Protection & Controls Analytics for a Reliable Grid

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Abstract— **This paper discusses the need and the process of developing Protection & Control (P&C) analytics for maintaining system reliability of transmission grid.**

This paper focuses on presenting methodology around development of analytics for transmission protective relaying. It discusses use of analytics to assess system risk associated with protective relays based on asset health and system impact. It describes application of P&C analytics in mitigating system risks associated with maintaining a diverse population of protective relays. Opportunity to use P&C analytics as a building block for development of a future Asset Health Center is addressed in this paper as well. Discussions surrounding usage of analytics as technical basis for development of Capital and O&M budgets are also part of this paper.

P&C analytics discussed in this paper were developed around protective relay assets owned and/or maintained by CenterPoint Energy, an electric transmission provider in the Greater Houston Area. CenterPoint Energy's protective relay fleet comprises of mostly electromechanical and microprocessor based relays, with a small number of solid state relays. For the purpose of development of P&C analytics, various health assessment parameters were analyzed and weightages assigned including Mean Time Between Failure (MTBF), misoperations, vintage and relay type. System impact due to failure/malfunction of protective relays is calculated based on station bus configuration, protection scheme and other factors including electrical load at risk, voltage level, station ownership and maintenance repair times. System risk is calculated based on probability of failure and system impact. The methodology and information related to relay life cycles used for development of P&C analytics is based on discussions held at Electric Power Research Institute's (EPRI) member utilities platform and contribution from CenterPoint Energy's subject matter experts.

This paper also describes the use of data integration methodology, smart algorithms and application of latest Information Technology (IT) capabilities as building blocks used during the development of transmission P&C analytics.

I. Introduction

CenterPoint Energy is a combination of gas and electric utility and is part of the Electric Reliability Council of Texas (ERCOT) Region. It serves around 5.2 million electric customers in the Greater Houston Area.

The Greater Houston area, one of the major load centers in ERCOT, interconnects to the transmission grid at 345 kV and 138 kV voltage levels. A combination of local generation and import power from external sources serves the extremely dense load of around 18,000 MW in this area.

The current protection systems in use in the Greater Houston area are comprised of mostly electromechanical and microprocessor based relays, with a small number of solid state relays. For the purpose of development of P&C analytics, various health assessment parameters were analyzed and weightages assigned including MTBF, misoperations, vintage, number of trips and relay type etc. System impact due to failure/malfunction of protective relays is calculated based on station bus configuration, protection scheme and other factors including electrical load at risk, voltage level, station ownership and maintenance repair times. System risk is calculated based on probability of failure/malfunction of protective devices and system impact.

II. System Protection

North American power infrastructure is presently in the process of change from electro-mechanical and static relays to the state of the art micro-processor based relays. Just like any other asset, P&C assets also undergo a life cycle. Upon reaching end of their life, these assets need to be replaced. Therefore, effective strategies need to be in place in advance of these assets reaching their end of useful life to maintain reliability.

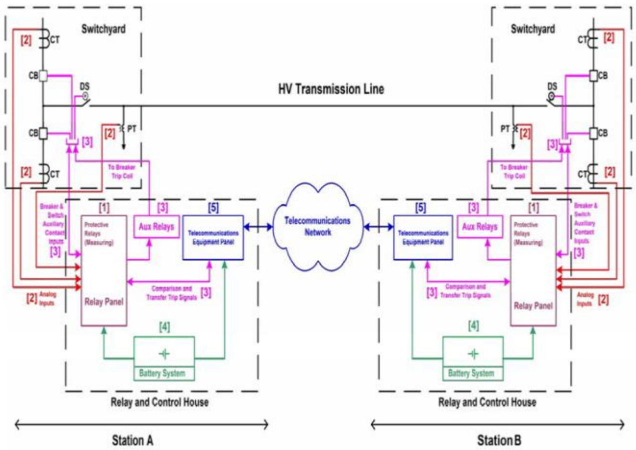

Figure 1: Typical Transmission System as defined by NERC Standard PRC-005-2 [1]

III. Need for P&C Analytics

Electric power industry has been exposed to asset analytics very recently. It is a relatively newer field being used for asset life cycle management purposes. At CenterPoint Energy, the key objectives for developing analytics for P&C are:

- Provide analytics to support asset replacement strategies and help mitigate asset failure risk
- Provide scoring methodology comparing condition of P&C assets
- Support asset strategies with actionable intelligence – reduce time for obtaining information
- Use consistent methodology for assimilating disparate data sources and analytics development that supports Subject Matter Experts decision making process
- Support Investment Prioritization for projects and programs
- Support knowledge transfer due to retiring workforce

IV. Relay Types – Industry Mix

In the electric utility industry, many of the existing electro-mechanical and solid state relays are functional but nearing obsolescence. Presently, electric industry protective relay assets comprise of following types of relays:

1. Electro-mechanical relays
2. Micro-processor relays
3. Solid state relays also known as static relays

Figure 2 below shows projected mix of different types of relays over several years. It shows projected mix for different types of relays over a time period of 1960’s to 2030’s. Shaded portion in the graph shows the mix of protective relays for a typical electric transmission provider.

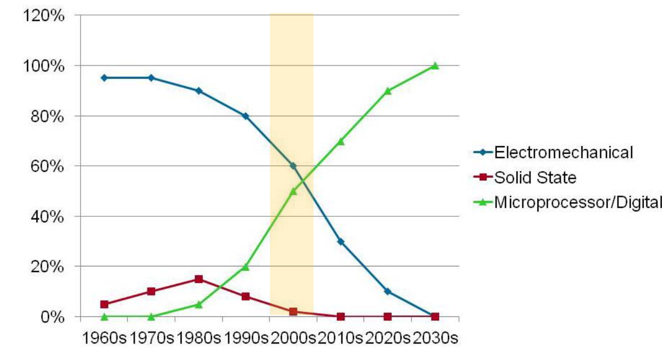

Figure 2: Conceptual trend of mix of Protective Relays [2]

The three basic categories of protective relays are described below:

1. Electro-mechanical Relays

Electro-mechanical relays function based on physical and electromagnetic properties using rotating disks, springs and other mechanical parts. Majority of Electro-mechanical relays have heavy burdens and have direct input from secondary instrument transformers such as CTs and PTs.

Figure 3: Electro-mechanical relay panel

Electro-mechanical relays were installed on the Houston area transmission system between 1950s and 1990s, making them the oldest relays in service. Significant number of electro-mechanical type relays has been replaced with latest microprocessor based relays recently, however, at present time demographic records indicate that electro-mechanical relays still predominate in CenterPoint Energy's system.

Since electro-mechanical relays depend on electro-magnetic properties and several mechanical parts, any wear, corrosion or dust accumulation on moving parts can affect relay accuracy and calibration. Additionally, aging of mechanical springs may cause changes in spring constants and affect relay accuracy and calibration. Repeated making and breaking of electric current leads to deterioration of relay output contacts and may lead to relay malfunction. Silver migration on the insulation between relay terminals is another issue that typically occurs on relays installed in areas with high pollution levels such as the coastal belt of Houston area. Silver migration is a slow process that takes 25-30 years necessitating replacement of relays to avoid any terminal shorting etc. Regular visual inspections, test results calibrations and historical performance are indices for assessing health and condition of electro-mechanical relays.

2. Solid-State Relays

Developed during the 1970's, solid state relays have fewer moving parts than electro-mechanical relays. These are also known as static relays. This type of relays have several analogue parts such as capacitors, diodes op-amps etc. Relay components are mounted on printed circuit boards. Root cause of failure/malfunction for majority of these relays is due to input card failure due to over voltage and over current conditions. Output contacts may also wear out and eventually fail. Power supply card failures may also lead to relay failure/malfunctions.

Figure 4: Solid state relay also known as static relays

Just like electro-mechanical relays, regular visual inspections, test results calibrations and historical performance are indices for assessing health and condition of solid state relays. Houston area does not have very many solid state relays installed on its transmission system. Majority of this type of relays were installed during 1990's.

3. Microprocessor-Based Relays

Microprocessor-based relays are computer based system with software based algorithms for detection and clearance of electrical faults. These are the most modern category of protective relays. This category of relays has much broader capabilities than electro-mechanical or solid-state relays. Since 2000's at CenterPoint Energy, all new protection scheme installations and replacements have utilized microprocessor-based relays.

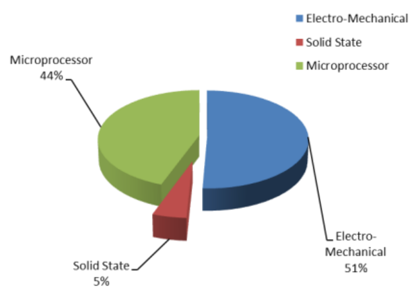

Figure 5: Mix of different types of relays for a typical electric transmission provider.

Main difference between microprocessor-based relays and solid-state relays is the use of software algorithms and numerical processing. As a result, aging processes and failure modes are more difficult to define and predict for microprocessor-based relays as compared to the other two types of relays. However, microprocessor-based relays often have self-diagnostic capabilities that can assist in assessing their health. Just like its predecessors, visual inspections and test results and historical performance are important indicators of the health and condition of microprocessor-based relays.

Figure 6: Microprocessor based relay panel

V. Mismatched Life Cycles

Substation equipment, such as a power transformer or a circuit breaker, typically has an expected life span of 40 years or even longer if properly maintained. In contrast, the life span of protection and control equipment varies significantly from electromechanical to microprocessor relays. Electromechanical relays have a typical life span of 30 to 40 years, which matches the life span of equipment, such as circuit breakers.

Microprocessor relays on the other hand have a much shorter life expectation than their predecessors and is in the range of 10-15 years. Therefore, a substation may require replacing microprocessor relays two to three times during the 40-year life cycle of high-voltage equipment. A holistic asset replacement strategy that takes into account mismatched life cycles for different transmission assets might be a solution in order to resolve this issue.

Figure 7: A control house seen here next to a switchyard

VI. Useful Remaining Life

Combination of statistical evidence and qualitative evaluations is required to determine a meaningful health index for protection systems. This evaluation is based around maintaining/improving system reliability and mitigating any financial or regulatory risks. P&C analytics health & risk indices assist with the identification of protection systems approaching the end of their useful lives. Figure 8 below shows the number of different types of relay groups and their age correlated to their useful life for a typical electric transmission provider.

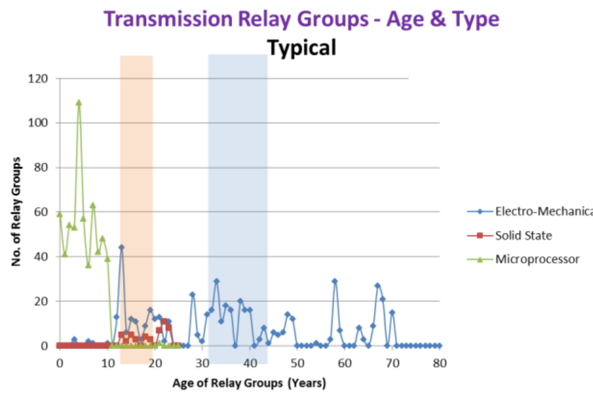

Figure 8: Mix of different transmission protective relays and their age for a typical electric transmission provider.

Based on above mentioned discussions, typical life cycle of a protective relays and discussions held among member utilities at EPRI's P&C Task Force meetings, parameters mentioned below were selected for consideration for health assessment of protective relays for analytics development purposes.

VII. Protection & Controls Analytics - Parameters

1. Age

Age by itself does not constitute as a parameter that determines protective relay's end-of-life. However, statistics show that failure/malfunction of equipment can be minimized by replacing it near its end of useful life. Typically, failure rates for protection and control devices, particularly solid-state devices, follow conventional bathtub curves. Therefore age was selected as an assessment parameter as a measure for condition assessment. For analytics development purposes, the end of useful life considered is 30 - 40 years for electro-mechanical devices, 15 - 20 years for solid state and microprocessor devices. Age for protective relays was calculated based on relays installation dates and in some instances, where the information was unavailable, control house installation date was used. According to relay demographics used for analytics development, the expected useful life of a relay was estimated to vary from 20 to 50 years based on technology used for its design and manufacturing.

2. Mean Time Between Failures (MTBF)

MTBF serves as an industry accepted in-service performance index. For protective measuring relays, multiplying a device's average age by the total population of that type of device, then dividing by the number of documented failure/malfunctions provides an accurate MTBF index defined as Device-Years/Failure. Industry-wide reliability is expressed in terms of mean time between failures (MTBF) or mean time to failure (MTTF). Failure Rate – rate at which failures occur in a specified time interval is called failure rate for that interval denoted by λ.

λ = number of failures / total mission time

MTBF is based on type of relay, its age and probability of failure based on the equations mentioned below:

Failure rate for electro-mechanical relays: λ_{EM}
$\lambda_{EM} = 0.0002 * e^{0.05756463t}$ [3]

Failure rate for solid state relays: λ_{SS}
$\lambda_{SS} = 0.0002 * e^{0.2262t}$

Failure rate for microprocessor based relays: λ_{MP}
$\lambda_{MP} = 0.0034$; $0 < t < 18$
$\lambda_{MP} = 0.000008 * e^{0.3202t}$; $t > 19$

MTBF = $1/\lambda$

The afore-mentioned equations were built on life cycle curves for protective relays shared by Pacific Gas & Electric (PG&E) Company with member utilities at EPRI's task force meetings [3]. These curves show the relationship between probability of failure/malfunction and age for the three types of relays, namely electro-mechanical, solid state and microprocessor based relays. Curve representing microprocessor based relays is based on actual relay failure/malfunction data while the curves for solid state and electro-mechanical relays are based on conservative assumptions since enough relay failure/malfunction data did not exist. MTBF was used as a performance based parameter for analytics development purposes.

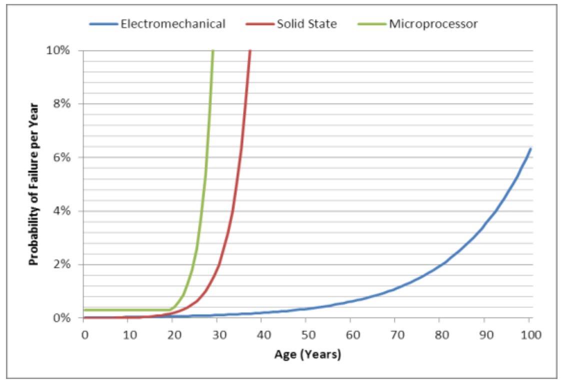

Figure 9: Life cycle curves for protective relays [3]

3. Operations & Maintenance (O&M) Expense

Historical unplanned and planned maintenance activity plays an important role in assessing health of protective relays. Maintenance activities for protective relays could be related to calibration and functional testing etc. Maintenance costs based on a financial tier is used as an indicator of the condition of the relays. O&M expense is used as performance based parameter for analytics development purposes.

4. Misoperations

According to Texas Reliability Entity (TRE), definition of misoperation includes:

- Failure to Trip During Fault – Any failure of a Protection System to operate for a Fault within the zone it is designed to protect. The failure of a Protection System component is not a misoperation as long as the overall performance of the Protection System for the Element it is designed to protect is correct;
- Failure to Trip Other than Fault – A failure of a Protection System to operate for a non-Fault condition for which the Protection System was intended to operate, such as a power swing, under-voltage, over excitation, or loss of excitation. Failure of a Protection System component is not a misoperation as long as the overall performance of the Protection System for the Element it is designed to protect is correct;
- Slow Trip During Fault – A Protection System operation that is slower than intended for a Fault within the zone it is designed to protect;
- Slow Trip Other than Fault – A Protection System operation that is slower than intended for a non-Fault condition such as a power swing, under-voltage, over excitation, or loss of

excitation for which the Protection System was intended to operate;

- Unnecessary Trip During a Fault – Any unnecessary Protection System operation for a fault not within the zone of protection;
- Unnecessary Trip Other Than Fault – Any unnecessary Protection System operation when no fault or other abnormal condition has occurred.

According to NERC misoperation report [4], approximately 65% of misoperations are grouped under three cause codes: Incorrect settings/logic/design errors, relay failures/malfunctions, and communication failures. Misoperation is used as a performance based parameter for analytics development purposes.

5. Relay Type & Obsolescence

Availability of spare parts becomes an issue once relays start to age specifically in the case of electro-mechanical type relays. Sometimes replacement parts can be obtained by salvaging old relays that have been retired from service. Cost of replacement of Electro-mechanical relays is also a consideration.

6. Station Bus Configuration

Bus configuration plays an important role in system impact in case of relay failure/malfunction. Based on analysis taking into account failure rates, repair time and outage duration during analysis of various bus configurations it is concluded that:

- Source line failures, which take into account both line as well as substation failures, impacts substation reliability indices, without changing the relationships between bus configurations
- Single Bus/Single Breaker (SBSB) configuration is the least reliable scheme
- Double Bus / Double Breaker (DBDB) configuration is the most reliable scheme
- Based on capital cost and operational reliability perspective, Breaker-and-a-Half (BAAH) leads all bus configurations

Appropriate weightages were assigned to various bus configurations based on reliability scores as shown in Table 1 below, for analytics development purposes.

Station Bus Configuration	Failure rate/year	Repair time (min)	Duration min/year	Reliability score
SBSB	0.055	80.5	4.42	98
Sectionalized	0.0459	76.35	3.5	79
BAAH	0.00356	175.56	0.63	15
DBDB	0.00572	125.14	0.72	12
Ring Bus	0.0235	92.2	2.17	41

Table 1: Substation reliability indices [5]

7. Station Impact

Loss of station due to a Failure to Trip misoperation was calculated based on station voltage level, electrical load at risk, ownership and maintenance repair time score. It is taken into account as an impact based parameter for analytics development purposes. The algorithm developed to compute station impact score is mentioned below.

Station Impact = 20% of Voltage Level Score
+ 20% of Max Electrical Load Score
+ 30% Electrical Load at Risk Score
+ 20% Ownership Score
+ 10% Repair Time Score

Since it is an impact based score, it is independent of condition or type of protective relay.

8. Protection Scheme

Various protection schemes are used for protecting assets in the power system. Analytics takes into account the type of protection schemes the relay is being used for protection purposes for calculating the system impact score e.g. system impact of bus differential scheme failure/malfunction at an can be greater than failure/malfunction of a line protection relay at that station, especially for a Single Bus/Single Breaker configuration. Analytics assigns higher weightages for higher impact protection schemes such as bus differential scheme. Protection scheme is used as an impact based parameter for analytics development purposes.

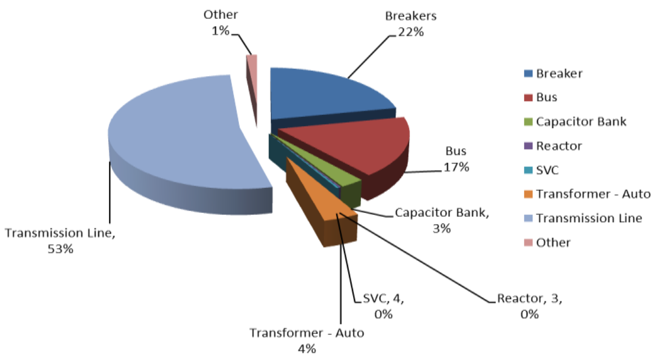

Figure 11: Mix of protection schemes for a typical electric transmission provider

9. Number of Operations

Manufacturer based rating for number of operations is an indicator of end of useful life. This is related to wear and tear and operational life due to mechanical and or electrical characteristics. Number of trips is used as performance based parameter for analytics development purposes.

The algorithms developed to calculate the System Impact, Health and Total scores are mentioned below:

Impact Score = {(X% Station Impact)
+ (Y% Protection Scheme)
+ (Z% Bus Configuration)} [4]

Health Score = A% ∑Performance Indices + B% Age

Total Score = (C% Impact) + (D% Health Score)

Risk Index = Probability of failure x System Impact

Weightages assigned to the individual terms are variables depending on the system configuration and electric utility's requirements.

VIII. Data Integration

Analytics development triggered integration of operational data stored in various databases into a consumable form for analytics development purposes. In-memory data integration from various databases on state of the art SAP HANA platform allowed faster data processing. Figure 12 below shows data integration for various data sources and subsequent application of smart algorithms to generate analytics results and reports. Databases shown contain relay demographics information such as relay type, age, manufacturer, protection scheme, O&M expense and misoperations etc.

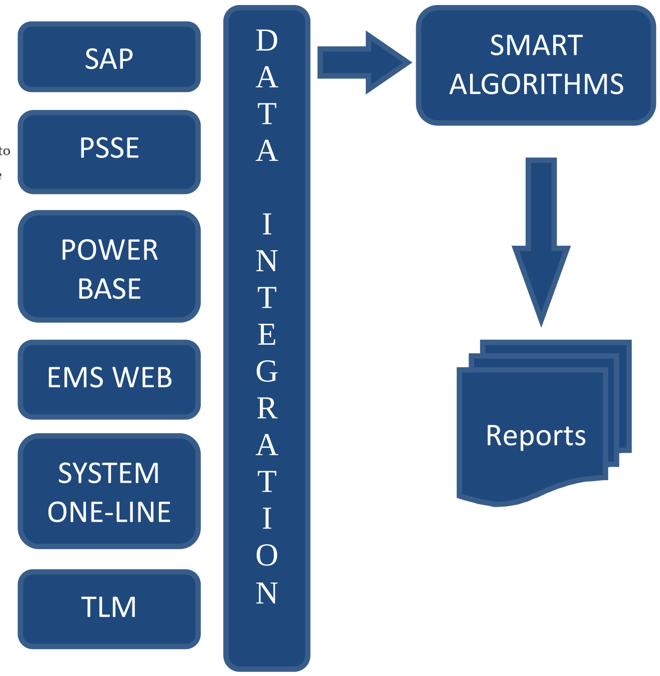

Figure 12: Database integration and analytics reporting

Application of smart algorithms on the integrated data generates dashboards such as shown below. Dashboards with tiles layout provides an efficient way to drill down and access detailed analytics results. This platform provides user functionality by providing the capability to create downloadable WEBI reports.

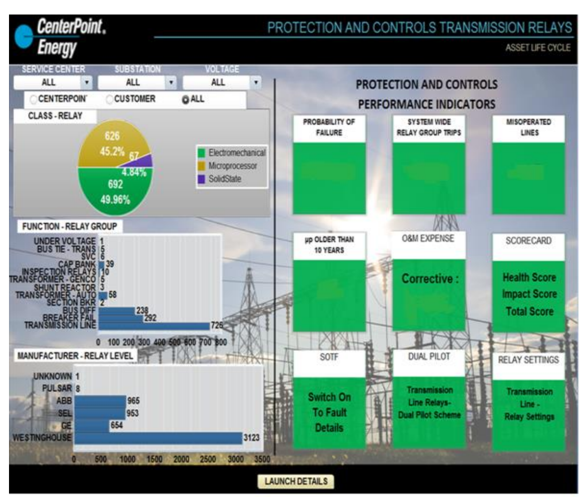

Figure 13: P&C analytics dashboard.

User also has the capability to create heat maps based on risk indices showing probability of failure Vs system impact system wide. The heat map is divided into four quadrants whereby the top right quadrant lists the high risk and high impact protective relays. Relay panels identified in such heat maps help asset managers prioritize protective relay replacements. Analytics residing on SAP HANA platform besides providing the health, system impact, and total scores, also provides reporting capabilities in the form of downloadable spreadsheets including protective relays with Switch-On-To-Fault (SOTF), relay settings system wide, corrective and preventive historical maintenance costs, list of microprocessor relays older than ten (10) years, firmware versions, line distance relays used as pilot schemes and misoperated line relays for compliance reporting purposes.

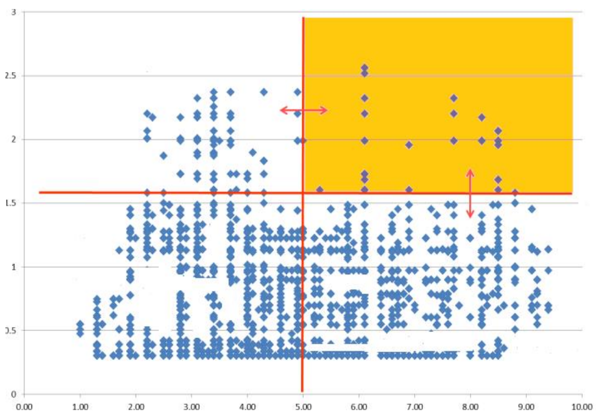

Figure 14: Heat map showing probability of failure on y-axis and station impact on the x-axis for a typical electric transmission provider.

IX. Technology – SAP HANA Platform

CenterPoint Energy's P&C analytics is built on SAP HANA platform. This platform provides several advantages over conventional platforms used as traditional data analytics technology. It eliminates several layers of analytics processing allowing in-memory processing. It allows data processing at speeds x1000 times faster providing faster business intelligence. Because it is very fast, simple analytics programs can be built that rely on single copy of information.

Traditional data analytics technology relied on layers of information which were copied at different levels of detail in order to present analytics results in the required format. In-memory data analytics technology does not require any optimizations allowing more data processing in less space. Information gleaned from various data sources is stored once and then the report or required response is calculated on demand. This means analytics information is calculated in real-time. New data analytics technology is not as expensive nor infrastructure intensive like its predecessor and there is no unnecessary time gaps involved between data creation and analytics reporting and its subsequent usage.

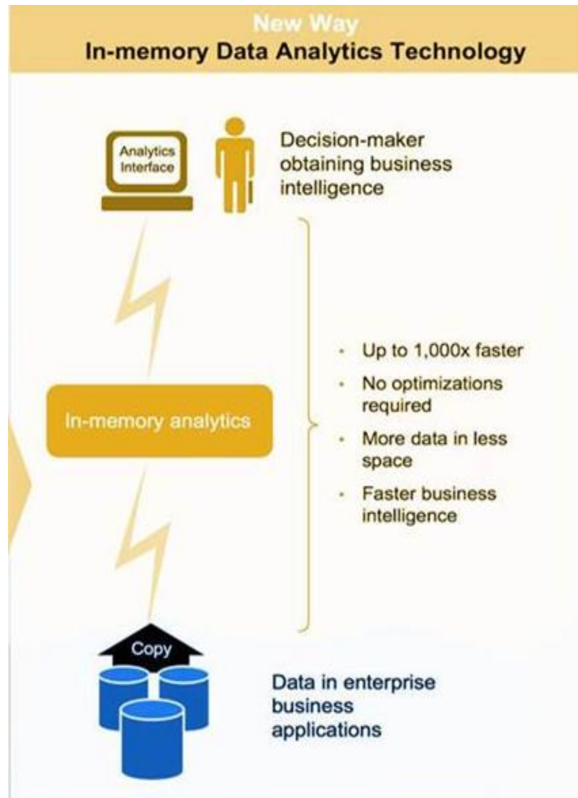

Figure 15: SAP HANA platform used for analytics development purposes [6]

At the core of the SAP HANA platform is the HANA database. It is a super-fast information storage and retrieval engine which can store and retrieve information in real-time. Integrated inside the platform are several functions which fit into a number of categories. This platform has data transformation, streaming and batch load capabilities. In addition there are a set of engines that sit inside the HANA platform and run in-memory. These include predictive libraries, business function libraries, a text, sentiment and search engine, a spatial and a graph engine. This means the business applications such as P&C analytics can reuse information over and over again without duplication or any transfer of information.

X. Concluding Remarks

Life cycle analytics is a relatively newer field in the electric power industry. Electric utilities have been exposed to this field very recently. This field is in evolution stage at this time. Advances in asset inspection, assessment, diagnostics and online monitoring have resulted in a wide variety of data that can be used in assessing asset performance. Asset performance data in turn can be used to make risk based financial and operational decisions. While some electric utilities were quick to embrace the life cycle analytics concept early on, majority of the electric utilities contemplated whether this concept was realistic enough. The few utilities which embraced the concept early on developed the analytics in-house while others have implemented the concept by purchasing and installing readymade off the shelf products available in the market.

Very recently, EPRI has piloted an initiative for providing a platform where member utilities are exchanging analytics development related information and exposing electric utilities to asset analytics related products developed by leading electric power solution providers.

P&C analytics development at CenterPoint Energy was a combined effort between subject matter experts of various departments including Substation Operations, Engineering, System Protection, Asset Management, Technology Operations, Transmission Planning, Standards & Materials and Applications & Development. Direction & support including resource availability from CenterPoint Energy management also played a critical role in development of P&C analytics. Lastly EPRI task force meetings provided necessary platform for sharing analytics development and feedback during analytics development stage. Blueprint for development of analytics was shared with EPRI member utilities and their comments and feedback incorporated during analytics development. Methodology, algorithms and reporting capabilities of the analytics program were also shared amongst electric utilities during Condition Based On-Line Monitoring of Electric Assets (COMET) 2015 conference arranged jointly by Qualitrol and University of Texas in Austin, Texas last year.

P&C analytics is one of the building blocks for asset analytics at CenterPoint Energy. At this time analytics around Substation class Transformers, T&D circuit breakers and Underground Residential Distribution (URD) cables has been developed. Results of these analytics are being used to support replacement decisions by Subject Matter Experts.

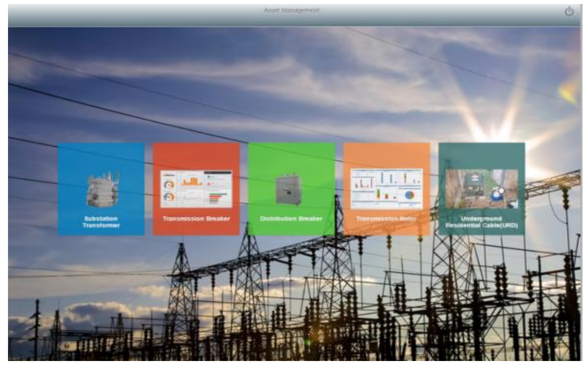

Figure 16: Asset Health Center - Future

As analytics continue to be developed for additional electric assets, the plan is to integrate and bring those under a single umbrella such as an Asset Health Center. Figure 16 above shows the envisioned dashboard for the future asset health center. Upon completion of the asset health center, Asset Managers and Subject Matter Experts with appropriate permission levels will be able to perform condition and risk analysis and generate actionable intelligence reports for their assigned assets system wide.

Availability of health and risk indices and asset failure information also provides an opportunity to marry it with appropriate economics and business rules. Results of this marriage can be used as technical basis for developing Capital and O&M budgets as shown conceptually in Figure 17 below. This is an avenue that CenterPoint Energy is exploring along with other electric utilities under EPRI's sponsored Transmission and Substation Asset Health Interest Group (AHIG).

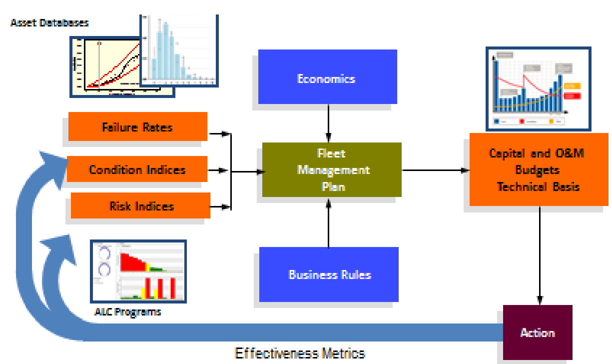

Figure 17: Analytics application in financial decisions - Future.

XI. References

[1] NERC, "Standard PRC-005-2 – Supplementary Reference and FAQ", 2012, p. 96.

[2] Y. Lu, "Lifecycle Management of Protection, Control and Associated Data Acquisition Infrastructure – Challenges and R&D Needs" in EPRI Technical Update, 2012, p A2.

[3] A. Feathers, A. Mubaraki, A. Nungo and N. Paz, "Relay Performance Index for a Sustainable Relay Replacement Program," presented during EPRI P&C Task Force Meeting held at Charlotte, NC, 2015.

[4] NERC, "Protection System Misoperation Task Force Report", April 2013, p 5.

[5] D. Nack, "Reliability of Substation Configurations", Iowa State University, 2005, p. 12.

[6] SAP, Available: http://sap.com

XII. Biography

Qasim Aziz is a Consultant in the Asset Management department at CenterPoint Energy. He has around eighteen years' experience in the electric power industry in various fields including engineering, protection, operation & maintenance, planning and project management in electric power generation, transmission and distribution fields. His current job responsibilities include development of asset life cycle analytics for CenterPoint Energy's assets. He has a Bachelor's degree in electrical engineering, MS Engineering and an MBA from San Jose State University, California. He is a member of EPRI's task force committees relating to asset management, P&C, transformer and circuit breakers. He is registered as a Professional Engineer in the states of Texas and California.

Gautam Sonde is a Solution Architect for the Operational & Corporate Analytics team at CenterPoint Energy with a combined experience of over twenty years in Information Technology. He has been charged with the delivery of innovative solutions in several areas such as finance, asset management and smart meter analytics. He has led his team through architecture development to implementation of business solutions which includes the delivery of data models, reconciliations, and value added self-service solutions using various state-of-the-art technologies.