Substation Transformer Replacement Plan

Josue Sanchez
Master of Engineering Management
Dr. Héctor J. Cruzado
Management
Polytechnic University of Puerto Rico

Abstract *— About half of the Gainesville Regional Utilities (GRU) substation transformers are above their industry usage limit standard of 45 years and are prone to catastrophic failure. This study critical health data was captured using an asset management software, called Cascade. The health of each power transformers was measured by multiple criteria such as gassing, hazard factor, age, customer count, percent of loading, switch ability, priority customer factor and fault count. These factors were combined and weighted using a Risk Priority Numbers (RPN) that provided a total risk of failure value. From a total of 52 power transformers, the utility found as a result 32 power transformers with high risk of failure. Energy Supply manage 18 of those transformers and Energy Delivery manage 14 of those transformers. It was recommended and planned to start developing the engineering and procurement process to replace these transformers based on the risk priority and the operations configuration of the system.*

Key Terms *— Electric Energy, Power Transformers, Substations, Utilities*

INTRODUCTION

Substation Power Transformers are one of the most important and costliest assets in the power grid. The principal function of a transformer is to transform voltage levels. Currently, the level of reliability required of electricity companies causes a high degree of functional characteristics information of their equipment, particularly their transformers [1]. About half of the Gainesville Regional Utilities (GRU) substation transformers are above their industry usage limit standard of 45 years and are prone to catastrophic failure. The failure of the lone transformer at a substation, or failure of multiple transformers at substations could be devastating. These types of failure events have the potential to result in substantial and extended customer load interruption, as well as adverse environmental and safety outcomes. The economic implications involving the operation of equipment failures are complex; hence, electric grid assets are considered critical, then the integrity of each one of its components must ensure. This integrity can be achieved by implementing new technologies for monitoring and evaluating their performance [2].

On the one side, the old transformer in-service consistently exceeds its service life limitation, leading to a high maintenance cost. On the other side, frequently replacing a transformer in pursuit of new transformers' high performance or higher capacity unless it is needed will result in unnecessary waste of capital budget. Nevertheless, the old transformer still occupies a large proportion of the power system at present, and the replacement work is very urgent. Therefore, considering the relationship between the transformer's health status and service life, it is critical to determine a transformer replacement decision method for providing the scientific basis for the power enterprises to carry out technology reconstruction of a power transformer. Good engineering practices would be to start planning to replace the transformers before they reach their life expectancy.

Planned and sustained infrastructure replacement is both a cost-efficient and highly effective approach to maintaining reliability. A case study of Los Angeles Department of Water & Power, clearly demonstrate that, when comparing the outages experienced by customers during the 2007 heat storm with a similar heat storm in 2014, following a period of sustained investment in infrastructure replacement. As a result of planned infrastructure replacement, customer outages lasting over 24 hours were reduced by 99.3% during the 2014 heat storm over the 2007 heat storm, as shown on Figure 1 [3].

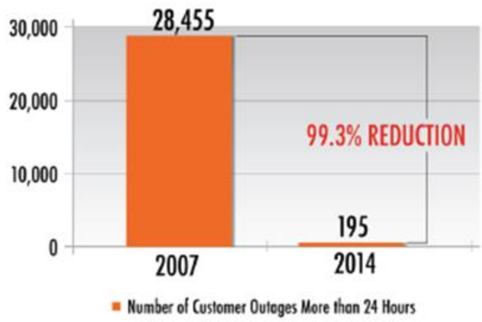

Figure 1
Los Angeles Comparison of 2007 and 2014 Heat Storms

OBJECTIVES

The objectives of this project were to:

- Finalize a plan with budgetary estimates for the transformer replacement.
- Execute the plan and replace the transformers.

BACKGROUND AND METHODOLOGY

GRU aims to achieve asset management ISO 55000 certification by managing assets to deliver the best business value to its customers. The asset management program minimizes expenditures to keep pressure off customer prices; however, cost reduction must be balanced against critical network performance objectives. GRU's asset management objectives are broken into safety, regulatory compliance, environmental, economic, and customer service.

To achieve GRU's asset management objectives for substation power transformers, a transformer replacement plan of 5 years is presented from identifying the primary issues of substation power transformers and strategies for managing them, including maintenance and operational functions. In this study, safety, reliability, and strategic management are considered strong drivers, including managing the risk of failure of in-service power transformers in aged or poor conditions. In this report, detailed quantitative risk assessments were carried out for each of the proposed transformer replacement plans. The proposed transformer replacements were based on asset condition as per the GRU transformer criticality, health, maintenance history, and safety guidelines. The primary outcome of the engineering analysis established that 14 power transformers of Energy Delivery need to be replaced with high priority. Energy Supply has 18 aged power transformers that require planning to replace as well.

The methodology of this project has a dual-purpose. First, complete the analysis and the plan. Second, implement the transformer replacement plan.

This document outlines the need and options available for managing the replacement of Substation Transformers within the GRU network. It is related only to the class of assets known as substation power transformers. A transformer must be suitably rated to carry the full load of the circuit it is placed in and be able to withstand periods of cyclic overloading to meet peak and emergency demands. In general, a transformer is moderately loaded for most of the time. It is called upon to operate at full nameplate load or greater during peak periods of daily seasonal load cycles. GRU substation transformers range in age from nine to 58 years, with an average of 34 years. Manufacturers will generally design for a substation power transformer life expectancy of approximately 40 to 45 years for a transformer loaded continuously to its full rating. Few manufacturers claim extended life expectancy; however, it is not the industry standard. However, due to the varying operating conditions (load and temperature cycles, frequency of system faults, etc.) this life is not guaranteed. A transformer must also be designed to withstand the abnormal voltage peaks (resulting from lightning strikes and switching surges) and current peaks due to system faults.

A transformer must be suitably rated to carry the full load of the circuit it is placed in and be able to withstand periods of cyclic overloading to meet peak and emergency demands. In general, a transformer is moderately loaded for the majority of the time. It is called upon to operate at full nameplate load or greater during peak periods of daily seasonal load cycles. GRU substation transformers range in age from nine to 58 years, with an average of 34 years. Manufacturers will generally design for a substation power transformer life expectancy of approximately 40 to 45 years for a transformer loaded continuously to its full rating. Few manufacturers claim extended life expectancy; however, it is not the industry standard. However, due to the varying operating conditions (load and temperature cycles, frequency of system faults, etc.) this life is not guaranteed. A transformer must also be designed to withstand the abnormal voltage peaks (resulting from lightning strikes and switching surges) and current peaks due to system faults.

The following list summarizes what the study should cover and how it should be broken down to better understand each business case:

- Analysis of the status of all transformers
- Recommendations
- Budget estimation
- Propose 5-year replacement plan to be executed

ASSET MANAGEMENT STRATEGIES

The lifecycle management of substation power transformers will assist GRU in creating a reliable and cost-effective distribution network. This requires enforcing the Asset Management Strategy established by the GRU team.

The Asset Management Strategy is: "To optimize the capital investment through targeted replacement of assets, based on an assessment of asset condition and risk, and also seeks to provide sustainable lifecycle management of assets through the use of condition monitoring and life assessment techniques."

The objectives to meet GRU's asset management strategies are broken down as follows:

- **Safety** – Maintain and operate assets such that the risks to employees, contractors, and the public are maintained at a level as low as reasonably practical.
- **Regulatory Compliance** – Meet all regulatory requirements associated with the Electrical Distribution Networks.
- **Environmental** - Maintain and operate assets so that the risks to the environment (such as oil spills, etc.) are kept as low as reasonably practicable.
- **Economic** – Ensure that costs are prudent, efficient, consistent with accepted industry practices, and necessary to achieve the lowest sustainable lifecycle cost of providing electrical distribution services.
- **Customer Service** – Maintain and operate assets consistent with providing a high level of service (safety and security of supply) to customers.

The lifecycle management of substation power transformers is comprised of multiple stages. This will help ensure that GRU’s transmission and distribution network operation meets industry and regulatory standards while providing an optimal return to ratepayers and satisfying community requirements.

DEVELOPMENT OF ANALYSIS

The proposed replacement program is a continuation of an existing risk-based replacement for the asset replacement management plan strategy (ARMP). This replacement program is a continuation of a current condition-based replacement strategy for substation transformers.

The replacement of substation transformers is required due to the degradation of materials, components, and performance over their service life. If left to degrade, substation transformers will eventually fail in-service, potentially leading to an extended interruption of customer load and finally leading to catastrophic failure (with associated negative safety and environmental consequences).

In general, the degradation of substation transformers results from the expected electrical and mechanical aging incurred during the regular operation of the transformers over a long period. Table 1 breakdown more in detail the types of failures that are evaluated at the time of power transformer failures. In addition, these internal and external factors are what it is tried to be avoided by performing preventive asset maintenance. However, some other factors also contribute to the need for replacement:

- Environment
- Loading
- Obsolescence
- Safety

Table 1
Typical Causes of Transformer Failures

Internal	Insulation deterioration Loss of winding clamping Overheating Oxygen Moisture Contamination in the insulating oil Partial discharge
External	Design and manufacture Winding resonance Lightning strikes System switching operations System overload System faults (short circuit)

REPLACEMENT DECISION MATRIX

GRU has been capturing all transformer maintenance data in the Asset Management Software, Cascade since 2013 This data includes 75 equipment from 55 transformers and 20 LTC, 36 procedures and 914 inspection forms, 569 triggers points, 1,545 preventative, and 1,093 corrective maintenance work orders. The maintenance data provides valuable information about the transformer's risk status in Cascade, which is the multiplication of their criticality and health number. Individual transformer's criticality was found from their dissolve gas and fluid quality results, power factor testing, oil temperature, bushing, and cooling fan condition. Health is substation specific. The following formula calculates the risk priority numbers (RPN) of the individual transformer. The risk, gassing, hazard, and age have a high weight in RPN calculations to transformer's status ranking, as shown in Figure 2.

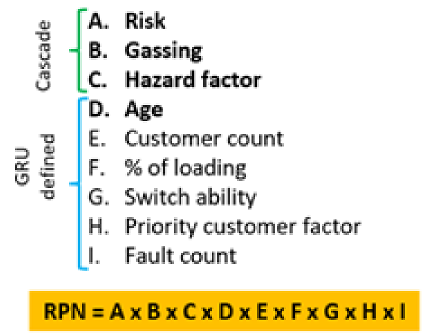

Figure 2
Risk Priority Configuration

GRU has a total of 52 substation transformers. From that total, 21 transformers already are over the life expectancy of 45 years. In addition, 12 of those 21 transformers are equal/over 50 years plus of being in service.

In addition to age, another critical factor is risk, which is a combination of factors described above. Cascade categorizes the risk based on multiple formulas and a predictive failure analysis algorithm.

Ownership of the high-risk power transformer fleet is divided between Energy Supply and Energy Delivery departments. Currently, Energy Supply has most of the power transformers with high risk and over their useful life. The power transformer ownership breakdown is shown in Table 2.

Table 2
Ownership Breakdown

Owner	Quantity
Energy Supply	18
Energy Delivery	14

ECONOMIC ANALYSIS

From a financial point of view, when considering the cost of energy losses, failure risk, and maintenance, the investment cost and the transformer's residual value at the moment of repair or replacement needs to be considered. The economic optimal replacement cycle can be determined by calculating the transformer's Equivalent Annual Cost (EAC) and searching for the minimum. This method can be used when the transformer does not reach the end of life. Another analysis that can be used is Net Present Value (NPV). However, most of the transformers considered to be replaced in this report are priority since they are already over their useful life and do not have a significant residual value. The maintenance costs are over the normally expected maintenance costs.

As an example, economic analysis with Serenola Substation T-91 transformer is developed by calculating the Equivalent Annual Cost (EAC) and the Net Present Value (NPV). The result from the calculation will help to make a repair, rebuild or replacement decision of the transformer. A similar result can be derived from all other aged transformer's financial analyses.

EQUIVALENT ANNUAL COST

In the EAC, all cost components are re-calculated to the present monetary value. It takes an Annuity Factor (AF) into account, which should be based on a carefully chosen discount rate. This AF can then be calculated as follows:

AF (i,n)=(1-1/〖(1+i)〗^n)/i

The EAC, in the event that the transformer will be replaced, can be calculated as follows:

((New tranformer initial cost))/(AF(i,n) * n)-((Residual Value Today))/(AF(i,n)* n)+Running cost (x) new

The longer the replacement cycle, the more the investment can be spread over the entire period and the lower its influence on the annual cost will be.

The EAC, in the event that the transformer will remain in place at least one more year, can be calculated as follows:

$$\frac{(initial\ cost)}{AF(i,n)*(n+1)} - \frac{Residual\ value\ (x)}{AF\ (i,n)*(n+1)} + Running\ cost\ (x) old$$

The EAC in the event of a transformer rewinding (or other substantial repair action), can be calculated as follows:

$$\frac{(initial\ cost + repair\ cost)}{AF(i,n)*(n+1)} - \frac{Residual\ value\ (x)}{AF\ (i,n)*(n+1)} + Running\ cost\ (x)\ after\ repair$$

With n = the age of the transformer, and the running cost for next year calculated as follows:

$$Running\ cost\ (y)\ years = no\ load\ losses + load\ losses + maintenance\ cost + cost\ of\ failure\ risk$$

The best decision will be the one with the lowest EAC.

The average annual running cost will increase with increasing the life cycle because the energy losses, maintenance costs, and failure risks increase with transformer aging. The residual value of the transformer appears as a negative cost and consequently also increases with increasing the life cycle [4]. The transformer will have a minimum EAC at a life cycle length n where the increasing and the decreasing part of the equation equal each other.

RUN-TO-FAILURE MAINTENANCE STRATEGY

Allowing the identified poor condition and aged transformers to remain in-service will likely lead to higher operational costs, due to the increased maintenance required to keep these assets in-service as their condition deteriorates. Furthermore, their eventual failure in-service will increase the cost of replacement due to the investments needing to be replaced under emergency rather than planned.

The status quo is an option that we strongly not advised; if this option is taken, then major system failure is likely to occur.

Under a "run-to-failure" counterfactual approach, the identified substation transformers would be permitted to fail in-service rather than being replaced proactively based on condition, age, and risk factors. The critical issue associated with this approach is that it would increase the risk of significant and extended load interruptions for customers when the assets fail in-service. Many of GRU's power transformers were installed at the same time and are now in a similarly deteriorated condition. In this case, a second power transformer may fail when the first transformer already fails in service. This scenario can arise for two reasons:

- The "through-fault" when the first transformer fails produces significant electrical and mechanical forces in the adjacent transformer and results in sympathetic failure, especially when both transformers are in poor condition; and
- If the second transformer does not fail, it will bear substantially increased demand, often at or above its rated capacity. This high demand for a transformer can lead to a shorter lifespan after the initial transformer failure.

Under a "run-to-failure" counterfactual approach, the increased rate of failure in-service for substation power transformers will prevent the safe and efficient operation of the network.

Qualitatively, the failure in-service of substation transformers has several potential consequences:

- **Extended interruption of customer load:** Substation power transformers perform a critical role in the network in supply, transforming high voltage power into a low voltage, usable form for the customer. Their failure can lead to lengthy disruptions to supply for customers. There is typically a long lead-time associated with asset repair or replacement, and there are no alternative means of supplying low voltage power once a unit fails.
- **Loss of access to substation sites:** When substation power transformers are found to be in poor condition, and therefore at an elevated risk of experiencing a catastrophic failure, a substation site restriction can be imposed on the substation for safety reasons. This restricts both site access and the scope of work that can be performed on-site, adding cost to routine works, extending preventative and routine maintenance periods on nearby assets, and inhibiting operation of the network.
- **Safety:** Safety cannot be compromised. The no-action could lead to a catastrophic failure/explosion. That could negatively affect GRU technicians and/or the community in general.

5-YEARS STRATEGIC REPLACEMENT PLAN

For this report and budgeting, we are only considering the Energy Delivery power transformers. However, the planning team will be working closely with Energy Supply to help them manage and budget for these projects. The analysis suggests a multi-year implementation replacement project, considering a transformer priority based on system configuration, risk, and budget. A rough budgetary allocation is presented in the next section below, showing a 5-year transformer replacement plan. There are a total of 14 power transformers that need to be replaced under Energy Delivery ownership.

CONCLUSION AND RECOMMENDATIONS

Maintenance and inspection data, Cascade Software algorithm, and engineering analysis have shown that a substantial amount of GRU power transformers' health is at risk of failure and no longer meets industry standards. The transformers' status represents a high risk to the asset management strategy of GRU. The repair and rebuilding of the aged transformers is not practical considering their current status and finances. The probability of their catastrophic failure is high and repairing these transformers is not realistic. Any outage on one of these transformers will force an outage to thousands of customers for a period of time up to 12-18 months. The only viable alternative is to continuously replace all of the power transformers recommended in this report. Completing the replacement will also address reliability concerns by avoiding potentially catastrophic damage to other equipment within the substations.

Based on the engineering analysis, it is recommended that it is cost-effective to replace all 14 high-risk Energy Delivery power transformers with new transformers. It is crucial to take advantage of this time to plan and procure accordingly to replace these transformers and standardize a maximum of only two transformer manufacturers, which will be more cost-effective and productive to maintain.

The power transformers replacement plan is presented in the report. The Planning team recommends prioritizing these projects to be completed within the next 5 years before it becomes an emergency. The new transformers would allow the substation team to focus its ongoing maintenance program with other equipment on the system to improve the system's reliability of the GRU electrical grid.

REFERENCES

[1] G. Lambert-Torres, A. A. A. Esmin , "Application Of Particle Swarm Optimization To Optimal Power Systems," International Journal Of Innovative Computing, Information And Control, Vol. 8, No. 3A, Pp. 1705-1716, 2012.

[2] EL Bonaldi, LEL De Oliveira, JG. Borges Da Silva, G Lambert-Torres & L E Borges Da Silva, "Predictive Maintenance By Electrical Signature Analysis To Induction Motors," In Induction Motors— Modelling And Control, Croacia, Intech, 2012, Pp. 487-520.

[3] Los Angeles Department Of Water & Power, "2016-17 Power Infrastructure Plan," Los Angeles, 2015.

[4] B. D. Wachter, "Application Note Mv Transformer Replacement Decisions," European Copper Institute, P. 22, 2017.