied to circuit breaker maintenance testing, is very convenient when looking at the equipment's external frame, but has its limitations when piercing through enclosures. Motivated by the increased popularity and effectiveness of the testing technique, circuit breaker manufacturers now design their enclosures to include infrared scanning windows through which hot-spot visualization of internal components is possible.

¹² Three-phase alternating current (ac) electric power is the most common method of power generation, transmission, and distribution. Given the system's architecture, circuit breakers provide interruption capability across all phases and will disconnect all three phases during switching operations.



Source: *Fluke Imaging*, <http://thermal-imaging-blog.com>

Figure 4-2: Thermal Imaging Equipment and Example of Circuit Breaker Hot-Spot

4.5 MV Circuit Breaker Failure Modes – Summary

Although detailed reliability information is unavailable, from an industry standpoint it is clear that mechanical and thermal monitoring are the first and second most effective means of assessing circuit breaker health.

These two leading health indicators, when placed in the context of observed failure rates in the German electrical distribution system and the U.S. Nuclear Generation sector, lead to the conclusion that upwards of 60% of failures are detectable. This is only possible given that gradual mechanical degradation precedes most failures.

Although it would be impossible to design an M&D system capable of identifying all *failure signatures*, it is reasonable to assume that 40-60% of failures should be detectable with M&D systems incorporating mechanical and thermal trending capabilities, plus the already existing parameters such as equipment observed voltage and current. Verification of this claim, however, requires more detailed reliability information and extensive M&D field-testing.

5 THE BUSINESS CASE FOR MV CIRCUIT BREAKER M&D

Chapter 5 examines the potential customer savings and OEM business opportunities for M&D applications when applied to MV circuit breakers. Conclusions are based on a better understanding of MV circuit reliability.

5.1 The Business Case for OEMs

Figure 2-4: ABB, Competition, and Utility Customer Simplified Interaction *Diagram*, on page 24, shows that one of the main challenges for OEMs in the U.S. is the restricted access to substation equipment. Although an oversimplification of actual OEM-Utility interactions, the figure reveals one of the main reasons for the lack of comprehensive reliability information and also illustrates what is a difficult landscape for marketing intelligence.

In other words, Figure 2-4 highlights the difficulties that could change as the benefits of M&D applications become evident and comprehensive reliability information becomes readily available to enhance market intelligence. This scenario, coupled with an industry that is transitioning slowly towards service-oriented business models¹³ would grant OEMs insight into how their equipment is behaving in the field, and provide a means of providing better service to their utility customers.

To emphasize, Figure 5-1 presents a simplified view of how M&D could alter OEM-customer interactions. Rather than depend on the mostly one-way communication between customer maintenance operations and ABB customer support personnel (Figure 2-4), M&D would allow ABB to leverage real-time data and historical records as a source of information to gain insight into substation-level equipment conditions and do so in a collaborative manner with customers.

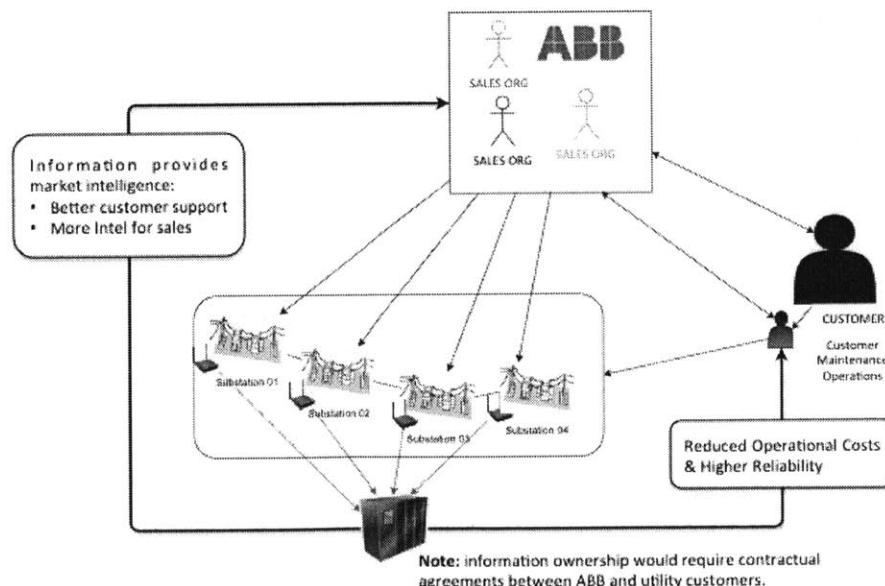


Figure 5-1: M&D Impact on OEM Market Intelligence and Customer Operations

¹³ Service oriented business models are part of ABB's 2015 strategic vision. These models are becoming more commonplace in European T&D markets.

Beyond the ability of OEMs to monitor the circuit breakers that they have sold, and provide better servicing capability, M&D applications can also be deployed onto competitor's equipment granted the sensing technology and diagnostics are generic enough to detect anomalies across a broad range of circuit breaker makes and models.

Such system applications would provide valuable market intelligence to OEMs, and would also decrease the complexity required to aggregate and analyze the information from the multiple MV circuit breaker models typically found in a utility fleet. The ability to provide M&D solutions across a broad spectrum of MV circuit breakers is a major design objective for this project.

A counter argument for the deployment of M&D, as depicted in Figure 5-1, is that of "cannibalization" of equipment sales. Although this might hold true in the short-term, the increased market intelligence provided by M&D systems, in addition to the opportunities presented as a result of ageing infrastructure, offer long-term prospects as the industry shifts more towards services business models.

5.2 The Value Proposition for Utility Customers

To better understand the value proposition of a MV circuit breaker M&D application, a simplified *Cost & Savings* model was developed. The model, in the context of an *Accelerated Proof of Concept Team*, is a means to better understand the customer's operational costs and evaluate distinct M&D solutions rapidly.

The model, coded in Matlab and available for reference in Appendix A-10.2, examines the baseline costs associated with MV circuit breaker operation, as well as outage costs incurred with equipment failure. In parallel, the model also calculates the operational and outage costs that customers would likely observe with an M&D system and utilizes this to compute the expected savings over time (default of 10 years).

The model's unit of reference is cost per breaker. A description of the model's main input variables as coded in Matlab (*in parenthesis*) follows. These variables help recreate the status quo and M&D cost scenarios introduced above.

5.2.1 Baseline Operations – Status Quo Inputs

The *Cost & Savings* model parameters detailed below provide a means to approximate the operational costs of utilities across the United States. Default values represent that which is typically observed, or assumed, across the industry; adjustment of these parameters will reflect distinct operational realities.

i) Maintenance Operations Costs

- **Labor rate** (*labor*) – hourly cost of labor in USD. *Default value set to \$100.*
- **Number of workers** (*workers*) – individuals, per breaker, involved when performing maintenance. Includes support personnel (e.g., dispatch). *Default value set to 1.6.*
- **Time on site** (*downTime*) – yearly down time, per breaker, expected for planned maintenance. *Default value set to 2 hours per IEEE 493 [14].*
- **Travel and logistics** (*travelLog*) – time, per breaker, dedicated to travel and planning in order to support maintenance operations. *Default value set to 1 hour per IEEE 493 [14].*

ii) Equipment Failure Costs

- **Yearly failure rate** (*rate0*) – baseline failure rate for MV circuit breaker fleet. Recommended values are 0.02-0.05 per Ch. 3 conclusions. *Default value set to 0.0334.*
- **Yearly failure rate increase** (*rateD*) – yearly failure rate increase, as a percent of current failure rate, associated with ageing infrastructure. *Default value set to 0.05 (5.0%).*
- **Circuit breaker replacement cost** (*cbCost*) – value associated with purchase of new circuit breaker. *Default value set to \$20,000 (USD).*
- **Failure incurred labor burden** (*failTime*) – average time dedicated to repair work after a failure. *Default set to 36 hours per IEEE 493 [14].*
- **Ratio of failures resulting in CB replacement** (*failRep*) – recommended value range is 0.5-1.0. *Default value set to 1.0 as replacement of ageing equipment is very likely.*
- **Outage cost** (*failCost*) – *Default value set to \$25,000 (USD).* Refer to text below*.

In concert with the limited reliability information available for the sector, the costs associated with outages stemming from MV substations are also largely unknown. On the one hand, the costs of unserved energy costs and the potential resulting penalties depend on factors such as location, time, day, etc. On the other hand, circuit breaker misoperation induced outages frequently result in damage and/or reduced life to other substation components. Recognizing these limitations, this thesis assumes a conservative **outage cost of \$25,000 (USD) based on conversations with industry experts. It should be noted that this input variable does not consider the MV circuit breaker replacement cost.*

5.2.2 M&D Scenario Inputs

The inputs below allow a rapid financial evaluation of distinct M&D scenarios. The default values reflect the findings presented in Ch. 3 and Ch. 4.

i) M&D Long-Term Impact on Operations

- **Failure rate reduction** (*monitEff*) – percent reduction in observed failure rates. Per Ch. 4 conclusions, recommended range is 0.4-0.6. *Default value set to 0.5.*
- **Maintenance effort reduction** (*downRed*) – percent decrease in time dedicated to equipment maintenance. Recommended range is 0.0-0.25. *Default value set to 0.25.* Refer to text below*.

**IEEE 493 [14] shows that limited extension of maintenance time intervals has only a slightly higher failure rate in time-based maintenance schemes (Table 5-1). With M&D, where maintenance is condition-based, it is a conservative assumption to expect that optimization of resources will allow for a 25% reduction in overall maintenance effort, while at the same time allowing for an overall failure rate reduction. This reduction assumes that maintenance practices where M&D solutions are installed follow OEM yearly equipment inspection guidelines.*

Alongside maintenance time interval failure information, Table 5-1 also shows IEEE 493 survey results relating the impact that maintenance practices have on observed failure rates. Results are interesting as they highlight the limited improvement that above-average

maintenance practices—mostly time-based—have on overall reliability. Condition-based maintenance schemes, enabled through M&D, are capable of a much larger impact.

Equipment Time Based Maintenance Practice Assessment*			Failures vs. Months Since Maintenance*	
Maintenance Practice	Surveyed Sites %	Failure Rate Multiplier	Months Since Maintained	Circuit Breaker Failures %
Above Average	25%	0.91	< 12 months	12.5%
Average	58%	1.06	12-24 months	19.2%
Below Average	17%	1.28	> 24 months	36.7%

*Data collected 1974 Survey

Source: © 2007 IEEE. Reprinted, with permission, *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems*, IEEE Std 493-2007, June 2007

Table 5-1: IEEE 493 Assessment of Maintenance Practices on Distribution Reliability

ii) M&D Operational Adoption

- **M&D fleet deployment period** (*deployDur*) – years required to install the circuit breaker M&D equipment throughout the fleet. *Default value set to 4.*
- **M&D analytics training period** (*trainDur*) – years required to fine-tune analytic engine to achieve expected failure rate reduction. *Default value set to 5.*
- **M&D operational adoption period** (*opsLearn*) – years required for utility customer to fully take advantage of M&D potential. *Default value set to 7.*

Figure 5-2 is a graphical representation of the five-abovementioned model inputs with corresponding default values:

- BLUE trace describes a four-year deployment of M&D across a CB fleet.
- RED trace describes a 50% reduction in observed failures across the CB fleet. Goal achieved after five years from initial deployment.
- GREEN trace describes a 25% maintenance effort reduction across the CB fleet. Goal achieved after seven years from initial M&D deployment.

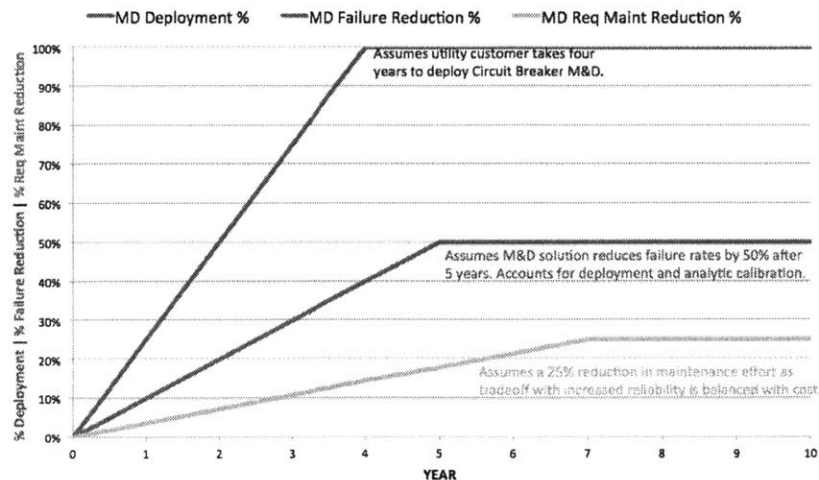


Figure 5-2: Graphical Representation of M&D Timing and Effectiveness

iii) M&D Customer Costs & Financial Variables

In order to assess the value proposition to the customer, the total cost of an M&D system considers an up-front acquisition purchase cost that takes place upon equipment installation, and a subsequent service fee collected for active monitoring and analytics performed by the OEM. Modification of these parameters allows for the analysis of distinct customer pricing alternatives.

- **M&D upfront cost** (*costMD*) – acquisition cost per breaker for M&D equipment. Recommended cost range \$1,500-\$3,000 (USD) per breaker. *Default value set to \$2,500 (USD).*
- **M&D service fee** (*servMD*) – yearly service fee charge per breaker. Will vary largely on customer and market conditions. *Default value set to \$200/yr (USD/yr).*
- **Inflation** (*infl*) – This is utilized to adjust, over time, the costs associated with labor, equipment, and outages. *Default value set to 0.02, the value of inflation at the end of 2012.*
- **Cost of Capital** (*capDisc*) – Cost of money as observed by the market. Term utilized for equipment deferral cost calculations. *Default value set to 0.03, the rate value of 30 year U.S. Treasury Bonds at the end of 2012.*
- **Labor Discount Factor** (*laborDisc*) – Cost of capital applied to labor. Distinction allows adaptation of distinct company policies regarding the cost of labor over time. *Default value set to 0.03, the rate value of 30 year U.S. Treasury Bonds at the end of 2012.*
- **Outage Discount Factor** (*outDisc*) – Cost of capital applied to outage costs. Distinction allows adaptation of distinct company policies regarding the cost of outages over time. *Default value set to 0.03, the rate value of 30 year U.S. Treasury Bonds at the end of 2012.*
- **Equipment Discount Factor** (*eqDisc*) – Cost of capital applied to equipment. Distinction allows adaptation of distinct company policies regarding investments in asset expansion and replacement. *Default value set to 0.11 - approximates Investor Owned Utility investment policies [5].*
- **M&D Discount Factor** (*mdDisc*) – Cost of capital applied to M&D equipment and services. Distinction allows adaptation of distinct company policies regarding investments in novel equipment that entail higher risks. *Default value set to 0.11 - approximates Investor Owned Utility investment policies [5].*
- **Deferral Analysis Flag** (*defFlg*) – Boolean variable that when set TRUE includes equipment replacement deferred costs in M&D savings analysis. Variable must be FALSE (0) or TRUE (1). *Default value is set to FALSE.*
- **Deferral Timespan** (*defRepTime*) – Life extension span, in years that M&D brings to ageing MV circuit breaker fleet. *Default value set to 5 years per Survivability Simulation results (Ch. 3.4).*
- **Depreciation Analysis Flag** (*depFlg*) – Boolean variable that when set TRUE includes linear depreciation of newly acquired assets when performing M&D equipment deferral calculations (*defFlg = 1*). Variable must be FALSE (0) or TRUE (1). *Default value is set to FALSE.*
- **Depreciation Timespan** (*depLenYr*) – Period, in years, over which linear depreciation of newly acquired assets is to happen. *Default value set to 30.*

5.2.3 Customer Costs & Savings Model Results

Applying the above-mentioned assumptions to a ten-year analysis period, the model's projected per-breaker NPV savings are just above \$7,000 USD with a payback period of 6 years. Figure 5-3 presents a comparative cost breakdown for maintenance, circuit breaker equipment replacement, and outage penalties/damages for both baseline and M&D scenarios considered.

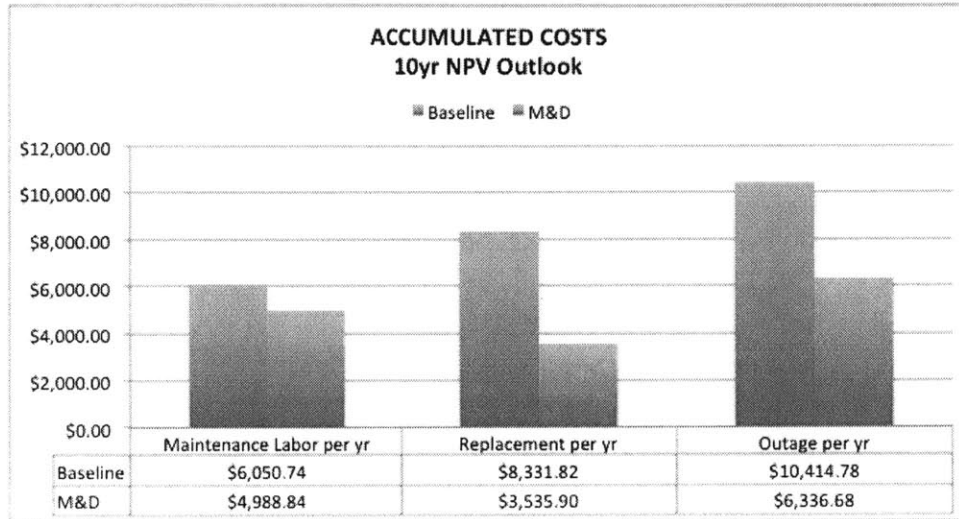


Figure 5-3: M&D Financial Impact - Does not Include Deferral or Depreciation Analysis

The results are encouraging if one considers that the overall savings are higher than the assumed M&D equipment and service costs. Figure 5-4 shows the system paying for itself within 5-7 years when maintaining the model's input variables reflective of the *typical utility* (default values previously noted) and modifying the failure rate mitigation term (*monitEff*) to reflect a 35-65% outage reduction.

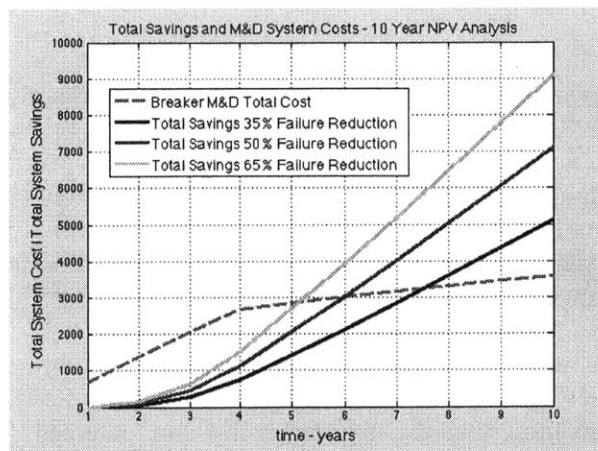


Figure 5-4: NPV Accumulated Costs & Savings for Three Failure Reduction Scenarios

Acknowledging that a 40-60% failure rate reduction is uncertain, and understanding that a 25% reduction of onsite maintenance will be specific to a utility's reality, the need to strengthen the business case for M&D is critical.

Such a case is possible when looking at utilities faced with ageing assets that need replacement. In such a scenario, M&D is a means to extend the life of existing assets and defer acquisition costs. Figure 5-5 shows that, for the *typical utility*, the M&D system pays for itself within its first year of deployment when considering a five-year deferral and a thirty-year linear depreciation policy ($defFlg = 1$, $defRepTime = 5$, $depFlg = 1$, $depLenYr = 30$).

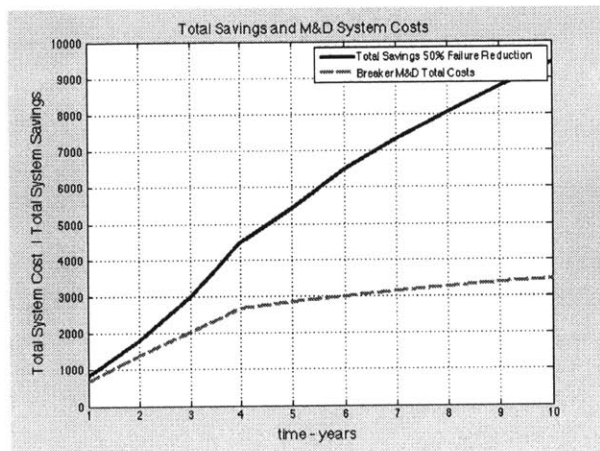


Figure 5-5: NPV Accumulated Costs & Savings - Includes Deferral and Depreciation

5.3 MV Circuit Breaker Business Case Summary

The need for M&D applications, in the context of an ageing distribution infrastructure, is clear. The justification for such systems is now possible given the advanced state of telecommunications infrastructure and the low cost of necessary sensing and computing technologies.

On the one hand, smart-grid represents a business opportunity, and on the other, it represents a paradigm shift in how OEMs and utility customers interact as these relationships resemble more and more service oriented business models. With this as a reference, M&D applications offer the possibility of extracting equipment and market information directly from customer sites, and have the potential of reducing utility operating costs and increasing reliability. OEMs who are able to engage utility customers with M&D products and services will position themselves for a market that will undergo significant change in the next five-ten years.

A simple *Costs & Savings* model, put in place to better understand the realities faced by utility customers, shows that a MV circuit breaker M&D system could pay for itself within 5-7 years in a *typical utility* setting as described by the reliability and potential failure rate reductions presented in Ch. 3 and Ch. 4.

In addition, the case for M&D is strengthened when viewed as a means to extend the life of aged equipment. In this scenario, the system pays for itself within the first year of operation as

equipment replacement deferral costs reflect themselves as savings¹⁴. Such results indicate that an M&D system with failure rate mitigation lower than 40% would still be worth exploring from a financial standpoint.

In conclusion, in the near future, as computing and sensing technology costs continue to decrease, and as M&D applications begin collecting data and improving their failure prediction capabilities, the business case for M&D will become increasingly attractive.

¹⁴ Assumes a five-year life extension.

6 EXISTING M&D ANALYTICS FOR MV CIRCUIT BREAKERS

With a focus on circuit breaker temperature and mechanical operation monitoring, Chapter 6 provides an overview of existing work conducted in the asset health and diagnostics field. This work is the foundation upon which system integration and analytics come together.

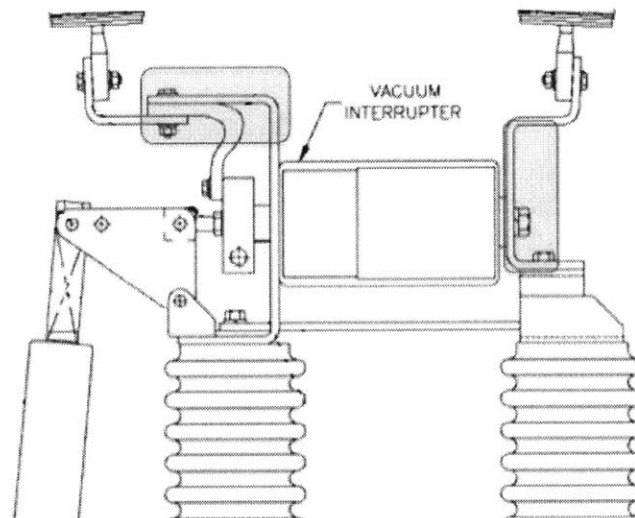
This chapter also presents a brief background and justification for the sensing technologies selected, and gives an overview of the integrated M&D system.

6.1 Thermal Monitoring of MV Circuit Breakers

From a real-time monitoring perspective, thermal-imaging technologies presented in Ch. 4.4.2 are limited by high cost, are restricted to field of view, and require complex image deciphering algorithms that limit their flexibility as an M&D system for electrical equipment. In lieu of this, other alternatives are required.

For instance, the main source for hot-spots in MV circuit breakers stems from the interrupter's contact surface, which over time will degrade and will result in a higher electrical resistance and temperatures. If undetected for a long time, and decay reaches a critical state, arcing across the contact surface—a high temperature phenomenon—is likely to occur.

With this knowledge, industry has sought to develop reliable long-life sensors capable of withstanding the harsh environment that exists in the area immediately outside the circuit breaker's contact enclosure indicated by the red regions in Figure 6-1.



Source: *MV Circuit Breaker User Manual*

[http://www05.abb.com/global/scot/scot235.nsf/veritydisplay/7e5daa7afc45ac4bc1257574004dd7bc/\\$file/r-mag%20instruction%20book%201val255101-mb%20rev%20e.pdf](http://www05.abb.com/global/scot/scot235.nsf/veritydisplay/7e5daa7afc45ac4bc1257574004dd7bc/$file/r-mag%20instruction%20book%201val255101-mb%20rev%20e.pdf)

Figure 6-1: Temperature Monitoring Preferred Areas in MV Circuit Breaker M&D

6.1.1 Thermal Monitoring and Analytics

Thermal protection for circuit breakers has existed in the HV space since the mid 90s [23] and the underlying physics are well understood and documented. It is only now, as technology has evolved, that it is possible to apply such monitoring schemes in the MV space.

The levels of monitoring protection range from simple alarms that trigger upon reaching a pre-determined temperature threshold, to the more advanced real-time modeling of the interrupter's temperature relationship with current and heat transfer mechanisms.

Alarm thresholds are typically set at limits established by ANSI or IEEE standards [24], or driven by application specific considerations. In most all cases, an alarm signifies equipment abuse and higher probability of failure, as equipment should rarely exhibit such high temperatures.

Real-time monitoring schemes begin with a physical model for the energy balance of the interrupter: heat energy supplied to the interrupter from its resistance to current must add up to the heat convected to the interrupter's surroundings and the system's stored heat—reflected in the equipment's temperature (6.1).

$$RI^2dt = K\theta dt + mCd\theta \quad (6.1)$$

$R = \text{Interrupter Resistance } [\Omega]$

$I = \text{Interrupter Current [Amps]}$

$K = \text{Characteristic Constant of Heat Exchange [Watt/}^\circ\text{K]}$

$\theta = T_i - T_e [^\circ\text{K}]$

$T_i = \text{Interrupter Internal Temperature } [^\circ\text{K}]$

$T_e = \text{Interrupter External Temperature } [^\circ\text{K}]$

$m = \text{Interrupter Mass [kg]}$

$C = \text{Interrupter Heat Capacity [Watt/kg]}$

$t = \text{time [seconds]}$

Further manipulation of (6.1) is possible when an interrupter is in steady state with known temperatures and load current. Utilizing this information as boundary conditions, a solution is possible (6.2) in which multiple system constants condense into a single constant τ termed the *system's characteristic thermal time constant* [25].

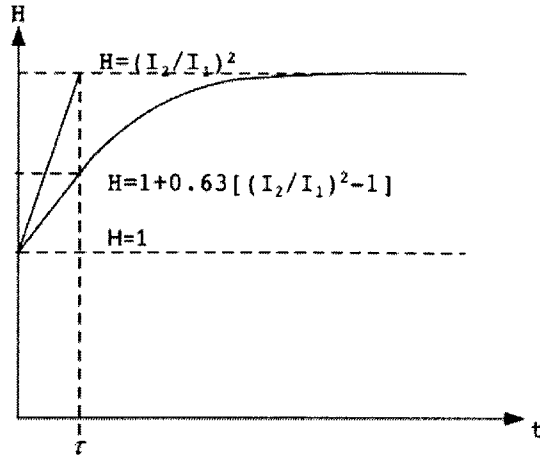
$$\theta = \frac{RI_1^2}{K} \left\{ \left(\frac{I_2}{I_1} \right)^2 - \left[\left(\frac{I_2}{I_1} \right)^2 - 1 \right] e^{-t/\tau} \right\} \quad (6.2)$$

$I_1 = \text{Interrupter Current Initial State [Amps]}$

$I_2 = \text{Interrupter Current End State [Amps]}$

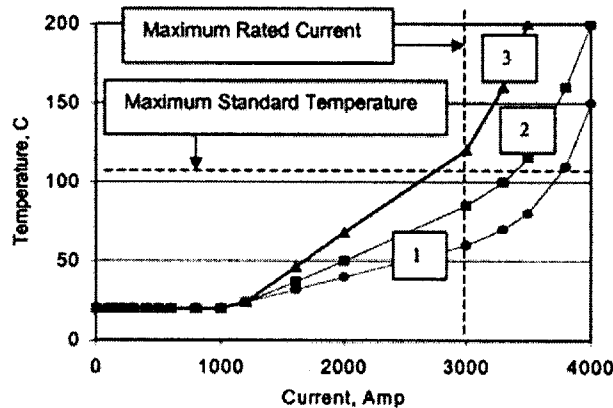
Figure 6-2 shows heat rise and characteristic term τ as a function of $H = \theta_2/\theta_1$ as described by (6.2). From a trending perspective, as the equipment degrades and τ decreases, shifts in thermal response times and temperature levels are detectable. Figure 6-3 shows the effect of current and interrupter condition on observed apparatus temperature.

Worth noting in Figure 6-3, is that temperature behaves linearly in the equipment's normal operating range. At higher than normal loads there is a clear upward inflection point: such conditions are the type of situations thermal M&D applications are designed to detect.



Source: Sallam, A. A., & Malik, O. P. Electric Distribution Systems, 2011

Figure 6-2: Interrupter Heat Rise Characteristic



Source: © 2005 IEEE. Reprinted, with permission, Livshitz, A (et al.), *On-Line Temperature Monitoring of Power Distribution Equipment, Petroleum and Chemical Industry Conference, 2005*

Figure 6-3: Interrupter Steady State Thermal Behavior: Normal (1), Worn (2), Faulty (3)

Real-time temperature prediction schemes to monitor MV circuit breaker behavior are based on mathematical solutions such as (6.2). When deviations from normality occur, corrective action is possible via the issuance of preventive maintenance alarms.

An alternate method for monitoring thermal degradation, one that is useful in conditions where current and temperature are highly dynamic, and predictive accuracy may be difficult, is achievable by observing and tracking the steady state value of θ for conditions in which ambient temperature and current are stable. Over time, and when deployed across a fleet of circuit breakers, the information offers a means of identifying high risk assets as well as judging ageing trends.

6.1.2 Temperature Sensor Selection

Temperature sensing technologies typically considered across diverse industries are thermistors, Resistance Temperature Detectors (RTDs), thermocouples, and quartz thermometers. Although packaging exists that permits the installation of these technologies on MV circuit breakers, the transmission of information captured by such sensors requires a power source or batteries, both of which are undesirable characteristics for a circuit breaker M&D application.

As communication technology has evolved, and energy requirements for the transmission of information have drastically declined, some manufacturers [26] have developed battery powered sensor kits capable of broadcasting information for 5-10 years.

Although such sensors are very attractive for advanced age MV circuit breakers, their use on other MV equipment is restrictive as battery replacement is highly undesirable from a maintenance standpoint.

Understanding that a wireless and passive sensor is ideal for MV equipment, and other applications in the electrical industry, the project team selected Surface Acoustic Wave (SAW) based technology adapted for electrical equipment temperature monitoring [27]. SAW sensors are capable of reading across a wide range of temperatures (-40 to 220 C).

The SAW sensor system is comprised of a transceiver and the sensor itself. The operating principle, as depicted in Figure 6-4, is as follows [28]:

- (i) The transceiver emits an electromagnetic pulse that is received by the sensing element's antennae.
- (ii) The signal is then conducted to an Interdigital Transducer (IDT) that will convert the energy of the signal into a surface acoustic wave that will propagate and bounce off the sensor's reflectors back to the IDT. The temperature of the device affects wave propagation speed across the sensing element.
- (iii) Back at the IDT, the surface acoustic wave is re-converted into an electromagnetic response that is picked-up by the transceiver.
- (iv) The transceiver will then compute the time distance for steps i-iii and translate this into a temperature reading.

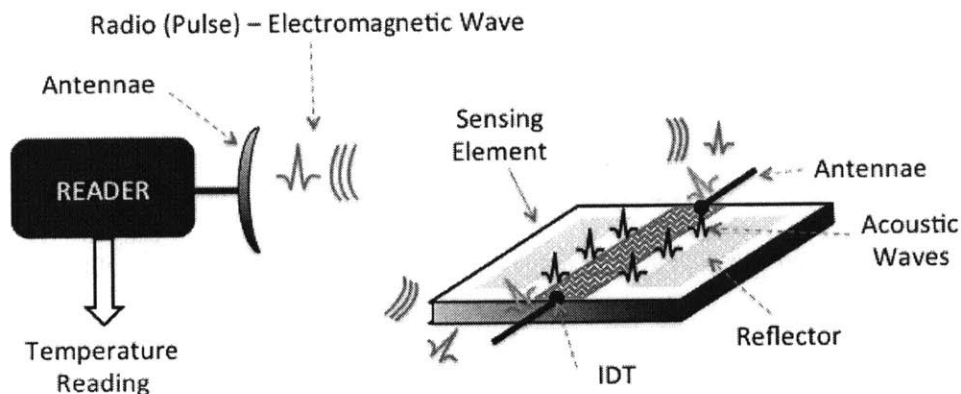


Figure 6-4: SAW Wireless Temperature Sensing System

6.2 Mechanical Operation Monitoring of MV Circuit Breakers

The equipment utilized by industry to capture mechanical operation snapshots is the *Circuit Breaker Time-Travel Analyzer* presented in Ch. 4.4.1. This analyzer, utilized in production and in time-based maintenance programs (HV space), requires that trained personnel install high frequency current sensors on the circuit breaker's open/close coils, place and calibrate displacement transducers on all three interrupters, and connect the analyzer to the circuit breaker's electronic control card.

The information obtained from a *Circuit Breaker Time-Travel Analyzer* is very precise and extremely valuable from a maintenance and troubleshooting standpoint, as experienced technicians are able to diagnose and isolate potential problems based solely on which circuit breaker components are in motion at the time an anomaly is detected.

From a MV circuit breaker M&D perspective though, this level of accuracy is unnecessary as the objective of real-time monitoring is not to diagnose equipment, but rather to provide advanced warning of impending equipment issues. This, and cost constraints, are the main drivers behind M&D solutions requiring fewer sensors.

6.2.1 Circuit Breaker Mechanical Operation Monitoring

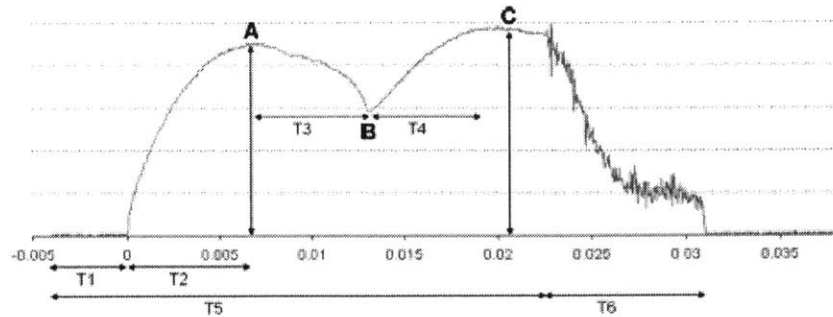
Real-time monitoring of circuit breaker operation dates back to the mid-90s [29] and since then, has slightly varied. The idea is that of capturing and analyzing the circuit breaker's actuation coil currents from open and close operations, and utilizing this information to trigger preventive maintenance alarms.

Unlike *Circuit Breaker Time-Travel Analyzers*, which require the aggregation of multiple sensed parameters, the above-mentioned approach limits itself to one or two high frequency current sensors that are installed on the circuit breaker's open and close coils, and on occasion, a limited number of inputs from the circuit breaker's control card/circuit [30][31][32][33].

Figure 6-5 depicts what a typical pulse might look like, and what possible definitions its characteristic amplitude and timing features could take. A description of these equipment specific features for the OPEN pulse shown, is as follows:

- **T1** – Time between circuit breaker relay initiating an OPEN operation and the actuator coil observing the beginning of the pulse current.
- **T2** – Time from initial pulse current rise to first local maximum value **A**.
- **T3** – Time from first local maximum value **A** to local minimum value **B**.
- **T4** – Time from local minimum value **B** to second local maximum value **C**.
- **T5** – Time between circuit breaker relay initiating an OPEN operation and the circuit breaker transitioning to a fully open state.
- **T6** – Time required for remaining actuator pulse current to dissipate into a heat sink (electrical resistance).

The algorithms required to extract the above described timing and amplitude information exist, and have already been successfully applied to circuit breakers [34].

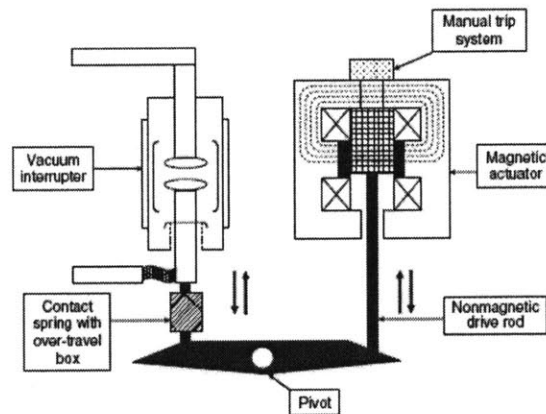


Source: © 2008 IEEE. Reprinted, with permission, Johal, H. & Mousavi, M.J., *Coil Current Analysis Method for Predictive Maintenance of Circuit Breakers*, Transmission and Distribution Conference and Exposition, April 2008

Figure 6-5: MV Circuit Breaker Trip Coil Current Characteristic Features

6.2.2 Actuation Systems

The main reason that signature monitoring of actuator current is effective for circuit breakers is that its behavior is tightly coupled with the actuator system. Within the MV space, circuit breakers are either *spring* or *magnetically* actuated. Magnetic actuation systems provide the simplest means of describing how the open and close coil current signatures relate directly to the circuit breaker's operating characteristics. Figure 6-6 presents a simplified schematic of a generic magnetic actuator system.



Source: Gill, P., *Electrical Power and Equipment Maintenance and Testing*, 2008

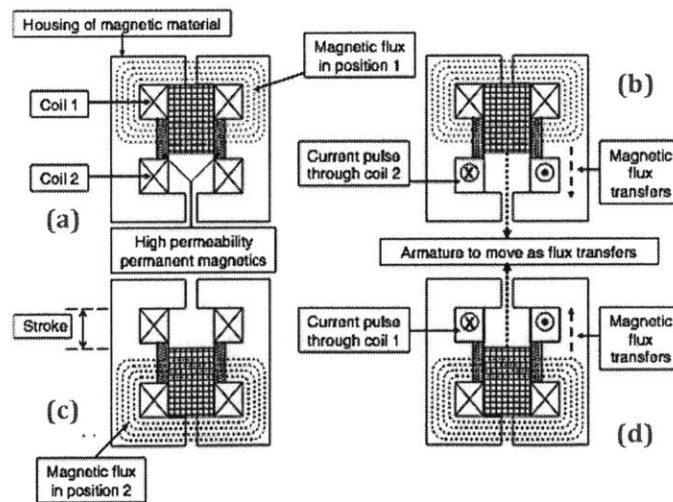
Figure 6-6: Generic Magnetic Actuator System

Focusing on the magnetic actuator, Figure 6-7 and Figure 6-8 show the basic mechanical operation principles and how they relate to the characteristic currents observed by the OPEN and CLOSE coils. Indices a-d (Figure 6-7) and i-vi (Figure 6-8), shown in the figures and described below, explain each of the breaker's states and open/close transitions¹⁵:

¹⁵ Color-coding provided to facilitate system operation understanding of indices a-d and i-vi.

- (a) **OPEN STATE** – Magnetic flux around upper coil latches the armature in the open position.
- (b) **CLOSE ACTION** – Current in the close coil (lower coil) shifts magnetic flux and causes armature travel. Sequence of events is as follows:
 - (i) **ENERGY BUILDUP** – Current in the close coil increases as a result of a capacitor/battery discharge.
 - (ii) **MECHANICAL ENERGY TRANSFER** – Once enough energy has been stored in the coil to overcome mechanical friction, the actuator begins to move (amber band).
 - (iii) **HARDSTOP PHYSICAL CLOSURE** – As the interrupter finally closes, movement will cease and a momentary energy buildup in the coil will occur.
 - (iv) **THERMAL ENERGY TRANSFER** – Remaining energy in the coil dissipates into a heat sink (electrical resistance).
- (c) **CLOSE STATE** – Magnetic flux around lower coil latches the armature in the open position.
- (d) **OPEN ACTION** – Current in open coil (upper coil) shifts magnetic flux and causes armature travel. Sequence of events is as follows:
 - (v) **ENERGY BUILDUP** – Current in the open coil increases as a result of a capacitor/battery discharge.
 - (vi) **MECHANICAL ENERGY TRANSFER** – Once enough energy has been stored in the coil to overcome mechanical friction, the actuator begins to move (amber band).
 - (vii) **HARDSTOP 100% OPEN STATE** – As movement ceases, any remaining energy in the coil is dissipated into a heat sink (electrical resistance).

As seen by the sequences described by i-vii, the fundamental principle behind the movement of the interrupter is an energy transfer that takes place when the open or close magnetic coils see electric current. The pulse characteristics are directly impacted by the physical resistance of all movable parts, and thus, the current's profile can be utilized as a means of detecting shifts and/or abnormalities in the mechanical operation of a magnetically actuated circuit breaker.



Source: Gill, P., *Electrical Power and Equipment Maintenance and Testing*, 2008

Figure 6-7: Magnetic Actuator Operation – OPEN/CLOSE State and Transitions (a-d)

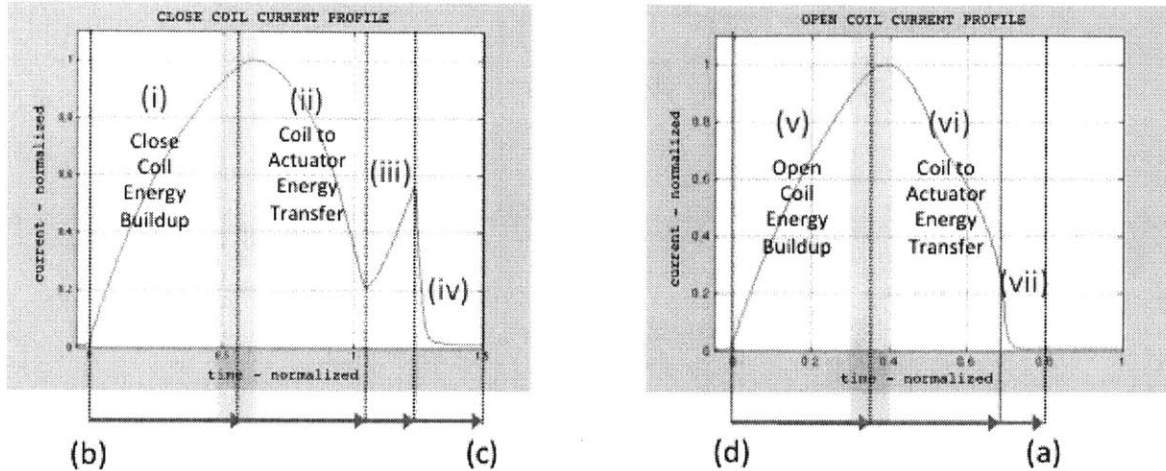
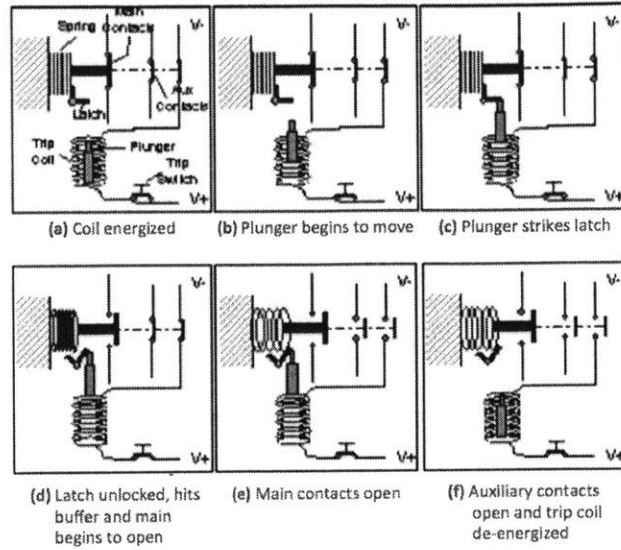


Figure 6-8: Magnetic Actuator Pulse Relationship to Mechanical Operation – (i-vii)

It is also possible to monitor trip and/or close coil current signatures on spring-actuated circuit breakers (previous generation actuation technology). Figure 6-9 and Figure 6-10 show the operation basics behind spring actuated circuit breakers and how they relate to the characteristic currents observed by the open-trip coil. Indices a-f, shown in the figures and described below, describe the sequence of events a typical spring actuated circuit breaker goes through during an OPEN switching operation:

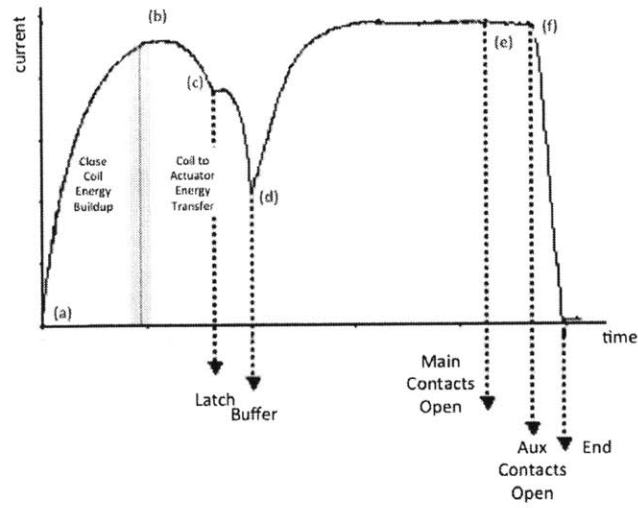
- (a) **Coil Energized** – The circuit breaker’s trip coil is energized. Power source is either a capacitor bank or a storage battery.
- (b) **Plunger Movement** – As the current in the trip coil increases, there will come a point after which the actuator’s plunger will begin to move (magnetic—mechanical energy transfer).
- (c) **Plunger Latch Strike** –The plunger will strike the latch mechanism holding back the circuit breaker’s OPEN spring mechanism.
- (d) **Latch Unlock** – Towards the end of the plunger’s travel, the latching mechanism will completely unlock and release the OPEN spring mechanism—circuit breaker main contacts begin to separate.
- (e) **Main Contacts Open** – Once the OPEN mechanism springs fully extend the interrupter main contacts will be completely OPEN.
- (f) **Trip Coil De-Energized** – Once the main contacts are open, auxiliary contacts supplying energy to the trip coil will also open and de-energize the actuation system.

Spring based circuit breakers have the disadvantage that when monitoring coil current, some insight pertaining to the mechanical operation of the apparatus is lost once the plunger has released the latch-buffer system. Despite this, the approach provides valuable timing information that can be used in conjunction with existing primary and/or auxiliary interrupter contact position signals in order to produce a more effective real-time monitoring system.



Source: © 2007 IEEE. Reprinted, with permission, from Strachan, S., & McArthur, S., *Providing decision support for the condition-based maintenance of circuit breakers through data mining of trip coil current signatures*, IEEE Transactions on Power Delivery, Vol. 22, No 1, Jan 2007

Figure 6-9: Spring Actuator Trip Operation Sequence Description – (a-f)



Source: © 2007 IEEE. Reprinted, with permission, from Strachan, S., & McArthur, S., *Providing decision support for the condition-based maintenance of circuit breakers through data mining of trip coil current signatures*, IEEE Transactions on Power Delivery, Vol. 22, No 1, Jan 2007

Figure 6-10: Spring Actuator Pulse Relationship to Mechanical Trip Operation – (a-f)

From a design perspective, the ability to monitor both spring and mechanical actuation systems satisfies the design objective of creating an M&D system capable of monitoring a wide variety of vacuum interrupter MV circuit breakers¹⁶.

¹⁶ Approach applicable to many SF₆ circuit breaker systems as well.

6.2.3 Mechanical Operation Monitoring and Analytics

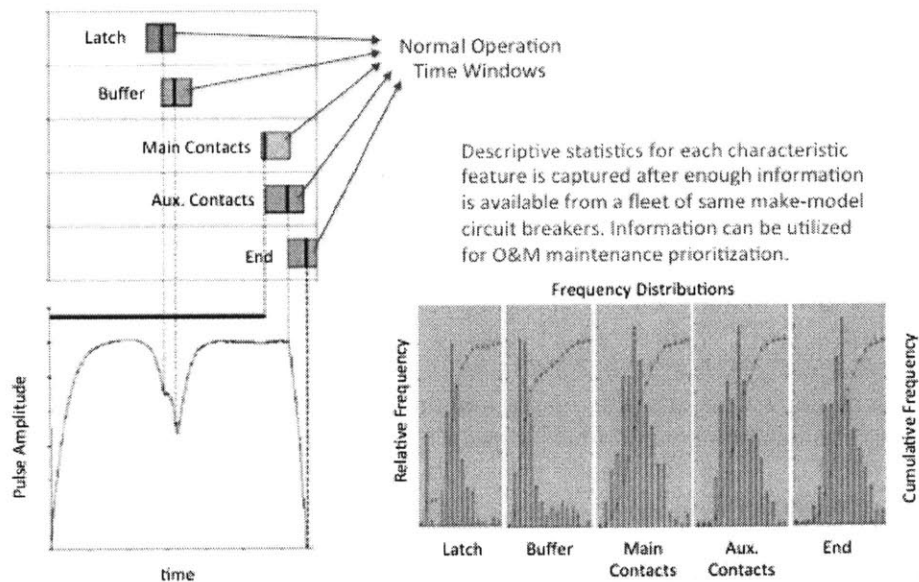
From an analytical perspective, when considering magnetic coil current signatures as a means to infer asset health, the main challenge that industry and academia have tried to address is to extract meaningful insight from the limited data that exists for MV circuit breakers in the field.

The fragmented and siloed utility landscape, the fleets of MV circuit breakers composed of distinct makes and models, the lack of deployed sensors, and the fact that more than 90% of circuit breakers are only utilized once or twice a year, all explain the aforementioned information void.

Academic research has looked into data mining techniques [29] and Bayesian methods [35] in order to make sense of the data and provide some measure of equipment health. Research also exists in the area of pattern recognition algorithms required to extract the defining amplitude and timing features of each signal (noted in Ch. 6.2.1).

The left-hand side of Figure 6-11 provides an example of an abnormal condition detection scheme in which the characteristic features of the trip coil's pulse are expected to fall within pre-determined time windows—operation outside these expected tolerances results in a warning to the equipment owner.

From a fleet analysis perspective, the right hand side of the figure provides the relative and cumulative frequency distributions for all characteristic features monitored for a fleet of same make-model circuit breakers. Plots like these can be used as inputs for more effective maintenance planning.



Source: © 2007 IEEE. Reprinted, with permission, from Strachan, S., & McArthur, S., *Providing decision support for the condition-based maintenance of circuit breakers through data mining of trip coil current signatures*, IEEE Transactions on Power Delivery, Vol. 22, No 1, Jan 2007

Figure 6-11: Spring Actuator Circuit Breaker Coil Monitoring Analytics – OPEN Pulse

Beyond the ability to detect abnormal operations, fleet wide analytics offers the promise of identifying high-risk assets (e.g., a circuit breaker taking too long to open or close) due to the fact that MV circuit breaker requirements have resulted in distinct models exhibiting similar open-close timing characteristics. These similarities allow for the analysis—albeit not perfect—of a diverse range of makes and models to happen as an aggregate in what is a simple first-pass technique of identifying high-risk assets in a fleet.

One of the challenges yet to be resolved from an analytics standpoint is learning how to account for the impact ambient temperature has on mechanical operations—and do so in the context of a fleet of circuit breakers. Equally challenging is developing a framework that will anticipate excessive stiction arising from long periods of equipment inactivity.

The development of circuit breaker coil monitoring analytics for fleet analysis is still an immature area of research that will require access to field data that currently does not exist. Despite this limitation, the use of OPEN/CLOSE actuation coil currents has clear merits given that the pulse's signature contains information that is immediately actionable, from a maintenance point of view, upon deployment of the M&D system.

6.2.4 Mechanical Operation Sensor Selection

In order to capture the current flowing through the actuation system's coils, a sensor capable of rapid response times is critical in order to observe the pulse's defining features during an open or close transition—events that last 40-200 milliseconds.

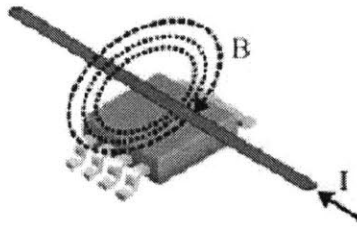
A sampling frequency of 2kHz provides enough fidelity to perform equipment diagnostics and analytics. Such sampling frequency, on a 40-millisecond pulse, will result in potential timing resolution errors of $\pm 1.3\%$. The minimum frequency deemed marginally acceptable for circuit breaker actuator coil monitoring is 1kHz. It should be noted that pulse-timing resolution is the main parameter driving sampling requirements, as pulse magnitude resolution errors are less sensitive to sampling frequency.

In addition to the sampling capability requirements, the sensor's packaging needs to be small enough such that installation in crowded spaces is possible. It also needs to be designed in such a way that placement of the sensor can occur without having to disconnect any of the wiring in the circuit breaker's low voltage cabinet—the area where actuator coils and control circuitry are typically installed.

The sensor technology that fits the above requirements is a Hall-effect current-to-voltage transducer that responds to magnetic fields. Such technology is extensively used in industrial and automotive applications, and has already proven its viability as a circuit breaker actuator pulse characterization instrument [36].

A typical concern when utilizing these types of sensors is the magnitude of neighboring magnetic fields and the potential sensing distortions that could affect the actuator coil's readings. With this in mind, development of a novel repackaging of an IC Hall-effect transducer (Figure 6-12) was made possible through the collaborative efforts of an external supplier working with the team assembled for this project at ABB Medium Voltage Headquarters¹⁷. The resulting current sensor is part of the M&D kit piloted at a customer site.

¹⁷ Details regarding the resulting sensor are proprietary and confidential to ABB's external supplier.



Source: © 2010 IEEE. Reprinted, with permission, from Makki, A., & Bose, S., *Using Hall-Effect Sensors to Add Digital Recording Capability to Electromechanical Relays*, 2010 63rd Annual Conference for Protective Engineers, March-April 2010

Figure 6-12: Hall-Effect Transducer and Current Induced Magnetic Field

6.3 MV M&D Integrated System Overview

The integrated system is comprised of sensors physically connected to a commercially available communication gateway capable of hosting the data aggregation and analytics software.

The temperature sensor kit is composed of the SAW sensors and transceiver antennae described in Ch. 6.1.2, and a reader-decoder that is physically connected to the communication gateway where real-time processing and storage takes place.

The mechanical operation sensor kit includes two Hall-effect sensors (described in Ch. 6.2.4) connected to an A/D converter box via Ethernet cable. The box, which can handle multiple breakers, has eight analog inputs capable of a 100-meter range.

In addition to the above, one ambient temperature sensor is also connected to the A/D converter box. This temperature parameter is utilized by both the thermal and mechanical operation M&D analytics.

The communication gateway selected for this application is ABB's COM600, which is capable of monitoring multiple substation circuit breakers as well as hosting many other grid automation tasks [37].

Besides the implementation flexibility that the COM600 offers, the device is an attractive proposition as remote analytic software upgrades—a certainty in any M&D application—are safe to conduct given that the gateway satisfies the stringent cyber security requirements expected by utility customers in the United States.

Figure 6-13 is an overview of how the M&D system for MV circuit breakers is integrated. The figure also gives insight into how O&M personnel could potentially interface and use the information stored in the COM600. In this schematic, circuit breaker observed current and voltage are also included as these parameters provide valuable fault and equipment overloading information (Ch. 4.2).

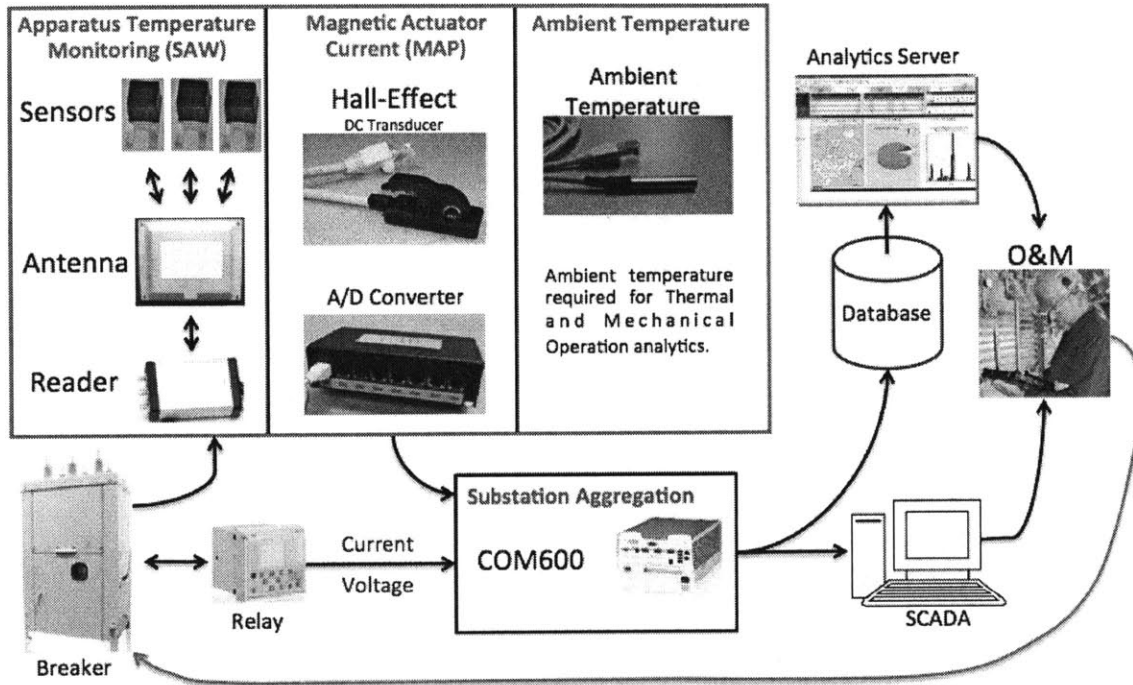


Figure 6-13: MV Circuit Breaker M&D Integrated Sensor Kit

6.4 MV Circuit Breaker M&D System - Summary

The proposed M&D system consists of technology readily available and analytics based on parameters the industry is familiar with: mechanical operation and thermal state.

In the case of thermal monitoring, the heat transfer physics are simple enough that effective tracking of thermal shifts, and evaluation of long-term equipment degradation, are only a matter of developing software, capturing data, and fine-tuning the analytic algorithms over time. In addition, from a technological standpoint, the availability of reasonably priced wireless-passive temperature sensors makes thermal monitoring a safe and practical proposition.

The basics of mechanical operation monitoring are also well understood, but development of effective analytics is challenging given the lack of field data, and the fact that generalizing the approach across multiple circuit breaker platforms is difficult. Nonetheless, widespread adoption of such a monitoring scheme would quickly provide enough information to identify assets at risk.

As discussed in Ch. 3-5, as the value proposition of analytics is understood, it is reasonable to expect that integrated M&D systems like the one proposed in this chapter will allow utilities and manufacturers to capture, store, and analyze information across fleets of MV circuit breakers. This information, with the aid of analytic algorithms that will become more effective over time (learning period), will help utilities reduce maintenance operation costs while maintaining a high degree of service reliability.

From a cost perspective, the proposed system's simplicity, limited number of sensors, and flexibility to connect to multiple breakers, should keep the per-breaker price within the \$2,000-

3,000 (USD) range targeted at the beginning of the project. Meeting these cost constraints is possible when considering production economies of scale and detailed engineering work that needs to occur before the product is brought to market. It should be noted that detailed pricing and sourcing details cannot be presented in this thesis as it is safely guarded competitive information proprietary to ABB.

Although not presented in this chapter, the Accelerated Proof of Concept Team did explore the possibility of monitoring other parameters within the circuit breaker, as well as utilizing other sensing technologies as a means of measuring circuit breaker health. Appendix B-11 provides a comparative overview of the pros and cons to these alternatives [38-52].

7 LABORATORY TESTING AND RESULTS

Towards the end of the project's research phase (July-Sept), the opportunity presented itself to pilot the integrated system described in Ch. 6.3. The fleet to monitor consists of six 15 kV magnetically actuated vacuum circuit breakers (Ch. 6.2.2) utilized for reactor bank switching. Unlike a protection application where circuit breakers operate once or twice a year (if at all), circuit breakers utilized for reactor bank control turn ON and OFF once or twice a day¹⁸.

The opportunity to deploy the integrated M&D system in a high utilization environment is an ideal setting for collecting vast amounts of data. The opportunity also justified a thorough testing effort to demonstrate the viability of the mechanical operation analytics designed for this particular application.

Hence, Chapter 7 describes the steps taken to characterize the 15 kV circuit breakers OPEN and CLOSE actuation pulse current profiles, the experiment sequence design, and results obtained.

7.1 Sequence of Experiments Design

Understanding that the budget for conducting tests was limited, much effort went into searching ABB internal resources that could aid in the design of an efficient test sequence. This effort led to some design/certification test results and production data for a 38 kV magnetically actuated vacuum circuit breaker sharing similar technology to that of the equipment in the pilot program.

The data from the 38 kV circuit breaker clearly showed that interrupter wear and temperature have a measurable impact on pulse characteristics (e.g., timing and magnitude) and suggested that these relationships are potentially linear. The data also indicated that machine-machine variability is an important consideration when designing the analytic algorithms for fleet analysis.

The sequence of experiments design focused on characterizing the most important pulse distinctive features as a function of temperature (-40 to 40 °C) and interrupter ageing/position across all three A-B-C phases¹⁹ for both symmetrical and asymmetrical scenarios (i.e., distinct interrupter conditions).

The most important pulse defining features for 15 kV equipment tested are listed below and identified in (Figure 7-1).

OPEN & CLOSE PULSE DEFINING FEATURES

- **MAX CURRENT (I_{MAX})**– Value of maximum current observed in the pulse signal. Parameter is a measure of energy levels required to operate the system.
- **MAX TIME (T_{MAX})**– Time distance between the beginning of the pulse and point where MAX CURRENT is registered. Parameter provides an approximate time-coordinate indicating the beginning of interrupter movement (Ch. 6.2.2).
- **END TIME (T_{END})**– Duration of pulse from beginning to end. Indicates end of switching operation.

¹⁸ Reactor bank switching is a practice utilized by utilities to compensate for reactive power in the grid. Reactor switching circuit breakers are typically disconnected during high network load conditions, and connected during low load periods.

¹⁹ In a three-phase architecture, A-B-C each corresponds to an electric phase.

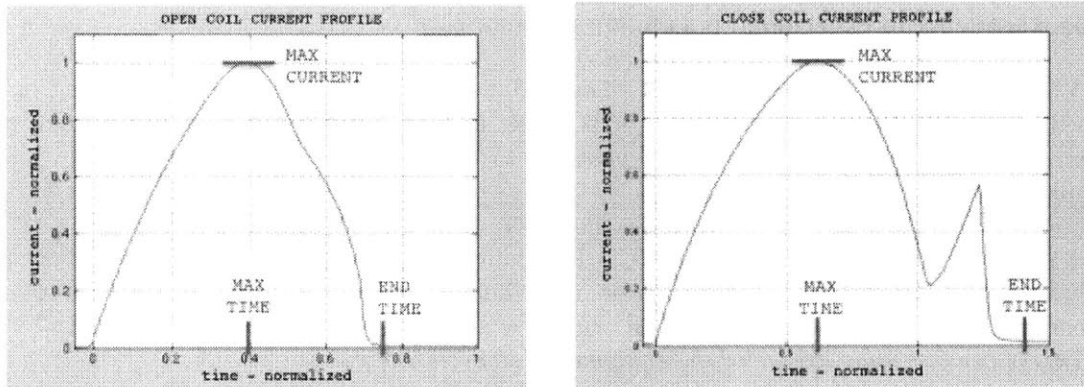


Figure 7-1: 15 kV Circuit Breaker Most Important Coil Current Pulse Defining Features

In addition to the three noted features, the developed profile recognition algorithm is also capable of identifying the CLOSE pulse's local minima and maxima (current and time coordinates) that occur between MAX TIME and END TIME. Characterization of these parameters, however, is deemed unnecessary²⁰ as MAX CURRENT provides the clearest indication of energy available to the system and END TIME offers the best overall timing assessment of switching capability for the circuit breaker.

As described in Ch. 3.1, whenever vacuum circuit breakers interrupt a live circuit, a small amount of metal in the electrode material evaporates. Over time, this loss of material results in a reduced compression between electrode contact surfaces when the circuit breaker is in CLOSE position—a condition that results in higher interrupter electrical resistance and higher potential for arcing.

In order to recreate this ageing condition in the laboratory, the interrupter for each circuit breaker phase was manually adjusted to reflect the position an interrupter tip would observe under normally deteriorated circumstances. This position, a measure of the closing mechanism's overtravel capability—a means of ensuring positive interrupter pressure and compensating for contact erosion, is referred to in the industry as contact wipe or WIPE.

Contact wipe is typically measured in millimeters (or inches) or as a percent value based on manufacturer specified min-max overtravel thresholds. For the purposes of this thesis a WIPE setting of 100% represents an interrupter in pristine condition, whereas a setting of 0% is associated with a completely deteriorated interrupter with no overtravel capability.

Along with temperature and WIPE, the sequence of experiments also considered the effect of primary current across all three phases on the OPEN and CLOSE actuator pulse profiles, but because the influence of primary current was found to be negligible, it will not be included in this thesis. Worth noting is the fact that the injected current was only 1000 Amperes (lab restrictions). Expert opinion however suggests that similar results will be observed under normal load conditions²¹.

²⁰ CLOSE profile local minima and maxima parameters were occasionally evaluated during testing to confirm that their characterization was unnecessary given other parameters MAX CURRENT, MAX TIME, and END TIME.

²¹ Further testing is required to determine the impact fault/short-circuit currents have on mechanical operation characteristics.

The final sequence of experiment is as follows (Figure 7-2):

- (a) **SYMMETRICAL WIPE TESTING** - Focused on characterizing the equipment’s response to distinct WIPE settings: 5%, 25%, 50%, 75%, and 95%. WIPE adjustment symmetrical across all phases (A-B-C). **This phase of testing exercised the equipment 150 cycles (approx.).*
- (b) **ASYMMETRICAL WIPE TESTING** - Evaluation of asymmetrical WIPE settings across phases (A-B-C) aimed to shed light on individual phase contributions to actuator pulse characteristics. The following WIPE settings are considered: 25%, 50%, and 75%. **This phase of testing exercised the equipment 250 cycles (approx.).*
- (c) **WIPE & TEMPERATURE INTERACTIONS** - Testing in a temperature chamber at 10°C increments across a -40 to 40 °C range sought to characterize the equipment’s response with different ambient temperatures. Temperature “sweeps” with three distinct symmetrical WIPE settings: 25%, 50%, and 75%, expected to capture WIPE settings and temperature interactions. **This phase of testing exercised the equipment 900 cycles (approx.).*
- (d) **WIPE RESULT REPRODUCIBILITY** - After more than a thousand operations, a subset of tests conducted for (a) is repeated for WIPE settings of 25%, 50%, and 75%—intended to evaluate reproducibility of results after two-four years’ worth of operations and quantify long-term equipment operational shifts. **This phase of testing exercised the equipment 100 cycles (approx.).*
- (e) **PRIMARY CURRENT INFLUENCE** - Tests conducted for (d) are repeated for a “live” circuit breaker observing 1000 Amperes across each interrupter phase—introduced to determine the impact of primary current on magnetic actuation pulse behavior. **This phase of testing exercised the equipment 100 cycles (approx.).*

**For each of the identified test conditions in Figure 7-2, the circuit breaker was exercised 30+ times in order to gain insight into the equipment’s operating variability: a more accurate determination of the defining feature’s mean value and standard deviation.*

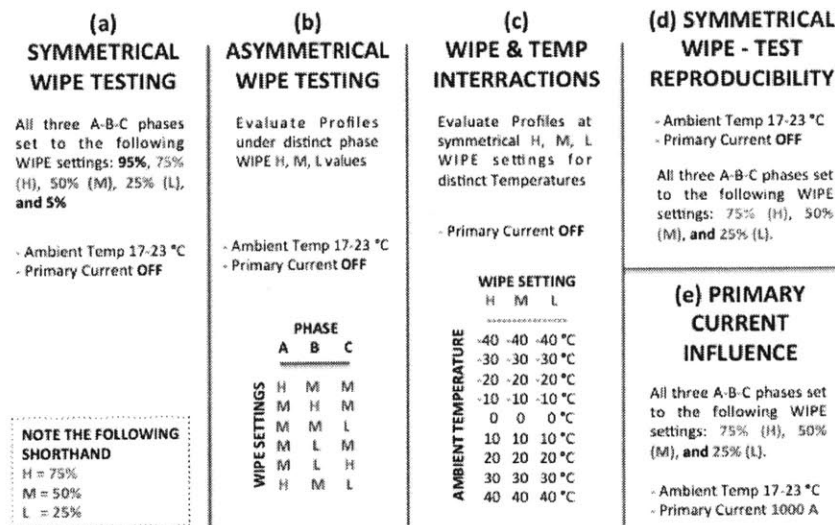


Figure 7-2: Sequence of Experiments - Test Flow

7.2 Test Results

Results for each set of tests identified in Figure 7-2 follow. As defined in Ch. 7.1, the independent parameters analyzed are MAX CURRENT, MAX TIME, and END TIME for both OPEN and CLOSE profiles. *Information is presented on a normalized scale.*

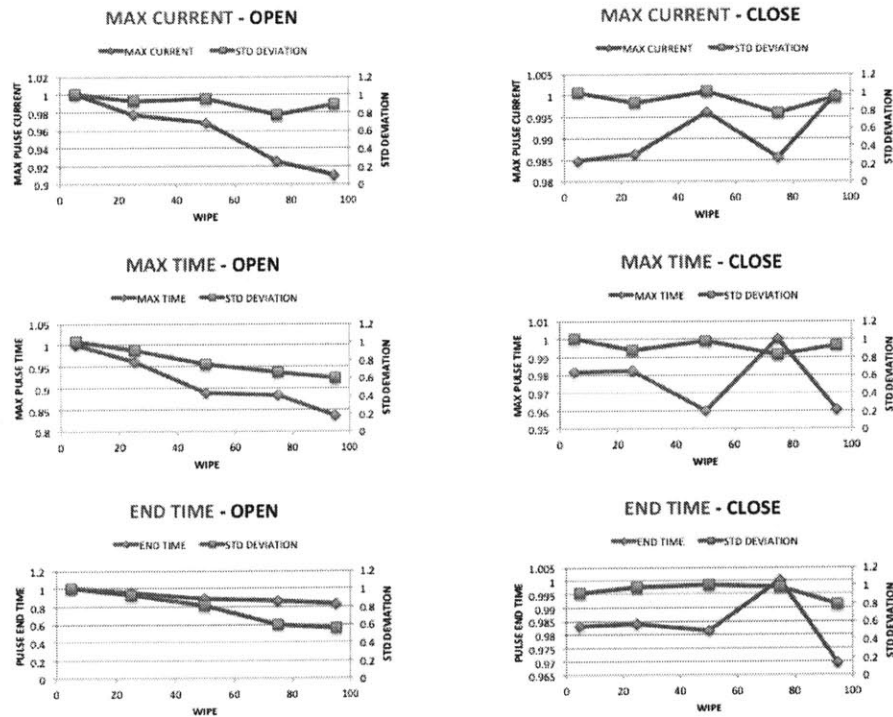
7.2.1 (a) - Symmetrical Testing Across 95%-75%-50%-25%-5% WIPE settings

The objective of the test was to better understand, and characterize if possible, the influence that symmetrical WIPE setting has on the circuit breaker's magnetic actuation OPEN and CLOSE current pulses.

Results for symmetrical WIPE settings (Figure 7-3), indicate that interrupter erosion—WIPE reduction—has a strong linear influence on the OPEN pulse's characteristics. As WIPE is reduced from 95% to 5%, the following is observed:

- MAX CURRENT increases by nearly 10%.
- MAX TIME increases by as much as 20%.
- END TIME increase is slightly higher than the change observed by MAX TIME.
- For all three parameters, standard deviation increases.

The level of change observed for the CLOSE pulse was relatively small and did not follow an evident trend; standard deviation also remained fairly constant throughout the entire WIPE envelope.



Note: both average and standard deviation values have been normalized independently

Figure 7-3: Test Results - Magnetic Actuator Pulse Characteristics as a Function of WIPE

7.2.2 (b) - Asymmetrical WIPE Testing to Evaluate Phase Interactions

A source of concern in the development of an M&D system dependent on the circuit breaker's OPEN and CLOSE magnetic actuation pulses is the uncertainty surrounding the analytic capability of detecting a low WIPE condition affecting a single interrupter-phase (asymmetric WIPE). The objective of this test was to understand what, if any, correlation exists between phases and the observed OPEN and CLOSE actuation pulses, and determine if individual phase low WIPE settings are detectable.

Table 7-1 below shows the WIPE settings tested:

	WIPE PHASE A	WIPE PHASE B	WIPE PHASE C
Test Setting #1	75%	75%	75%
Test Setting #2	75%	50%	50%
Test Setting #3	50%	50%	50%
Test Setting #4	50%	75%	50%
Test Setting #5	50%	50%	25%
Test Setting #6	50%	25%	50%
Test Setting #7	50%	25%	75%
Test Setting #8	25%	25%	25%
Test Setting #9	75%	50%	25%

Table 7-1: ASYMMETRICAL WIPE TEST SETTINGS

Results for asymmetrical WIPE for the CLOSE profile did not show any significant influence on the profile's behavior. These results are in agreement with the results previously obtained for symmetrical WIPE testing.

For the OPEN profile, however, results show that it is prudent to assume that each of the circuit breaker phases contributes linearly to the OPEN profile's pulse characteristics. This result is significant, as the lowest WIPE setting in the apparatus will contribute slightly towards increasing MAX CURRENT and MAX TIME, and has a very noticeable effect on END TIME.

These characteristics allow the M&D system to detect a highly eroded interrupter (low WIPE), and thus protect the equipment from impending failure.

The expressions obtained that capture phase interactions are the following:

$$I_{MAX} = 0.982 - 0.0067 \left(\frac{WIPE_A - 0.5}{0.25} \right) - 0.0137 \left(\frac{WIPE_B - 0.5}{0.25} \right) - 0.0046 \left(\frac{WIPE_C - 0.5}{0.25} \right) \quad (7.1)$$

$$T_{MAX} = 0.945 - 0.0168 \left(\frac{WIPE_A - 0.5}{0.25} \right) - 0.0111 \left(\frac{WIPE_B - 0.5}{0.25} \right) - 0.0200 \left(\frac{WIPE_C - 0.5}{0.25} \right) \quad (7.2)$$

$$T_{END} = 0.940 - 0.0204 \left(\frac{WIPE_A - 0.5}{0.25} \right) - 0.0144 \left(\frac{WIPE_B - 0.5}{0.25} \right) - 0.0174 \left(\frac{WIPE_C - 0.5}{0.25} \right) \quad (7.3)$$

It should be clarified that an M&D application utilizing the magnetic actuator OPEN pulse will be unable to utilize the previous expressions to determine the WIPE condition for each interrupter. Rather, the insight given by the expressions (7.1), (7.2), and (7.3) is that an individual low WIPE setting will modify the OPEN pulse enough for it to be detectable. Figure 7-4 plots actual data compared against the predictions given by (7.1), (7.3), and (7.3), the intercepts for the expressions (dotted blue line), and confidence interval at 95% for each parameter (dotted red line).

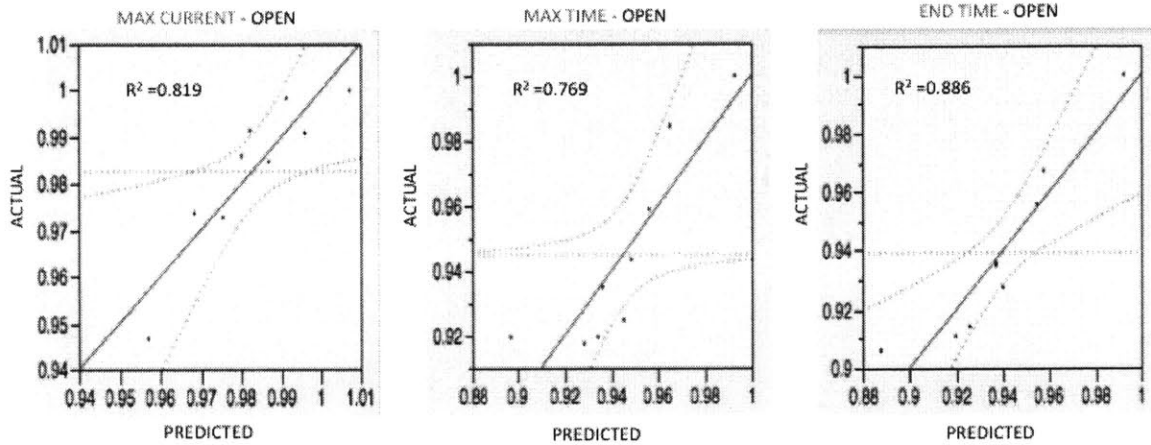
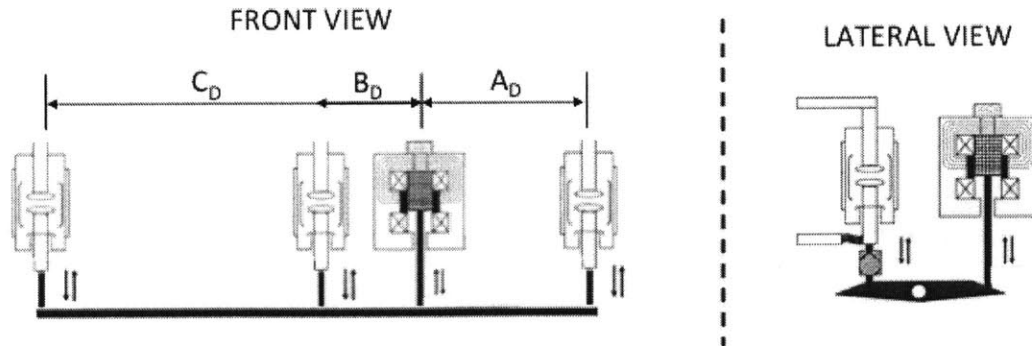


Figure 7-4: Test Results - Asymmetric WIPE Interactions - Predicted versus Actual Data

Worth noting is that each of the phases contributes distinctly to the overall profile’s characteristic with phase B having the highest impact, followed by phases A and C having a similar contribution on the pulse (7.1, 7.2, and 7.3).

Post-test result analysis determined that the most likely reasons for this is the torsional characteristics of the actuator-interrupter linkage shaft and the relative position of the magnetic actuator with respect to each of the interrupter assemblies. Figure 7-5, a simplified schematic of the actuator’s relative position to each phase interrupter, shows the proximity of phase B to the interrupter—this phase is the least prone to the connecting shaft’s torsional characteristics (e.g., radial displacement with torque).



Source: Gill, P., *Electrical Power and Equipment Maintenance and Testing*, 2008 (adapted)

Figure 7-5: Interrupter Distance to Magnetic Actuator – Simplified Schematic

7.2.3 (c) – Temperature and WIPE interactions

The objective of the test was to characterize, if possible, the influence that ambient temperature has on the circuit breaker’s magnetic actuation OPEN and CLOSE current pulses.

Both OPEN and CLOSE profiles exhibit very similar characteristics:

- There is no perceivable coupling between temperature and WIPE
- Behavior with temperature is linear for temperatures greater than -20°C.
- MAX CURRENT decreases as temperature increases. Circa 10% decrease observed within temperature range of -20°C through 40°C.
- MAX TIME and END TIME are insensitive to temperature.

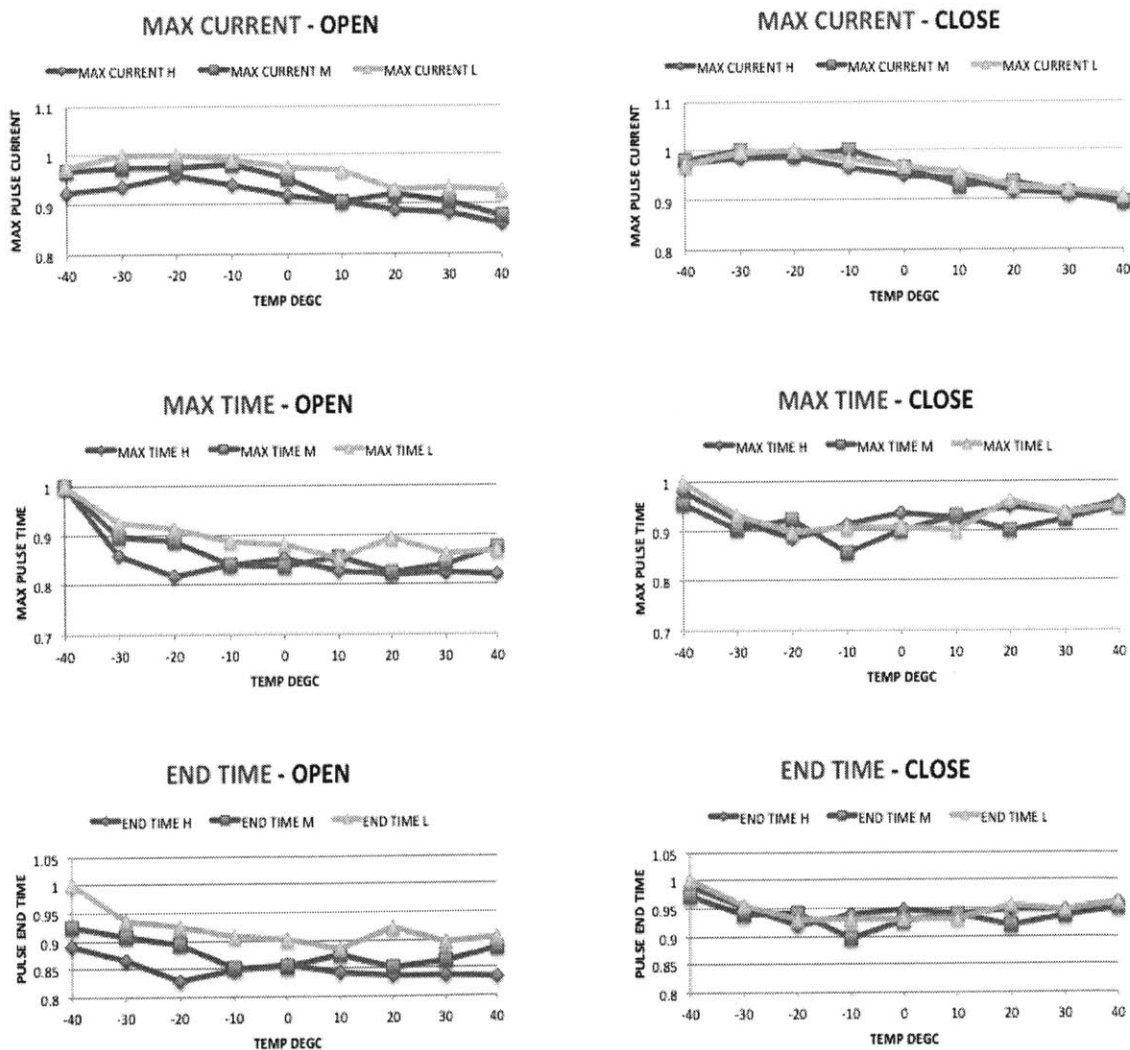


Figure 7-6: Test Results - Magnetic Actuator Pulse Characteristics with Temperature

7.2.4 (d) - Magnetic Actuator Mapping after 1000 Cycles

The objective of the test was to evaluate whether or not the circuit breaker’s behavior with respect to WIPE symmetrical settings is maintained after two-four years’ worth of operations (+1000 cycles). The test also intends to shed light on equipment operational shifts due to equipment ageing mechanisms independent of WIPE degradation. WIPE settings re-evaluated were 75%, 50%, and 25%.

A summary of the test results follows:

OPEN profile

- MAX CURRENT increased by 3-4% but MAX TIME and END TIME remained unchanged.

CLOSE profile

- END TIME decreased by 4-6%. Other parameters do not exhibit a clear trend.

These observations are interesting as they point to non-interrupter ageing mechanisms that are difficult to identify and quantify individually (versus interrupter wear). These results, however, do not invalidate previous findings and/or pose any visible risk to the development of an M&D application.

In the case of MAX CURRENT for the OPEN profile, the direction of the shift is in the same direction as that observed for interrupter deterioration—thus the risk of these signals cancelling each other out is non-existent.

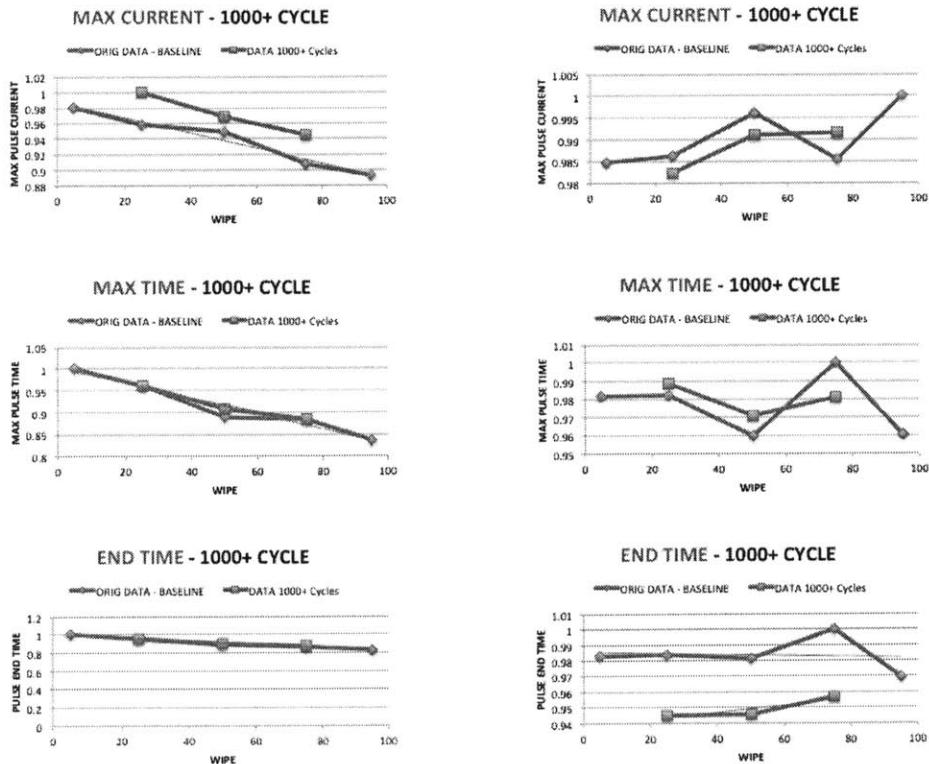


Figure 7-7: Test Results – Symmetric WIPE Actuator Pulse Profile after 1000+ Cycles

7.3 Results and Insight

The results obtained are encouraging from an analysis standpoint for the following reasons:

- There is no perceived coupling between interrupter position and temperature.
- For the OPEN pulse, observed equipment response is linear across both WIPE and temperature dimensions for the OPEN pulse. The only instance where this was not true is for temperatures lower than -20°C . As the bulk of circuit breakers do not operate at or below these temperatures, this range is ignored for the purposes of the M&D system being piloted²².
- For the CLOSE pulse, as observed in the OPEN pulse, behavior with temperature is linear for temperatures higher than -20°C . Again, temperatures below this value are ignored for the purposes of M&D.
- Single interrupter degradation issues (asymmetric interrupter condition) are still detectable in the OPEN pulse. Condition detection is degraded and will require availability of fleet statistics and “in-family” pulse profile trends to increase detection capability²³.
- Non-interrupter ageing and interrupter position/deterioration influences on OPEN MAX CURRENT and CLOSE END TIME pulse characteristics are additive.
- Standard deviation of all monitored parameters is predictable and contained to a narrow range.
- Testing and expert opinion suggest that phase current has a negligible impact on measured pulse characteristics.

Although the results obtained are not ubiquitous to all circuit breakers, the results do fall in line with expectations based on the limited information collected and analyzed for the 38 kV circuit breaker. Both the 38 kV and 15 kV circuit breakers share similar vacuum interrupter and actuator technologies.

The data collected as part of equipment design, certification, and in some instances, manufacturing, is extremely valuable when putting together a sequence of experiments and when determining the feasibility of any M&D solution.

Due to test restrictions, the experiment was limited to a single 15 kV circuit breaker and in consequence, accurate in-family machine-machine variation is unknown. As field information becomes available, assessing this source of variability, and its potential impact on fleet analytics, will be possible.

²² Geographic location where M&D system is to be piloted very rarely sees temperatures below -20°C .

²³ Fleet analytics is an area of future research identified by this thesis.

8 REACTOR SWITCHING—M&D ANALYTICS DESIGN

The deployed M&D system incorporates thermal monitoring capability as described in Ch. 6.1, and mechanical operation monitoring—analytics that will be described in this chapter.

Unlike settings in which circuit breakers are utilized primarily as protection devices, reactor-switching applications offer considerably more information that can be used to detect equipment misoperation on a daily basis, as well as establish short-term and long-term trends.

The results obtained during laboratory testing (Ch. 7) strongly influence the M&D approach, and analytics presented here in Chapter 8. *All plotted information has been normalized.*

8.1 Daily Operation Monitoring

Through visualization of all magnetic actuator pulses captured during laboratory testing, and accounting for reasonable machine-machine variability, it is possible to establish normal boundaries for each of the monitored parameters (e.g., MAX CURRENT).

These “strike-zones”, seen in Figure 8-1, offer equipment operators a first level of protection against gross misoperation: operation outside of these areas should alert operators of impending failure and the need for immediate action. In the figure, the strike-zones are placed in the context of the 1500+ OPEN and CLOSE profiles collected during laboratory testing (Ch. 7). The figure also shows hypothetical profiles that would trigger an alarm.

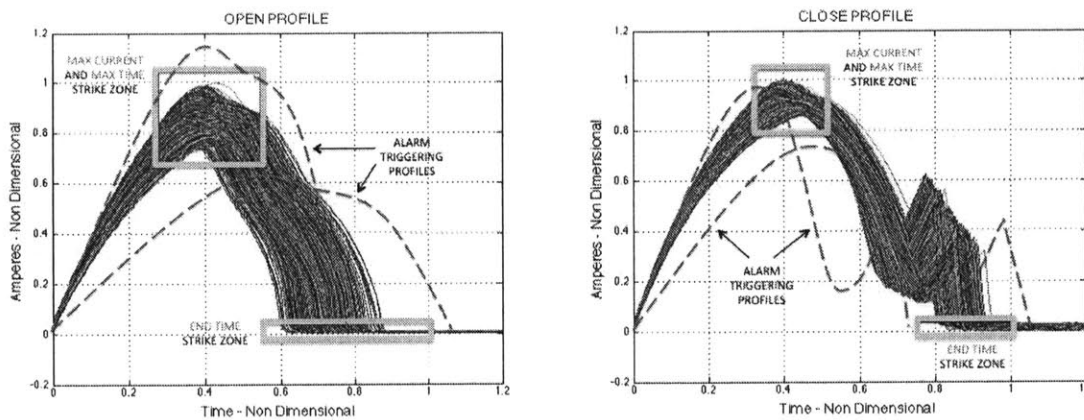


Figure 8-1: OPEN and CLOSE Strike-Zones with Hypothetical Alarm Triggering Cond.

Over time, as part of the analytics learning process, refinement of the “strike-zone” boundaries will be possible as machine-machine variability is better understood.

8.2 Short Term Trending – Operation Shift Detection

Daily use of the equipment opens the door to tracking each operation in the context of the circuit breaker’s past performance. The approach followed for short-term trending looks at the last 30 operations and computes average and standard deviation statistics for each of the pulse defining

features. This information is presented in a control chart format with upper and lower control limits equivalent to 3σ levels.

Figure 8-2 provides an example of these control charts. In this format, operation “shifts” can easily be observed and upper and lower limit excursions will trigger warnings that alert operators of potential maintenance action.

Embedded in this monitoring scheme are limits on the acceptable values σ can take. In order to minimize false positive alarms (type I errors), a minimum standard deviation is imposed based on observed behavior for the equipment being monitored. Likewise, a maximum value is also predetermined, and equipment observing higher variability than this threshold will also trigger a warning as irregularity is also a sign of potential equipment health problems.

In the case of MAX CURRENT, which is influenced by atmospheric temperature (circa $\pm 5\%$, Ch. 7.2.3), a correction factor is applied such that all readings are anchored at a reference temperature. This correction factor (Ch. 8.4 and Ch. 8.5) allows for a more direct performance comparison, given narrower upper and lower control limits. This is possible due to the linear relationship that temperature has on MAX CURRENT for the 15 kV circuit breaker monitored in the pilot program (Figure 7-6).

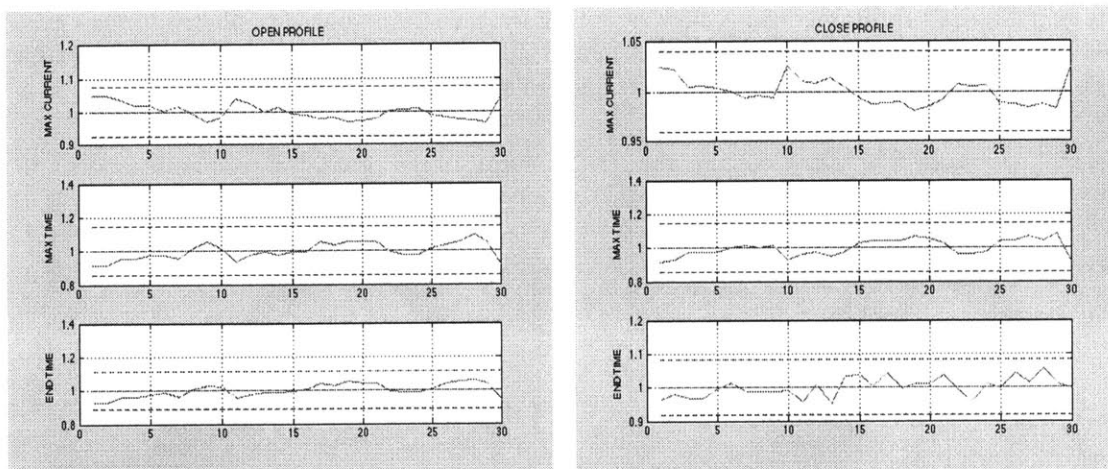


Figure 8-2: Mechanical Operation Control Charts – Data from Last 30 Operations

8.3 Long Term Trending – Deterioration Factor Calculation

Long-term trending focuses on the rate of change observed in the parameters monitored (e.g., MAX CURRENT²⁴, MAX TIME, END TIME) after enough data has been collected—12 months for reactor breaker application. The rate of change term, referred to herein as the parameter’s deterioration factor or deterioration rate, is obtained from the slope of a linear regression through the parameter’s dataset for the time period analyzed.

²⁴ Long term trending for MAX CURRENT will require a temperature correction term. Computation of correction term is discussed in Chapter 8.4.

Figure 8-3 graphically depicts the computation of a monitored parameter's deterioration factor (linear regression slope term). The figure is the result of a numerical simulation for a scenario assuming the following behavior for the monitored parameter:

- Parameter is subject to an observed standard deviation $\sigma_p = 0.025$ (2.5%).
- Parameter increases at a rate of 0.0002 units with each operation (normalized scale). This term is the deterioration factor that the slope of the linear regression will approximate.

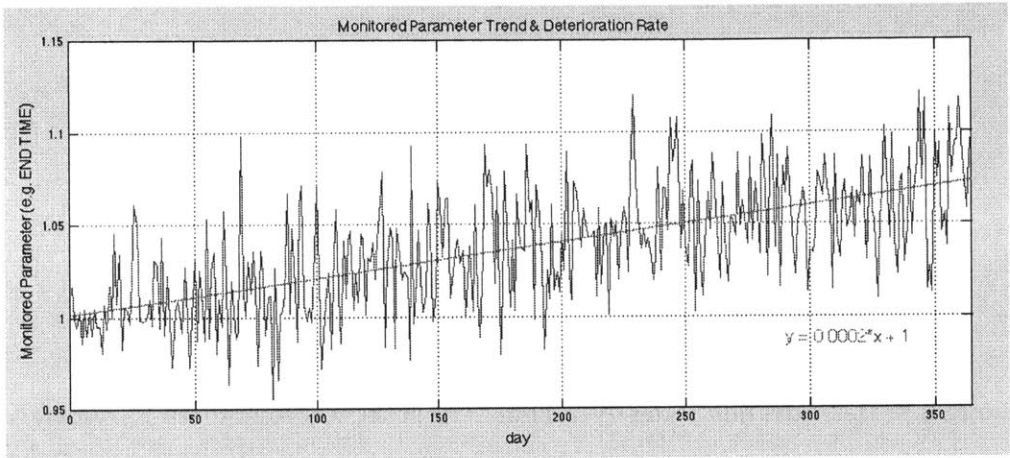


Figure 8-3: Monitored Parameter Deterioration Rate - Regression Slope

In the figure above (Figure 8-3), the linear regression correctly computes the deterioration rate term (0.0002 units per operation). In reality, however, the method's computed slope is subject to variability that, for the case examined, is measured by a standard deviation of $\sigma_D = 6.2\%$. This confidence measure is computed from recreating the described scenario 1000 times and re-running the linear regression through the data for each case. Figure 8-4 shows the simulation results for the 1000 scenario cases in histogram format. The deterioration factor's prediction variability is directly tied to the observed parameter's variability²⁵.

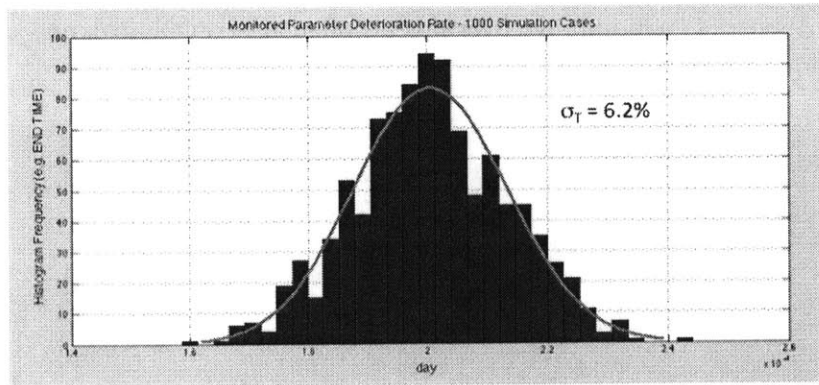


Figure 8-4: Monitored Parameter Deterioration Factor Accuracy Simulation Results

²⁵ Re-running the same simulation assuming an observed parameter variability of $\sigma_p=5.0\%$ results in reduced accuracy and confidence in the method as the value of the deterioration term's standard deviation increases to $\sigma_D = 11.9\%$.

Despite the method’s accuracy shortcomings, the deterioration factor information obtained provides enough insight for it to be utilized as an indicator of equipment health and ageing rate.

A good example is utilizing the information as a year-year historical record to identify upward trends in deterioration rates symptomatic of equipment accelerated ageing. Figure 8-5 depicts one such situation for a hypothetical monitored parameter where, beyond year 24-25, it is evident that the circuit breaker in question requires close attention from a maintenance standpoint.

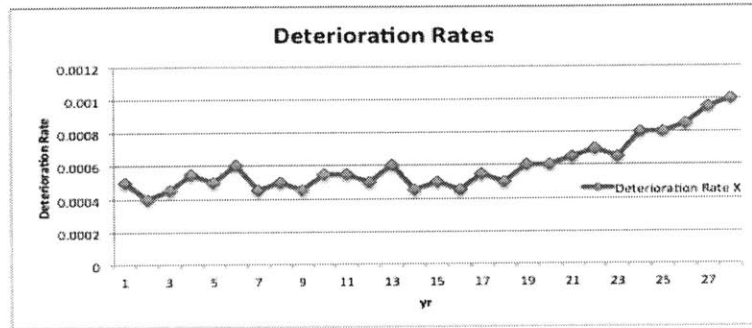


Figure 8-5: Deterioration Rates over Time – Hypothetical Monitored Parameter

Another application for the monitored parameters’ deterioration rates is its application in maintenance prioritization planning for a fleet of circuit breakers. In this context, a year’s worth of deterioration rate information for an entire fleet can be synthesized into a simple to read Fleet Status Board that can be used as a means of categorizing asset risk, and thus improving the effectiveness of maintenance resources.

Figure 8-6 shows one possible Fleet Status Board representation: on the x-axis the plot shows a monitored parameter’s deterioration rate, and on the y-axis information is provided pertaining to the monitored parameter’s standard deviation—also a measure of equipment health. Utilization of such a chart would provide utilities currently nonexistent information that could be incorporated into maintenance scheduling decisions. As discussed in Ch. 5.2.2, the quality of the information (i.e., risk level boundaries) will improve over time as more data is collected, analyzed, and used to fine-tune the M&D analytics.

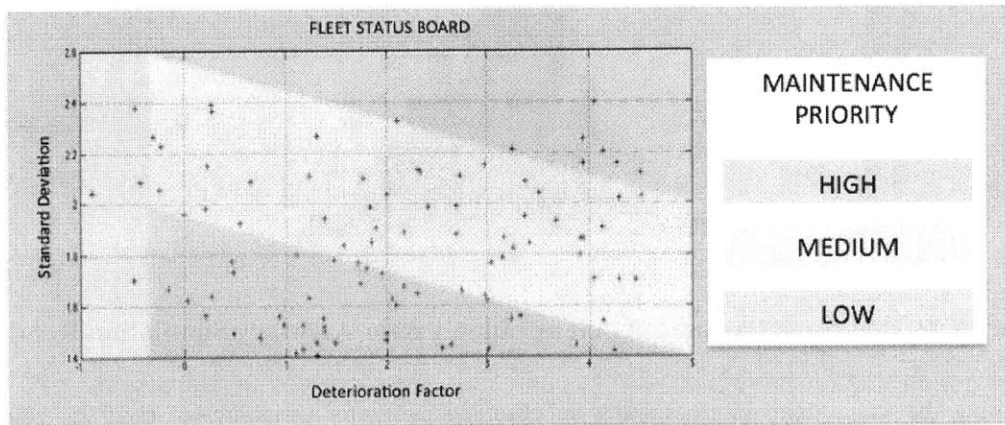


Figure 8-6: Fleet Status Board - Equipment Maintenance Prioritization

Also, at this point in time, it is difficult to identify which parameters will be the most useful to maintenance planning operations. Again, only time, field data, and fine-tuning of the analytic engines will allow for their identification. Despite it being early in the development of MV circuit breaker applications, the utilization of deterioration rates as presented in Figure 8-5 and Figure 8-6 is promising.

Utilization of M&D health indicators for circuit breaker fleet maintenance operation is a field for future research spanning the entire transmission and distribution spectrum.

8.4 Temperature Correction – M&D Analytics Calibration

As noted during laboratory testing, MAX CURRENT for both OPEN and CLOSE profiles is influenced by temperature and thus a correction term is required prior to performing the linear regression in order to extract the parameter's deterioration factor as described in Ch. 8.3. The correction term is also advisable when putting together the short-term control charts described in Ch. 8.2.

The initial temperature correction applied to the MAX CURRENT term, for both short and long-term trending, will be the one determined during lab testing (Ch. 7.2.3). This term, however, will vary slightly from machine to machine, and thus it is desirable for the M&D analytics to self-calibrate after enough data is collected. The following paragraphs describe the method for such self-calibration.

The calibration technique relies on the sinusoidal behavior of temperature throughout the calendar year (Figure 8-7). The data capture windows begin during the coldest or warmest times of the year and continue for 365 days, after which a new data capture cycle begins—this characteristic is further discussed towards end of this chapter.

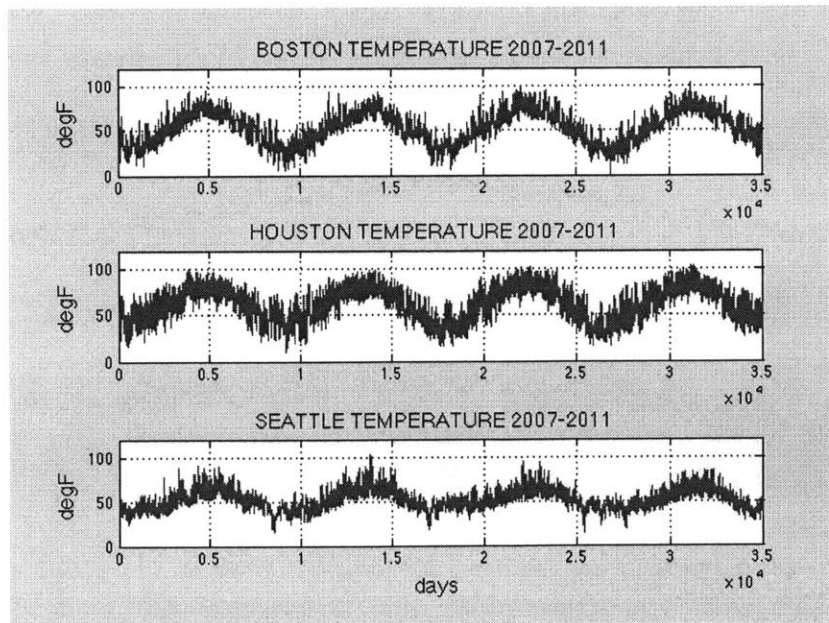


Figure 8-7: Hourly Registered Temperature for Three Major US Cities 2007-2011

Once a year’s worth of information is available, the temperature correction term—unique to each machine—can be extracted from the data by performing a linear regression for MAX CURRENT (or parameter of interest) against temperature: the computed slope from this operation becomes the circuit breaker’s specific temperature calibration term K_T .

This calibration term can be utilized to adjust all recorded MAX CURRENT readings to a standard temperature (T_{ref}) via an adjustment term computed as $K_T*(T_{ref} - T_{rec})$, where T_{rec} is the temperature registered during the circuit breaker’s switching operation.

This regression is possible only because of the decoupled and linear influence that both temperature and WIPE setting have on the OPEN and CLOSE actuator pulses (Ch. 7.2). It is noted that other MV circuit breakers might not exhibit such behavior.

Figure 8-8 graphically depicts how the temperature correction term is obtained at the beginning of the year after a year’s worth of data has been collected. The scenario assumes the following factors affect MAX CURRENT:

- Parameter is subject to an observed standard deviation $\sigma_{I_{MAX}} = 0.025$ (2.5%).
- Parameter increases at a rate of 0.0002 Amperes with each operation (normalized scale).
- Parameter shifts by 0.25% per °C.

In the figure, the top graph shows the temperature recorded during circuit breaker operation, the middle graph shows recorded MAX CURRENT for each operation, and the bottom graph is a plot of MAX CURRENT versus temperature with the inclusion of the abovementioned linear regression.

Once the equipment’s unique correction factor is known from the slope of the linear regression (calculated to be 0.25% in Figure 8-8), it can be used on the year’s worth of raw data in order to compute the “deterioration rate” that MAX CURRENT experienced throughout the year in a fashion identical to that described in the previous chapter (Ch. 8.3). The slope of this second linear regression will be the equipment’s observed deterioration rate (calculated to be 0.0002 in Figure 8-9).

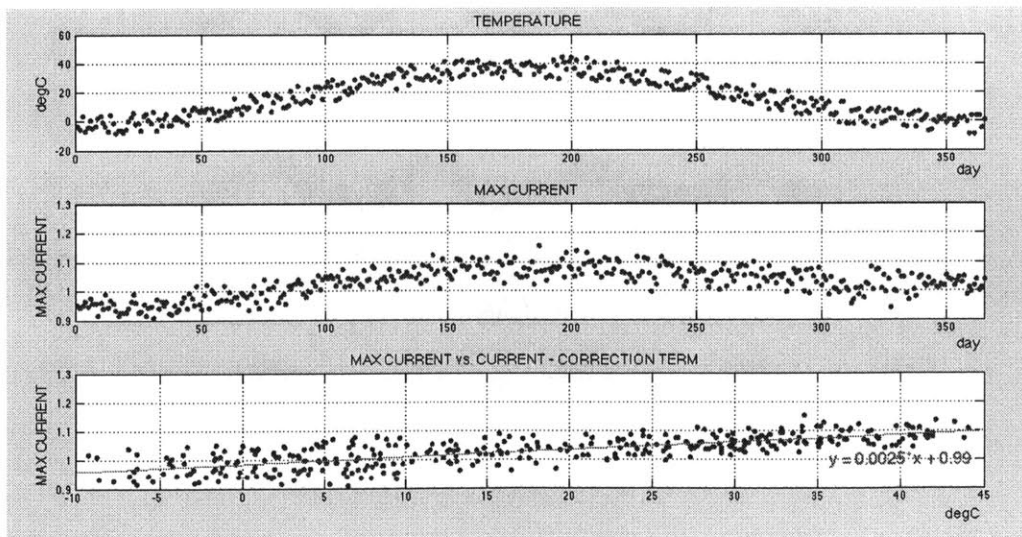


Figure 8-8: 365 Days of Temperature, I_{MAX} and Temperature Correction for I_{MAX}

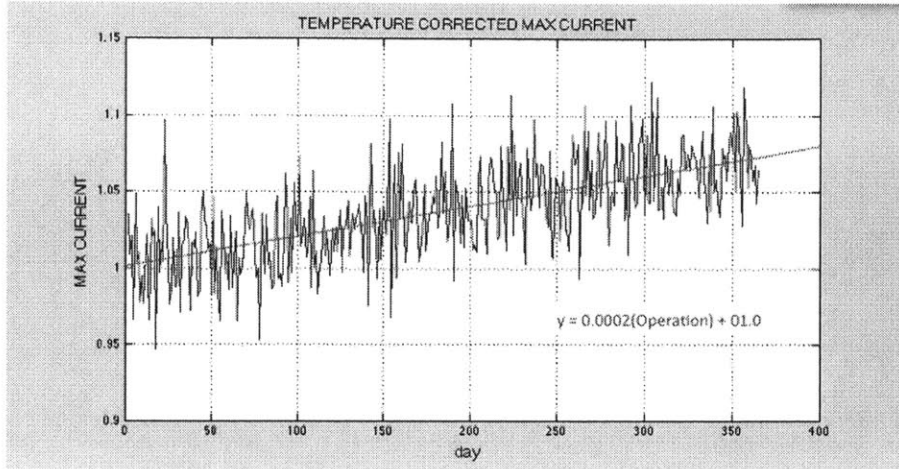


Figure 8-9: Temperature Corrected I_{MAX} & Deterioration Factor Linear Regression

These results, analogous to that observed in Ch. 8.3, are also prone to variability as depicted in Fig. 8-8 and Fig. 8-9. The temperature correction term's confidence is measured by $\sigma_T = 3.64\%$. Similarly, the equipment deterioration factor observes a $\sigma_D = 6.24\%$. Once again, these confidence measurements were computed from recreating the described scenario 1000 times and re-running the linear regressions through the data for each case.

Figure 8-10 shows the simulation results for the 1000 scenario cases in histogram format. The prediction variability for both the temperature correction and deterioration factor terms is directly tied to the observed parameter's variability.

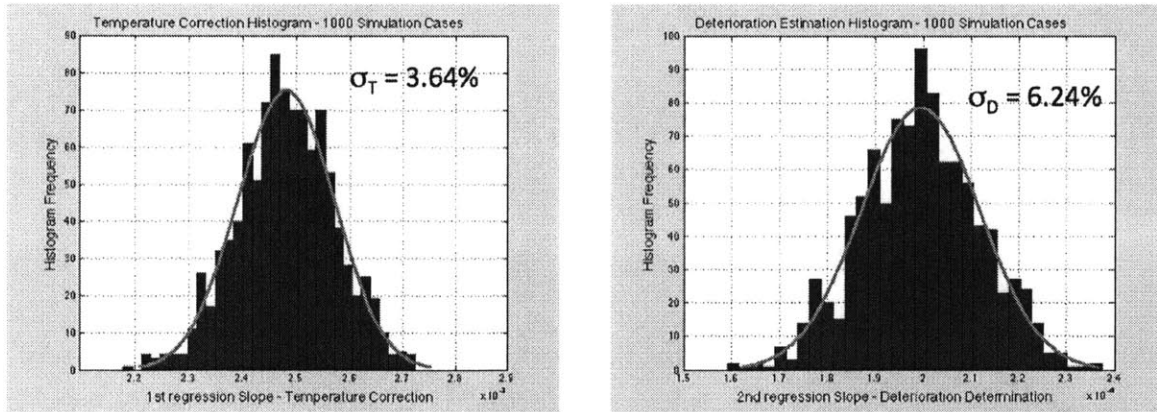


Figure 8-10: Temp. Correction and Deterioration Factor Accuracy Simulation Results

As noted at the beginning of this chapter, emphasis on respecting the data capture windows is important as deviations from the prescribed dates result in significant errors of up to $\pm 50\%$ (case dependent) as observed in Figure 8-11 (0.0013 or 0.0037 versus 0.0025). From the figure, the ideal dates to begin capturing data are late December – early January or late June – early July.

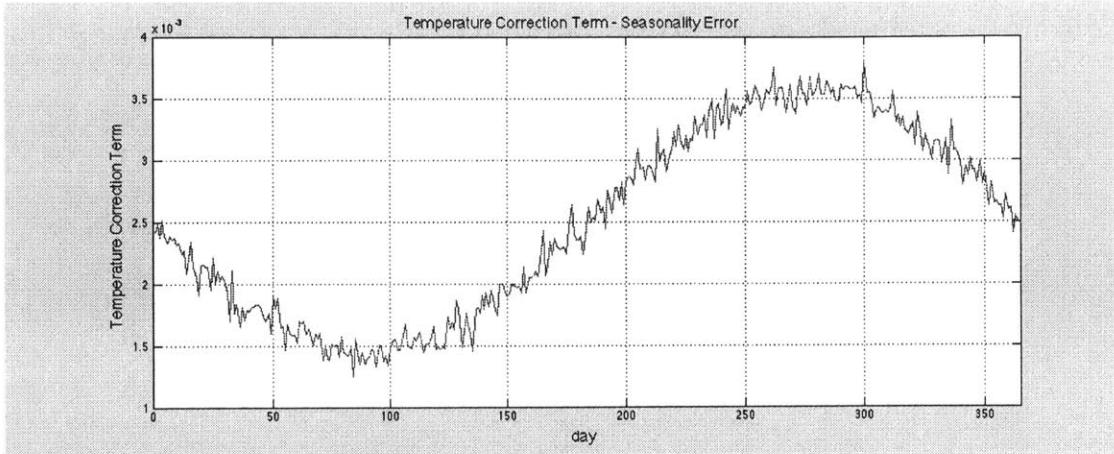


Figure 8-11: Temp. Correction Term as a Function of Data Gathering Window Start Date

The error introduced from computing the temperature correction term outside the prescribed windows stems from the distinct traces that MAX CURRENT has throughout the year. Figure 8-12 presents two examples of this²⁶: the plot on the left (accurate prediction of K_T) is representative of what would be expected when a year's worth of data is plotted early in January, whereas the plot on the right (grossly inaccurate prediction of K_T) is illustrative of what would be seen when the same amount of data is plotted early April.

The plots in Figure 8-12 visually describe the reason it is necessary to compute the temperature correction factor during the coldest or hottest months of the year (i.e., January or July)—it is only during these dates that the effects of temperature and deterioration rates on MAX CURRENT are graphically decoupled when performing the 1st linear regression to compute K_T .

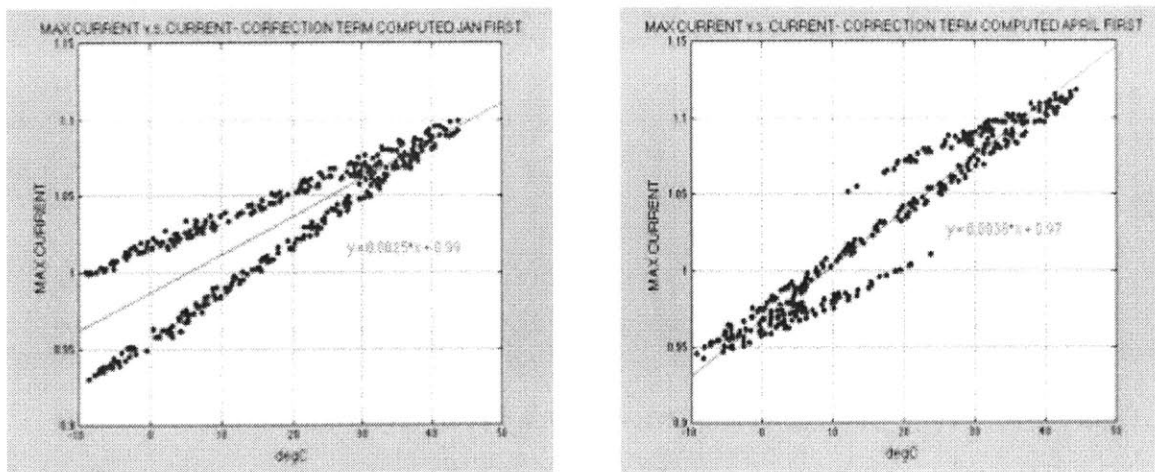


Figure 8-12: Temp. Correction Factor Time Window Computation Introduced Errors

²⁶ Scenario assumes MAX CURRENT experiences a deterioration rate of 0.0002 Amperes/operation (normalized) and shifts by 0.25%/°C. MAX CURRENT standard deviation was assumed to be negligible.

8.5 Deterioration Rate Estimation - Alternate Method

When equipment is not affected by temperature, or its influence is linear, the approach described in Ch. 8.3 and 8.4, provides an accurate means of computing the deterioration rate of parameters being monitored to assess long-term circuit breaker health. Recognizing, however, that the situation might arise where non-linearity exists, effort went into the development of an alternate method of estimating deterioration rates.

The main idea behind the method is to compare average machine behavior at two distinct points in time for which temperature mean and standard deviation are within a narrow range of each other, so that observed operating conditions between the two points are nearly identical. Computation of the mean and standard deviation describing the monitored parameters and temperature is based on the last 30 samples recorded during circuit breaker switching transitions.

Given the seasonality of temperature (Figure 8-7), and considering that the objective is to measure long-term rates of change, the method looks for a “temperature match” in a window spanning 320-410 days (Figure 8-13). Analysis of temperature patterns in the Continental United States found that a target mean temperature of 10°C ($\pm 2.5^{\circ}\text{C}$) gives a high probability of finding a matching pair for the analysis to take place²⁷.

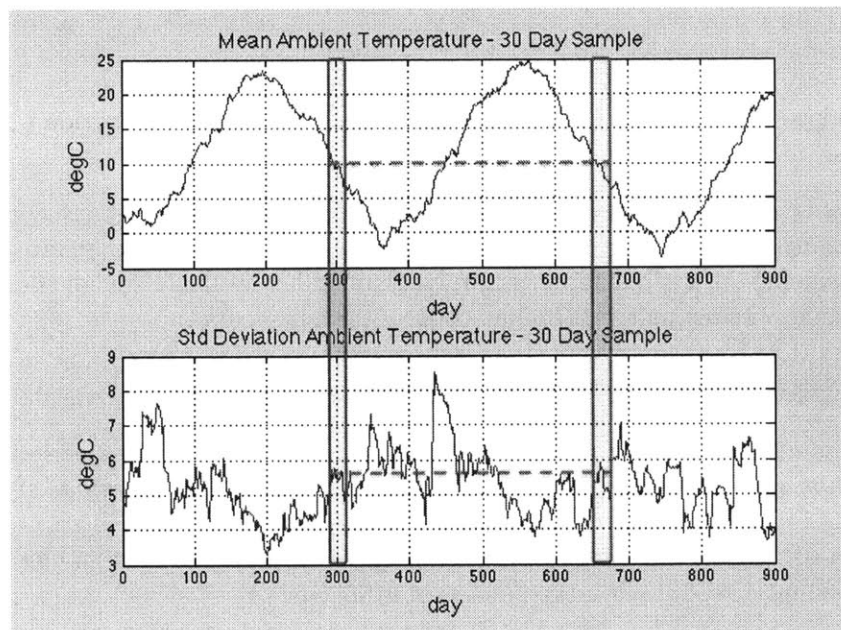


Figure 8-13: Average and Standard Deviation Temperature Match

Figure 8-14 shows the results of a simulation in which MAX CURRENT experiences a deterioration rate of 0.0002 Amperes per operation (normalized) and a temperature adjustment factor of 0.05 Amperes/ $^{\circ}\text{C}$. With these inputs, exaggerated in order to exemplify the method, a

²⁷ Conclusion reached after examination of hourly temperature patterns from 1990-2011 for Baltimore, Boston, Chicago, Colorado Springs, Houston, Los Angeles, Phoenix, Portland, Raleigh, San Francisco, and Seattle. Refer to code in Appendix A-10.3 for details on analysis.

deterioration rate of ≈ 0.00025 Amperes (normalized) is computed when comparing the mean MAX CURRENT readings between days 300 and 665.

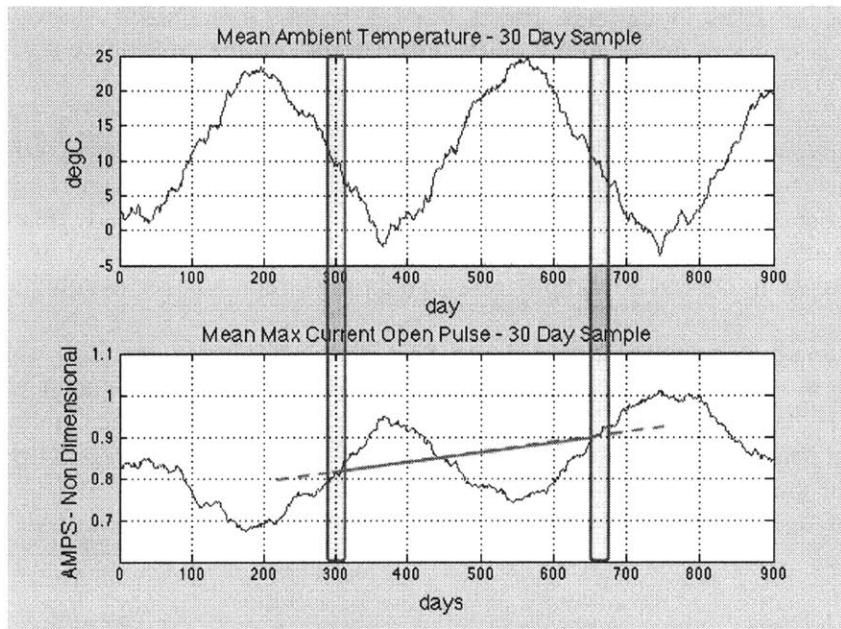


Figure 8-14: MAX CURRENT Deterioration Rate Visualization

Close inspection of the data shown in Figure 8-14 reveals that the method’s accuracy is poor. This is due to the variability in circuit breaker switching operations, and temperature itself. These factors are considered in a simulation constructed to further evaluate the method’s merit in regions with distinct weather patterns (Matlab code - Appendix A-10.3).

The model’s inputs and default values are the following:

- Hourly record of temperatures registered in a predetermined location for a period of 22 years. *Data was imported into Matlab from www.weathersource.com *.csv downloaded files.*
- A collection of magnetic actuator profiles (Figure 8-15) that reflect the variability observed during lab testing (Ch. 7.2). *These profiles were artificially constructed.*
- Variables (*time, len*) allow the user to determine the switching operation windows for OPEN and CLOSE operations. *The model is currently setup to randomly exercise the circuit breaker between 6:00-9:00 AM and 5:00-8:00 PM²⁸ each day.*
- Variables (*OMODrate, CMODrate, OMOT, CMOT*) allow adjusting the rates of deterioration and the impact of temperature on circuit breaker operation. *MAX CURRENT deterioration factor set to 0.0002 & 0.0001 (OPEN & CLOSE) Amperes/Operation and temperature adjustment set to 0.0025 Amperes/°C.*

²⁸ Times set to fit with typical electrical load curves.

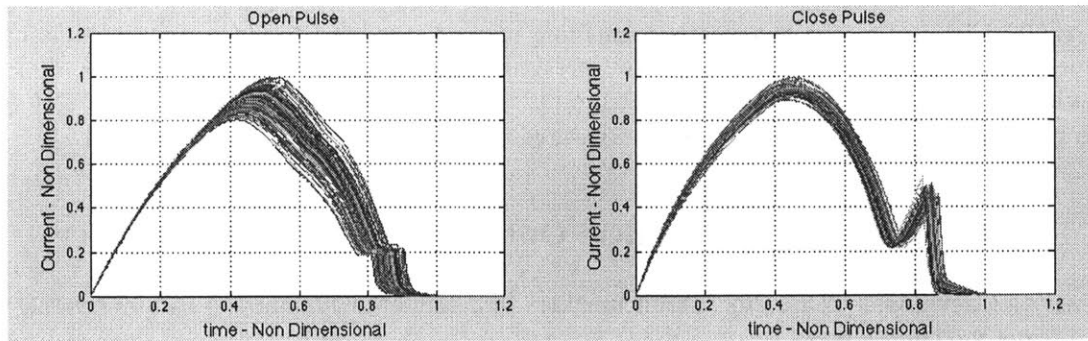


Figure 8-15: Collection of Simulated Magnetic Actuator Profiles - Equipment Variability

Figure 8-16 shows the simulation results for the city of Boston. The plot depicts both OPEN and CLOSE computed MAX CURRENT deterioration factors, computed yearly, over a time-span of 22 years. Although subject to considerable accuracy errors ($\pm 30\%$), results show that the method computes deterioration rates that resemble the 0.0002 & 0.0001 (OPEN & CLOSE) Amperes/Operation assumed in the simulation.

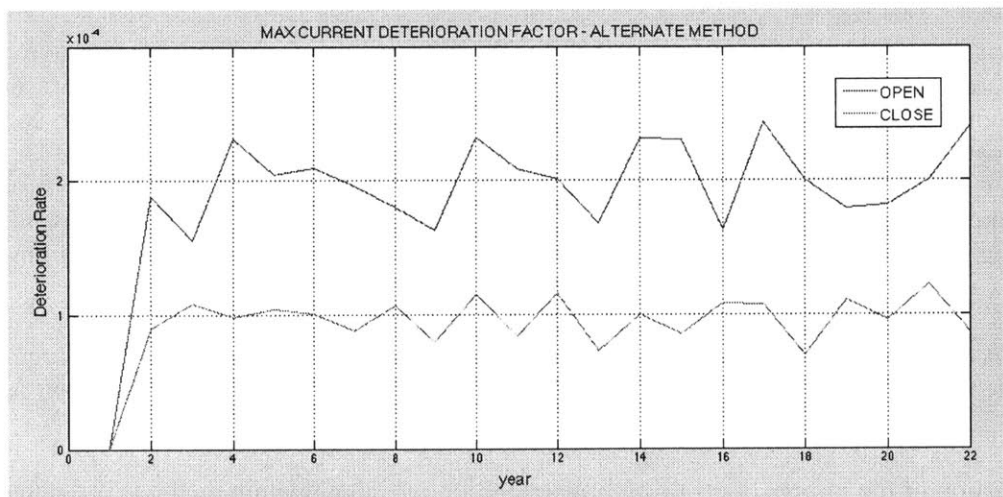


Figure 8-16: Deterioration Rate - Alternate Temperature Correction Simulation Results

Even though the use of deterioration rates computed with the alternate method is not as straightforward as those computed with the first method presented in Ch. 8.4, it is important to point out that the alternate method is not limited to equipment characterized by linear behavior. While yet imprecise, the alternate method does have the capability to detect fleet outliers, i.e., equipment experiencing advanced deterioration issues.

Although eliminating non-linear interactions is infeasible, mitigation of their influence is possible by maintaining the narrow temperature range over which operation comparisons are performed. The expectation is that quasi-linear behavior in this range will occur and that the two selected points will represent nearly identical operational realities.

As a result of its design, the temperature matching method is subject to not finding comparable conditions in the 320-410 day 'window' prescribed. However, experience gained during evaluation of the method shows that this situation is rare (less than 1%), and thus not a source for concern if utilized across a fleet of reactor switching circuit breakers.

8.6 Reactor Switching Mechanical Operation Analytics - Summary

The analytics developed to monitor circuit breakers in a reactor switching application operate at three distinct temporal levels:

- Individual operations are controlled for minimum acceptable behavior. For this to happen, magnetic actuator pulse defining features are expected to fall within a strike zone.
- Behavioral shifts and short-term trend analysis are possible as each individual operation is placed in the context of the past 30 operations with data presented in strip-chart format.
- Yearly long-term ageing trends and fleet analysis prioritization are possible by looking at the observed rates of change in the actuator's pulse defining features; these rates of change are coined "deterioration rates".

Given that the 15 kV circuit breaker utilized for the pilot program exhibits linear behavior with temperature, the deterioration rate computation is based on two linear regressions: one to calculate the equipment's thermal correction factor (utilized if needed), and a second to compute the parameter's rate of change.

Development of an alternate method for computing deterioration rates offers the capability of computing approximate deterioration levels without the need for temperature corrections. The method is also compatible with equipment that observes non-linear behavior.

The framework for long-term analytics is in place and deployed as part of the pilot program. A down-selection of the most adequate parameters to monitor ageing and health risks will require examination of a year's worth of data in 2014.

An evaluation of the effectiveness of both deterioration rate computation methods presented will also need to take place in 2014.

9 SUMMARY AND CONCLUSIONS

This project, developed in the context of an *Accelerated Proof of Concept Team*, looked at the challenge of M&D for medium voltage circuit breakers from a technical and financial perspective, and developed a feasible solution.

9.1 Background Information

Important elements of the development process were to understand equipment failure rates, associated failure modes, the impact to utility customer operations when the equipment fails, and the present and future landscape of smart-grid and M&D applications (Ch. 1-5).

The main findings from the abovementioned research are the following:

- Medium voltage circuit breakers observe a yearly failure rate of 2-5%.
- The leading failure mode for medium voltage circuit breakers is mechanical degradation.
- The U.S. medium voltage CB fleet is beginning to show higher failure rates due to old age.
- Market opportunity is large as there are 60,000 MV distribution substations in the U.S.
- Technology and required infrastructure for smart-grid M&D applications exists.
- A fragmented and uncertain policy landscape is a major hurdle for the development and adoption of new technologies in the utility sector.

9.2 M&D System Design and Integration

Examination of current maintenance practices, sensing technology, and academic work in the arena of circuit breaker analytics, led the development team to select interrupter temperature and mechanical actuation profiling as a means to diagnose impending equipment health problems (Ch. 6).

The expectation for these monitoring techniques, with associated analytics, is to reduce impending failure rates by as much as 40-60% and do so with a system that will pay for itself in 0-7 years when utilized in a typical utility environment. The integrated system is capable of monitoring a wide range of medium voltage circuit breakers.

The developed system, currently deployed in a pilot demonstration program as part of a fleet of six reactor-switching 15 kV circuit breakers, incorporates analytics tailored to provide mechanical operation monitoring and trending capability specific to the high use rate expected from the equipment (Ch. 8). The analytical framework presented is the result of ABB expertise and extensive laboratory testing (Ch. 7) that successfully characterized the equipment's behavior with temperature and interrupter condition.

9.3 Key Findings

The most important finding that this work has to offer is that the development of cost effective M&D systems for monitoring MV circuit breakers is possible and makes good business sense. Furthermore, it is the author's impression that the demand for such systems is beginning to reveal itself amongst utility customers.

Other important findings are:

- The methodology followed in the development of an M&D solution for MV circuit breakers provides a blueprint for future product development across distinct MV product lines.
- M&D systems have the capability of providing currently nonexistent reliability information.
- Perfection of analytics for MV circuit breakers will require several years of data collection given the industry-wide lack of information.
- Information rich environments offered by widespread adoption of M&D systems will enable utilities to shift towards more cost-effective service contracts with their OEM suppliers.

9.4 Future Challenges and Research Opportunities

The utility space is a segment that, when compared to other technologically driven sectors, has lagged in the development of highly integrated systems (e.g., auto industry).

The onset of smart-grid challenges the industry to manage a degree of complexity previously nonexistent and still not acknowledged throughout the sector. A better understanding of the changes required, in order to meet the opportunities smart-grid has to offer, is an area of research that could have tremendous impact.

One such opportunity is the development of integrated M&D applications—solutions that span multiple products and share common platforms. Research topics in this domain include:

- Understanding the impact on service reliability, day-day utility operations, and overall financial impact that integrated M&D platforms could have.
- Developing the analytic capability that will allow utility customers to synthesize massive amounts of information from multiple sources in order to improve operations.
- Providing the organizational framework that will drive cultural change and allow teams to engineer highly integrated systems.
- Proposing policy that will favor the development of integrated practices across the industry.

These areas of research are an extension of the work developed in this thesis

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10 APPENDIX A – MATLAB CODE

10.1 MV Breaker Survivability Study

User Notes:

- The code requires the user provide the profile information for the five survivability traces depicted in Figure 3-4 into variables PROF01 through PROF05 and stored in a file named PROF.mat.
- Model inputs described in Ch. 3.4.

```
%Survivor Curve Code

close('all'); clear; load PROF;

year(1:5,1:80) = 0;      % 80 year worth of data - X axis
equipAvgFitYr(1:79) = 0; % Array for Average & Computed Fit Trace
fitMult=1;              % Average Fit Trace Multiplier

% Read Profiles provided in PROF.mat file
while sum(equipAvgFitYr) < 100

    for i=1:80
        year(:,i) = i-1;
        equip(1,i) = min(100,max(0,interp1(PROF01(:,1),PROF01(:,2),year(1,i),...
            'linear','extrap'))));
        equip(2,i) = min(100,max(0,interp1(PROF02(:,1),PROF02(:,2),year(2,i),...
            'linear','extrap'))));
        equip(3,i) = min(100,max(0,interp1(PROF03(:,1),PROF03(:,2),year(3,i),...
            'linear','extrap'))));
        equip(4,i) = min(100,max(0,interp1(PROF04(:,1),PROF04(:,2),year(4,i),...
            'linear','extrap'))));
        equip(5,i) = min(100,max(0,interp1(PROF05(:,1),PROF05(:,2),year(5,i),...
            'linear','extrap'))));
        equipAvg(i) = sum(equip(:,i))/5;
        equipAvgFit(i) = min(100,max(0,0.012705*i^2 - 2.2326*i + 96.039));
    end

    for i=1:79
        equipAvgFitYr(i) = (equipAvgFit(i)-equipAvgFit(i+1))*fitMult;
    end

    fitMult = 100/sum(equipAvgFitYr);
end

% Bathtub Failure Rate Data
failRateZero = 0.05; % Initial Failure Rate
baseFailRate = 0.034; % Normal Failure Rate (post infant mortality phase).
failRateAdj = 0.05; % Yearly Failure Rate Increase (Ageing Effect)
failShift = 25; % Year at which Ageing Effect Begins to be Felt.

failRateAdjMD = 0.05; % Yearly Failure Rate Increase observed with M&D
effMD = 0.5; % Overall M&D Failure Rate Mitigating Impact
```

```

% MV Fleet yearly growth
growth = 0.01;

% Compute Failure Rate as a function of year given bathtub characteristics.
j=1;
for i=1:80
    if i==1
        failRate(i) = failRateZero;
        failRateMD(i) = failRate(i) - baseFailRate*(1-effMD);
    elseif i>1 && i<=4
        failRate(i) = failRate(i-1)-(failRateZero-baseFailRate)/3;
        failRateMD(i) = failRate(i) - baseFailRate*(1-effMD);
    elseif i>4 && i<=failShift
        failRate(i) = baseFailRate;
        failRateMD(i) = failRate(i)*(1-effMD);
    elseif i>25 && i <= 40
        failRate(i) = baseFailRate*(1+failRateAdj)^j;
        failRateTMP = baseFailRate*(1+failRateAdjMD)^j;
        failRateMD(i) = failRateTMP*(1-effMD);
        j=j+1;
    else
        failRate(i) = failRate(i-1);
        failRateTMP = baseFailRate*(1+failRateAdjMD)^j;
        failRateMD(i) = min(failRateTMP*(1-effMD),failRate(i));
        j=j+1;
    end
end
% Plot Failure Rate Curve - Bathtub Shape
figure; plot(failRate); hold; plot(failRateMD,'r'); grid;
xlabel('year'); ylabel('failure rate'); legend('base','MD');

% Compute Simulated Baseline and M&D Survivability Curves
for i=1:80
    if i==1
        simPop(i) = 100*(1-failRate(i)+growth);
        simPopMD(i) = 100*(1-failRateMD(i)+growth);
    else
        simPop(i) = simPop(i-1)*(1-failRate(i)+growth);
        simPopMD(i) = simPopMD(i-1)*(1-failRateMD(i)+growth);
    end
end

% Plot Results
figure; plot(year',equip','--'); hold;
plot(year(1,:),equipAvg(:),'k','linewidth',4);
plot(year(1,:),equipAvgFit(:),'r--','linewidth',2);
plot(year(1,:),simPop(:),'b--','linewidth',4);
plot(year(1,:),simPopMD(:),'g--','linewidth',4);
grid; xlabel('year'); ylabel('% age or older');

figure; plot(year',1-equip'/100,'--'); hold;
plot(year(1,:),1-equipAvg(:)/100,'k','linewidth',4);
plot(year(1,:),1-equipAvgFit(:)/100,'r--','linewidth',4);
plot(year(1,:),1-simPop(:)/100,'b--','linewidth',4);
plot(year(1,:),1-simPopMD(:)/100,'g--','linewidth',4);
grid; xlabel('year'); ylabel('%Failure/Retirement Cumulative Dist');

```

10.2 MV Breaker Cost & Savings Model

User Notes:

- Model inputs described in Ch. 5.2.1 and Ch. 5.2.2.

```
% BreakerMD Business Case Simulator

clear; clc; close('all'); fclose('all');
%*****
% MODEL INPUTS
%*****
for j=1:14

    %Sensibility Analysis
    sens(1:13) = 0;
    if j==2
        sens(2) = 1;    %Labor Rate Increase (yr)
    elseif j==3
        sens(3) = 1/60; %Downtime Increase of (hr)
    elseif j==4
        sens(4) = 0.001; %Failure Increase
    elseif j==5
        sens(5) = 0.01; %Failure Rate Increase
    elseif j==6
        sens(6) = 1000; %Outage/Damage Cost Increase
    elseif j==7
        sens(7) = 0.01; %Failures Resulting in Outage Increase
    elseif j==8
        sens(8) = 0.01; %Failures Equipment Replacement Increase
    elseif j==9
        sens(9) = 0.01; %Decrease of On Site Time
    elseif j==10
        sens(10) = 0.01; %Increase in Monitoring Effectiveness
    elseif j==11
        sens(11) = -1;    %Ops Learning Curve Increase (yr)
    elseif j==12
        sens(12) = -1;    %Analytics Learning Curve Increase (yr)
    elseif j==13
        sens(13) = -1;    %Deployment Learning Curve Increase (yr)
    end

    % Baseline information
    %*****

    % Labor Costs
    labor = 100+sens(2); % Labor Rate USD
    workers = 1.6; % Number of Technicians

    % Breaker Equipment Cost
    cbCost = 20000; % USD

    % Failure Outage Costs
    failCost = 25000+sens(6); % Outage Failure Costs
    failDur = 1; % Outage Duration (hr)
    failOut = 1+sens(7); % Per of failures resulting in Outage
    failRep = 1+sens(8); % Per of failures resulting in Eq. repl

    % Maintenance Costs
    downTime = 2+sens(3); % Yearly Down Time (hr) Sched Maintenance
```

```

travelLog = 1; % Travel and Log to support Maintenance (yearly hr)
failTime = 36; % Avg unscheduled maint hours per failure (hrs)
%Failure Rate information
rate0 = 0.0334+sens(4); % Initial failure rate
rateD = 0.05+sens(5); % Yearly failure rate increase

% MD information
%*****
downRed = 0.25+sens(9); % Percent reduction in Hours Down
monitEff = 0.5+sens(10); % Monitoring Effectiveness (Rel impr)
opsLearn = 7+sens(11); % Operations Learning Curve (yr)
deployDur = 4+sens(13); % Deployment Duration Time (yr)
trainDur = 5+sens(12); % Analytics training Duration Time (yr)
installTime = 2; % M&D Equipment Installation Time (hr)

outTimeDec = 0; % Unplanned Outage Time decrease (min)
divMaintGain = 0; % Diverted Maint Outage Gains x hr (Inc in rel)

costMD = 2500; % MD upfront cost
servMD = 200; % MD service cost

addSave = 0; % Additional Savings x Year

defFlg = 0; % Include deferral in Analysis (0=FALSE,1=TRUE)
defReplTime = 5; % Deferral replacement time (Yr)
depFlg = 0; % Include depreciation in Analysis (0=FALSE,1=TRUE)
depLenYr = 30; % Depreciation Time

% Model Run Information
%*****
dur = 10; % Analysis duration (Yr)

infl = 0.02; % Inflation
laborDisc = 0.03; % Labor Discount Factor
eqDisc = 0.03; % Equipment Discount Factor
outDisc = 0.03; % Outage Discount Factor
capDisc = 0.03; % Cost of capital
mdDisc = 0.03; % MD Investment Discount Factor

%*****
% COMPUTATIONS
%*****

for i=1:dur

    % Discount & Inflation Multipliers
    % Assumption is that prices will follow inflation.
    % NPV calculation based on discount factor (30yr bonds)
    laborAdj(i) = ((1+infl)^i)/((1+laborDisc)^i);
    eqAdj(i) = ((1+infl)^i)/((1+eqDisc)^i);
    outAdj(i) = ((1+infl)^i)/((1+outDisc)^i);
    MDAdj(i) = ((1+infl)^i)/((1+mdDisc)^i);

    % Failure Rate Over Time
    if i==1
        rate(i) = rate0*(1+rateD);
    else
        rate(i) = rate(i-1)*(1+rateD);
    end

    if i > defReplTime && (defFlg + depFlg) > 0
        if i == defReplTime + 1

```



```

        rate(i) = 0.05;
    elseif i == defReplTime + 2
        rate(i) = 0.038;
    else
        rate(i) = rate0;
    end
end

end

%*****
% Baseline Costs
%*****

% Maintenance Costs
maintCost(i) = laborAdj(i)*(labor*workers*...
                (downTime+travelLog) + (labor*failTime*rate(i)));

% CB Replacement Costs
replCost(i) = eqAdj(i)*cbCost*rate(i)*failRep;

% Outage Costs
outCost(i) = outAdj(i)*failCost*rate(i)*failOut;

% Opportunity Cost For Diverted Maintenance (Tentative)
divMaintCost(i) = laborAdj(i)*divMaintGain*downTime;

% Total Cost
totCost(i) = maintCost(i) + divMaintCost(i) + ...
             replCost(i) + outCost(i);

%*****
% BreakerMD System Costs
%*****

% MD Ops Learning Curve
if i<opsLearn
    opsCrv(i) = 1 - i*downRed/opsLearn;    % Ops Learning Curve
    downRedMin(i) = outTimeDec*i/opsLearn; % Downtime red (min)
else
    opsCrv(i) = 1 - downRed;              % Ops Learning Curve
    downRedMin(i) = outTimeDec;           % Downtime red (min)
end

%Downtime and travel are impacted by Operation Curve
downHr(i) = downTime*opsCrv(i);
travelHr(i) = travelLog*opsCrv(i);

% Statistics Learning Curve
if i<trainDur
    trainCrv(i) = 1 - i*monitEff/trainDur;
else
    trainCrv(i) = 1 - monitEff;
end

% Install Time Curve
if i<=deployDur
    deployCrv(i) = i/deployDur;           % Per Deployed
    purchCrv(i) = 1/deployDur;           % Per Purchased
    installCrv(i) = installTime/deployDur; % Per Install Time
else
    deployCrv(i) = 1;                    % Per Deployed
    purchCrv(i) = 1;                    % Per Purchased
end

```

```

        installCrv(i) = 0;                                % Per Install Time
    end

    % Failure Rate: a function of deployment and analytics learning
    rateMD(i) = rate(i)*(1-(1-trainCrv(i))*deployCrv(i));

    %MD Cost Calculations
    maintCostMD(i) = laborAdj(i)*(labor*workers*(downHr(i)+...
        travelHr(i) + installCrv(i)) + (labor*failTime*rateMD(i)));

    % CB Replacement Costs
    replCostMD(i) = eqAdj(i)*cbCost*rateMD(i)*failRep;

    % Outage Time Reduction (Part of Outage Cost Calculation)
    outTimeRedMD(i) = outAdj(i)*rateMD(i)*failOut*...
        failCost*downRedMin(i)/(failDur*60);

    % Outage Costs
    outCostMD(i) = outAdj(i)*failCost*rateMD(i)*...
        failOut-outTimeRedMD(i);

    % Opportunity Cost For Diverted Maintenance (Tentative)
    divMaintCostMD(i) = laborAdj(i)*divMaintGain*...
        (downHr(i)+installCrv(i));

    % Total Cost
    totCostMD(i) = maintCostMD(i)+divMaintCostMD(i)+...
        replCostMD(i)+outCostMD(i);

    % Saving Calculations
    maintSavMD(i) = maintCost(i) - maintCostMD(i);      %Maintenance

    %Replacement Savings - includes deferred and depreciation
    if i < defReplTime
        if i==1
            deferralSav(i) = ((cbCost*((1+capDisc)^i) - ...
                cbCost*((1+infl)^i)) ...
                / ((1+capDisc)^i));
        else
            deferralSav(i) = ((cbCost*((1+capDisc)^i) - ...
                cbCost*((1+infl)^i)) ...
                / ((1+capDisc)^i)) ...
                - sum(deferralSav(1:i-1));
        end
        depSavings(i) = (cbCost/depLenYr)*((1+infl)^i) ...
            / ((1+capDisc)^i);
    else
        deferralSav(i) = 0;
        depSavings(i) = 0;
    end

    replSavMD(i) = replCost(i) - replCostMD(i) + ...
        (deferralSav(i) + depSavings(i)*depFlg)*defFlg;

    outSavMD(i) = outCost(i) - outCostMD(i);            %Outage
    divMaintSavMD(i) = divMaintCost(i) - divMaintCostMD(i); %Divert
    addSavMD(i) = MDAAdj(i)*addSave*deployCrv(i);      %Additional

    % Aggregated Costs & Savings
    if i==1
        %Base
        maintCostTot(i) = maintCost(i);                %Maintenance
        replCostTot(i) = replCost(i);                  %Replacement
        outCostTot(i) = outCost(i);                    %Outage
    end

```

```

divMaintCostTot(i) = divMaintCost(i);    %Diverted
baseCost(i) = maintCostTot(i)+replCostTot(i)+... %Tot Cost
            divMaintCostTot(i)+outCostTot(i);

%BreakerMD
maintCostMDTot(i) = maintCostMD(i);      %Maintenance
replCostMDTot(i) = replCostMD(i);       %Replacement
outCostMDTot(i) = outCostMD(i);         %Outage
divMaintCostMDTot(i) = divMaintCostMD(i); %Diverted
%Total Cost MD
baseCostMD(i) = maintCostMDTot(i)+replCostMDTot(i)+...
            divMaintCostMDTot(i)+outCostMDTot(i);

%Savings MD
maintSavTot(i) = maintSavMD(i);          %Maintenance
replSavTot(i) = replSavMD(i);           %Replacement
outSavTot(i) = outSavMD(i);             %Outage
divMaintTot(i) = divMaintSavMD(i);      %Diverted Maint
addSavTot(i) = addSavMD(i);             %Additional
%Total Savings
totSavMD(i) = maintSavMD(i) + replSavMD(i) + ...
            divMaintSavMD(i) + outSavMD(i) + addSavMD(i);
else
    %Base
    maintCostTot(i) = maintCostTot(i-1) + maintCost(i);
    replCostTot(i) = replCostTot(i-1) + replCost(i);
    outCostTot(i) = outCostTot(i-1) + outCost(i);
    divMaintCostTot(i) = divMaintCostTot(i-1)+divMaintCost(i);
    %Total Cost
    baseCost(i) = maintCostTot(i)+replCostTot(i)+...
                divMaintCostTot(i)+outCostTot(i);

    %BreakerMD
    maintCostMDTot(i) = maintCostMDTot(i-1) + maintCostMD(i);
    replCostMDTot(i) = replCostMDTot(i-1) + replCostMD(i);
    outCostMDTot(i) = outCostMDTot(i-1) + outCostMD(i);
    divMaintCostMDTot(i) = divMaintCostMDTot(i-1)...
                        + divMaintCostMD(i);

    %Total Cost
    baseCostMD(i) = maintCostMDTot(i)+replCostMDTot(i)+...
                divMaintCostMDTot(i)+outCostMDTot(i);

    %Savings MD
    maintSavTot(i) = maintSavTot(i-1) + maintSavMD(i);
    replSavTot(i) = replSavTot(i-1) + replSavMD(i);
    outSavTot(i) = outSavTot(i-1) + outSavMD(i);
    divMaintTot(i) = divMaintTot(i-1) + divMaintSavMD(i);
    addSavTot(i) = addSavTot(i-1) + addSavMD(i);
    %Total Savings
    totSavMD(i) = maintSavMD(i) + replSavMD(i) + ...
                divMaintSavMD(i) + outSavMD(i) + addSavMD(i) ...
                + totSavMD(i-1);
end

%MD System Cost to Customer: looking at
%initial purchase and service fee
if purchCrv(i) < 1
    MDCOST(i) = MDAdj(i)*(servMD*deployCrv(i)+(purchCrv(i) +...
                rateMD(i)*failRep*costMD);
else
    MDCOST(i) = MDAdj(i)*(servMD*deployCrv(i)+...
                rateMD(i)*failRep*costMD);
end

%MD Aggregate Costs to Customer

```

```

        if i==1
            MDCOSTTOT(i) = MDCOST(i);
        else
            MDCOSTTOT(i) = MDCOSTTOT(i-1) + MDCOST(i);
        end
    end

    if j==1
        %Memory Holder for Sensibility Analysis
        totSavMDo = totSavMD(dur);

        %RESULTS
        figure;
        plot(totSavMD,'k'); hold; plot(MDCOSTTOT,'r'); grid;
        plot(maintSavTot,'b--');
        plot(replSavTot,'m--');
        plot(outSavTot,'g--');
        plot(addSavTot,'y--');
        plot(divMaintTot,'c--');
        title('Breaker MD Costs & Savings Model');
        xlabel('yr'); ylabel('$');
        legend('TOT SAVINGS','MD SYSTEM COST','Labor savings',...
            'Repl. savings','Outage savings','Additional savings',...
            'Diverted maint savings');

        figure;
        plot(totCost,'k'); hold; plot(totCostMD+MDCOST,'r'); grid;
        title('Baseline vs. BreakerMD Yearly Expenditure - NPV');
        xlabel('yr'); ylabel('$'); legend('Baseline','BreakerMD');

        figure;
        plot(baseCost,'k'); hold; plot(baseCostMD+MDCOSTTOT,'r'); grid;
        title('Baseline vs. BreakerMD Total Accumulated Expenditure');
        xlabel('yr'); ylabel('$'); legend('Baseline','BreakerMD');

    else
        saveDelta(j-1) = totSavMD(dur)-totSavMDo;
    end
end

end

% Sensitivity Analysis Results
%*****
sens(2) = 1;      %Labor Rate Increase (yr)
sens(3) = 1;     %Downtime Increase of (hr)
sens(4) = 0.001; %Failure Increase
sens(5) = 0.01;  %Failure Rate Increase
sens(6) = 1000;  %Outage/Damage Cost Increase
sens(7) = 0.01;  %Failures Resulting in Outage Increase
sens(8) = 0.01;  %Failures Equipment Replacement Increase
sens(9) = 0.01;  %Decrease of On Site Time
sens(10) = 0.01; %Increase in Monitoring Effectiveness
sens(11) = -1;   %Ops Learning Curve Increase (yr)
sens(12) = -1;   %Analytics Learning Curve Increase (yr)
sens(13) = -1;   %Deployment Learning Curve Increase (yr)

fprintf('\n\n');
fprintf('Sensibility Analysis: Impact on Total Savings \n\n');
fprintf('Labor Rate Increase of      %0.4f USD => %0.3f USD\n',...
    sens(2),saveDelta(1));
fprintf('Down Time Increase of        %0.4f min => %0.3f USD \n',...
    sens(3),saveDelta(2));
fprintf('Failure Increase of            %0.4f per => %0.3f USD \n',...

```

```

    sens(4),saveDelta(3));
fprintf('Failure Rate Increase of    %0.4f per => %0.3f USD \n',...
    sens(5),saveDelta(4));
fprintf('Outage Cost Increase of    %0.1f USD => %0.3f USD \n',...
    sens(6),saveDelta(5));
fprintf('Failure Outage Inc of      %0.4f per => %0.3f USD \n',...
    sens(7),saveDelta(6));
fprintf('Failure Equip Repl Inc of  %0.4f per => %0.3f USD \n',...
    sens(8),saveDelta(7));
fprintf('Decrease on site time of   %0.4f per => %0.3f USD \n',...
    sens(9),saveDelta(8));
fprintf('Increase of monitoring eff %0.4f per => %0.3f USD \n',...
    sens(10),saveDelta(9));
fprintf('Ops Learning Curve Incr    %0.3f hr  => %0.3f USD \n',...
    sens(11),saveDelta(10));
fprintf('Analytics Curve Incr       %0.3f hr  => %0.3f USD \n',...
    sens(12),saveDelta(11));
fprintf('Deployment Curve Incr       %0.3f hr  => %0.3f USD \n',...
    sens(13),saveDelta(12));
fprintf('\n\n');

```

10.3 Deterioration Rate Estimation - Alternate Method Simulation

User Notes:

- Simulation requires hourly temperature for a timespan of 22 years to be stored in DATA.mat variable TEMP of size 1 x 192840. Information downloadable from www.weathersource.com in *.csv format.
- Also required are OPEN and CLOSE magnetic actuator profiles. Code expects this information to reside in OPEN_PROF_ADIM.mat and CLOSE_PROF_ADIM.mat files. Each of these data files contains one hundred pulses that capture the pulse variability expected for the circuit breaker make-model considered (Figure 8-15). Time and amplitude information (x and y axes) is contained in 601 x 100 arrays (timeOpenSim, currOpenSim, timeCloseSim, and currCloseSim).
- Other model inputs described in Ch. 8.5.

```
clc; clear; close('all');
load DATA; % Contains Hourly Temperature Information 1990-2011.

% Analysis Control Variables
time=[6,17]; %Approx Times in the day when CB will operate - 24hr scale
len=[3,3]; %Window in hrs for CB operation from above "time" variable
tempLow = 45.5; %Lowest acceptable temperature (degF) for analysis
tempHigh = 54.5; %Highest acceptable temperature (degF) for analysis

%Deterioration Rate Definitions
OMODrate = 0.00005; %Open Max Current Deterioration Rate
OMTDrate = 0.000004; %Open Max Time Deterioration Rate
OETDrate = 0.000008; %Open Max Time Deterioration Rate

CMODrate = 0.0001; %Close Max Current Deterioration Rate
CMTDrate = 0.000005; %Close Max Time Deterioration Rate
OETDrate = 0.000010; %Open Max Time Deterioration Rate

OMOT = 0.001; %Open Max Current Temperate Multiplier (Non Dimensional/degC)
CMOT = 0.001; %Close Max Current Temperate Multiplier (Non Dimensional/degC)

% Data Storage Variable Initialization
tempReg = zeros(2,30);
tempHistReg = zeros(2,8001,30);
tempMean = zeros(2,8001,1);
tempStd = zeros(2,8001,1);
currMaxHist = zeros(2,8001,30);
timeMaxHist = zeros(2,8001,30);
timeEndHist = zeros(2,8001,30);

% Conduct two loops for OPEN & CLOSE Daily Operations - Reactor Switching
for I=1:length(time)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Initialize year information
dataYear = zeros(22,365*24);
leapYear = zeros(5,24);
hour = 0; day=1; year=1990; yrHr = 1; leap=0;
```

```

% Load Profile Information and determine MAX CURRENT, MAX TIME, END TIME
load OPEN_PROF_ADIM %Contains Adimensional Open Pulse Trajectories
for i=1:100
    for j=2:600
        if currOpenSim(j,i) == max(currOpenSim(:,i))
            currOpenMax(i) = currOpenSim(j,i);
            timeOpenMax(i) = timeOpenSim(j,i);
            maxOpenPos(i) = j;
        end
    end

    for j=maxOpenPos(i):600
        if currOpenSim(j-1,i) < 0.005
            timeOpenEnd(i) = timeOpenSim(j,i);
            break
        end
    end
end

% Load Profile Information and determine MAX CURRENT, MAX TIME, END TIME
load CLOSE_PROF_ADIM %Contains Adimensional Close Pulse Trajectories
for i=1:100
    for j=2:900
        if currCloseSim(j,i) == max(currCloseSim(:,i))
            currCloseMax(i) = currCloseSim(j,i);
            timeCloseMax(i) = timeCloseSim(j,i);
            maxClosePos(i) = j;
        end
    end

    for j=maxClosePos(i):900
        if currCloseSim(j-1,i) < 0.005
            timeCloseEnd(i) = timeCloseSim(j,i);
            break
        end
    end
end

% Map 1D TEMP array to a 2D array dataYear variable | Ignore Leap Years
for i=1:length(TEMP)

    % MAP HOURLY DATA TO A YEAR SQUARE MATRIX - IGNORE LEAP DAYS
    if year==1992 | year==1996 | year==2000 | year==2004 | year==2008
        if day == 60
            if hour == 0
                leap = leap + 1;
            end
            leapYear(leap,hour+1) = TEMP(i);
        else
            if day > 60
                dataYear(year-1989,yrHr-24) = TEMP(i);
            else
                dataYear(year-1989,yrHr) = TEMP(i);
            end
        end
    else
        dataYear(year-1989,yrHr) = TEMP(i);
    end
    yrHr = yrHr + 1;

    % UPDATE TIME AND CALENDAR INFO
    hour = hour + 1;
    if hour == 24
        day = day + 1;
    end
end

```

```

    hour = 0;
end

if year==1992 | year==1996 | year==2000 | year==2004 | year==2008
    if day == 367 && hour == 0
        year = year + 1;
        day = 1;
        yrHr = 1;
    end
else
    if day == 366 && hour == 0
        year = year + 1;
        day = 1;
        yrHr = 1;
    end
end

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Operation Time Calculation
operationTime = time(I)+round(len(I)*rand);
if operationTime == 24
    operationTime = 0;
end

% Initialize loop control variables
j=1; k = 0; p=0; yrHr = 0;
hour = 0; day=1; year=1;
operationFound = 0;

% Beginning of 22 year loop (8760 hours per year)
for i=1:22*8760

    yrHr = yrHr + 1;

    % Check to see if operation coincides with time of day
    if hour == operationTime
        p = p+1;
        operationFound = 1;

        % Record Temperature of Operation
        temp(I,p) = dataYear(year,yrHr);
        tempReg(I,j) = dataYear(year,yrHr);

        arrayPos = max(1,round(100*rand));
        if I<2
            %OPEN Pulse Signal Deterioration Rate Simulation

            currMax(I,p) = (currOpenMax(arrayPos) + (OMODrate)*p) ...
                -(OMOT)*(tempReg(I,j)-20);
            currMaxReg(I,j) = currMax(I,p);

            timeMax(I,p) = (timeOpenMax(arrayPos) + (OMTDrate)*p);
            timeMaxReg(I,j) = timeMax(I,p);

            timeEnd(I,p) = (timeOpenEnd(arrayPos) + (OETDrate)*p);
            timeEndReg(I,j) = timeEnd(I,p);

        else
            %CLOSE Pulse Signal Deterioration Rate Simulation
            currMax(I,p) = (currCloseMax(arrayPos) + (CMODrate)*p) ...

```



```

        -(CMOT)*(tempReg(I,j)-20);
currMaxReg(I,j) = currMax(I,p);

timeMax(I,p) = (timeCloseMax(arrayPos) + (CMTDrate)*p);
timeMaxReg(I,j) = timeMax(I,p);

timeEnd(I,p) = (timeCloseEnd(arrayPos) + (OETDrate)*p);
timeEndReg(I,j) = timeEnd(I,p);
end

% Counter up to 30 to begin mean and std deviation computation
j=j+1;
if j>30
    j = 1;
    if k==0
        k = 1;
    end
end

% Computation of mean and std deviation for TEMPERATURE,
% MAX CURRENT, MAX TIME, and END TIME
if k>0
    tempHistReg(I,k,:) = tempReg(I,:);
    tempMean(I,k) = mean(tempReg(I,:));
    tempStd(I,k) = std(tempReg(I,:));

    currMaxHist(I,k,:) = currMaxReg(I,:);
    currMaxMean(I,k) = mean(currMaxReg(I,:));
    currMaxStd(I,k) = std(currMaxReg(I,:));

    timeMaxHist(I,k,:) = timeMaxReg(I,:);
    timeMaxMean(I,k) = mean(timeMaxReg(I,:));
    timeMaxStd(I,k) = std(timeMaxReg(I,:));

    timeEndHist(I,k,:) = timeEndReg(I,:);
    timeEndMean(I,k) = mean(timeEndReg(I,:));
    timeEndStd(I,k) = std(timeEndReg(I,:));

    k=k+1;
end
end

% Update Time Information to Account for Daylight Savings and End of Yr
hour = hour + 1;
if hour == 24
    hour = 0;
    day = day+1;
    operationTime = max(0,min(24,round(24*rand)));
    if day >= 70 && day < 308
        operationTime = max(0,min(24,operationTime + 1));
    end
end

if operationTime == 24
    operationTime = 0;
end

if day == 366
    year = year + 1;
    day = 1;
    yrHr = 0;
end
end
end

```

```

% Initialization of temperature matching variables.
yearlyDaysMatched = zeros(22,1);      % Indicates if a match is found
separationDays = zeros(22,365)*NaN;  % Days of separation between match
tempsMatched = zeros(22,365)*NaN;    % Temperature at which match happens
m=0; z=1;

% Perform analysis for 21 years
for i=22:-1:2
    % Average and Standard Deviation tolerances
    muFilter = 0.5;
    stdFilter = 0.5;

    % Control variable to determine if a match has been found
    yearPointFound = 0;

    while yearPointFound == 0

        for j=365:-1:1
            m=m+1;
            yrHr = (i-1)*365+j-29;
            YRHR(m) = yrHr;

            tempStatTest = 0;
            for k=0:91
                if yrHr-k-320 > 0 %Sufficient time check (> 320 days)
                    % Check to see if temperature is within low/high window
                    if tempMean(I,yrHr) > tempLow && tempMean(I,yrHr) < tempHigh
                        % Check to see if temperature is within average range
                        if abs(tempMean(I,yrHr)-tempMean(I,yrHr-k-320)) <= muFilter
                            % Check to see if temperature is within std deviation range
                            if abs(tempStd(I,yrHr)-tempStd(I,yrHr-k-320)) <= stdFilter
                                % Computation of statistical information
                                mu = tempMean(I,yrHr); sigma = tempStd(I,yrHr);
                                ix1 = mu-3*sigma:0.1:mu+3*sigma;
                                iy1 = normpdf(ix1,mu,sigma);
                                mu=tempMean(I,yrHr-k-320); sigma=tempStd(I,yrHr-k-320);
                                ix2 = mu-3*sigma:0.1:mu+3*sigma;
                                iy2 = normpdf(ix2,mu,sigma);
                                figure; plot(ix1,iy1); hold; plot(ix2,iy2,'r'); hold;
                                tempStatTest = 1;

                                % Yearly Change
                                currMaxDelta = currMaxMean(I,yrHr) ...
                                    - currMaxMean(I,yrHr-k-320);
                                timeMaxDelta = timeMaxMean(I,yrHr) ...
                                    - timeMaxMean(I,yrHr-k-320);
                                timeEndDelta = timeEndMean(I,yrHr) ...
                                    - timeEndMean(I,yrHr-k-320);

                                break;
                            else
                                tempStatTest = 0;
                            end
                        else
                            tempStatTest = 0;
                        end
                    else
                        tempStatTest = 0;
                    end
                else
                    tempStatTest = 0;
                    break
                end
            end
        end
    end
end

```

```

% Compute deterioration rates and other results
if tempStatTest == 1
    matchFound(i) = 1;
    yearPointFound = 1;
    separationDays(i,j) = k+320;

    yearlyDaysMatched(i) = yearlyDaysMatched(i) + 1;
    tempsMatched(i,j) = tempMean(I,yrHr);
    trackTemps(i-1) = tempMean(I,yrHr);

    currMaxDeltaHist(I,i) = currMaxDelta/(k+320);
    timeMaxDeltaHist(I,i) = timeMaxDelta/(k+320);
    timeEndDeltaHist(I,i) = timeEndDelta/(k+320);

    operationsHist(I,i) = yrHr;

    break
end
end

% If data not matched, expand the average and std deviation windows
if yearlyDaysMatched(i) == 0
    if stdFilter == 1.5
        muFilter = muFilter + 0.25;
        fprintf('Mean Filter set to %f \n', muFilter);
    else
        stdFilter = stdFilter + 0.25;
        fprintf('StandardFilter set to %f \n', stdFilter);
    end
end
if stdFilter == 1.5 && muFilter == 1.5
    yearPointFound = 0;
end

end
end

figure; subplot(1,3,1);
yearlyDaysMatched(1,1) = nan;
plot(yearlyDaysMatched,'o'); ylabel('Days Matched'); grid;

subplot(1,3,2); ylabel('Temps Matched'); hold; grid;
for i=1:22
    plot(tempsMatched(i,:), 'o');
end

subplot(1,3,3); hold; ylabel('Separation Days'); grid;
for i=1:22
    plot(separationDays(i,:), 'o');
end

end

figure;
subplot(3,2,1); plot(currMaxMean(1,:)); grid; xlabel('day');
ylabel('Max Mean Curr Open');
title('Open Max Current - Mean');
subplot(3,2,3); plot(timeMaxMean(1,:)); grid; xlabel('day');
ylabel('Max Mean Time Open');
title('Open Max Time - Mean');
subplot(3,2,5); plot(timeEndMean(1,:)); grid; xlabel('day');
ylabel('End Mean Time Open');
title('Open End Time - Mean');

```

```

subplot(3,2,2); plot(currMaxMean(2,:)); grid; xlabel('day');
    ylabel('Max Mean Curr Close');
    title('Close Max Current - Mean');
subplot(3,2,4); plot(timeMaxMean(2,:)); grid; xlabel('day');
    ylabel('Max Mean Time Close');
    title('Close Max Time - Mean');
subplot(3,2,6); plot(timeEndMean(2,:)); grid; xlabel('day');
    ylabel('End Mean Time Close');
    title('Close End Time - Mean');

figure; subplot(2,1,1);
plot(currMaxMean(1,:)); hold; plot(currMaxMean(2,:), 'r');
grid; xlabel('day'); ylabel('Max Current Mean'); legend('OPEN', 'CLOSE');
title('MEAN MAX CURRENT');
subplot(2,1,2);
plot(currMaxDeltaHist(1,:)); hold; plot(currMaxDeltaHist(2,:), 'r'); grid;
xlabel('day'); ylabel('Deterioration Rate');

figure; subplot(2,1,1);
plot(timeMaxMean(1,:)); hold; plot(timeMaxMean(2,:), 'r');
grid; xlabel('day'); ylabel('Max Time Mean'); legend('OPEN', 'CLOSE');
title('MEAN MAX TIME');
subplot(2,1,2);
plot(timeMaxDeltaHist(1,:)); hold; plot(timeMaxDeltaHist(2,:), 'r'); grid;
xlabel('day'); ylabel('Deterioration Rate');

figure; subplot(2,1,1);
plot(timeEndMean(1,:)); hold; plot(timeEndMean(2,:), 'r');
grid; xlabel('day'); ylabel('End Time Mean'); legend('OPEN', 'CLOSE');
subplot(2,1,2);
plot(timeEndDeltaHist(1,:)); hold; plot(timeEndDeltaHist(2,:), 'r'); grid;
xlabel('day'); ylabel('Deterioration Rate');

```

11 APPENDIX B – SENSOR/PARAMETER MERIT ASSESSMENT

During the development of this project, multiple monitoring parameters and sensing technologies were researched.

The final M&D system utilizes a Hall-effect current sensor to monitor the magnetic actuator’s timing characteristics and a wireless/passive SAW temperature sensor to track the interrupter’s thermal behavior. The justification for the selected technologies is both technical and financial, and ensures that each component utilized is mature and ready for deployment in the risk adverse utility space.

Table 11-1 summarizes the merit of all monitoring parameters and sensing technologies considered during the development phase of the project. A simple technology score provides a degree of overall merit.

PPMV Smart Grid Accelerator Team - Sensor & Monitoring Evaluation Summary											
Monitoring Parameters	Cost	Dev. Time	Access To Data	Reliability	Life Expectancy	Maturity	Fault Detection Accuracy	Overall Failure Reduction	Technology Score <small>10=1 0=0 -1=-1</small>	Existing Solution	References
Trip/Close Coil Current Profiling	~	✓	✓	✓	✓	~	✓	✓	6	N	[29-35]
Apparatus Temperature (SAW)	~	✓	✓	✓	✓	~	✓	✓	6	N	[23-28]
Humidity	✓	✓	~	✓	~	✓	~	~	4	Y	ABB Experts
Trip/Close Coil Continuity	~	~	~	✓	✓	✓	✓	✗	3	Y	ABB Experts
Position Prox Sensors	✓	~	~	✓	✓	✓	~	✗	3	N	ABB Experts
Primary/Secondary Fault Current (Interrupter Wear)	✓	✓	✗	✓	✓	✓	✗	✗	2	Y	ABB Experts
Interrupter Pressure Sensors	✗	✗	✓	✓	~	✓	✓	~	2	N	ABB Experts
Position Travel Sensors	✗	✗	✓	~	~	✓	✓	✓	2	N	ABB Experts
Interrupter Resistance	✗	✗	✓	✓	✓	✗	✓	✗	0	N	ABB Experts
Primary/Secondary Fault Current (Timing/Trending)	~	✗	✗	✓	✓	✗	~	~	-1	N	[38]
Vibration	✓	✗	✗	✓	✓	✗	✗	~	-1	N	[39-40]
Partial Discharge (Ozone)	✓	~	✗	✗	✗	✗	~	✗	-4	N	[41-42]
Partial Discharge (Elect)	✗	✗	✗	✗	✓	✗	~	✗	-5	Y	[43-52]

Table 11-1: Sensor and Parameter Selection Assessment