DECISION MAKING PROCESS FOR COST EFFECTIVE AND RELIABLE DISTRIBUTION SUBSTATION SOLUTIONS

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ABSTRACT

This paper presents a methodology for modelling, analyzing, and selecting suitable single line configurations for distribution substations based on different criteria, such as reliability requirements, load flow, cost of interruption, initial investments, operation and maintenance. These criteria are combined in Life Cycle Costs (LCC) with associated interest rates and substation life cycle period. The methodology is implemented by utilizing specialized tools for calculating reliability, estimating cost efficiency and ranking substation alternatives. It is applied for typical distribution substations using conventional and alternative technologies.

To implement methodology we used two analytical software tools, SubRel™ and SubRank™, developed by ABB. The SubRel™ tool is used to model substation alternatives, assess their reliability, and calculate the life cycle cost. With SubRank™ the asset owner can combine the substation life cycle cost with his own estimation of different environmental and performance attributes in order to rank the substation alternatives.

INTRODUCTION

This paper presents a reliability analysis, economic evaluation and ranking for several substation alternatives. The reliability performance of this type of substations has a large influence on the overall customer plant reliability. Historically, the substation reliability estimation has been ad hoc and based on the designer's engineering experience. Such approach precludes the possibilities to find an optimal substation solution from technical and economical points of view.

The objective of this paper is to find the impact of substation design and technology to achieve an optimal solution with respect to reliability, performance and cost. A process to select a substation configuration by optimizing the total life cycle cost rather than investment cost is presented. Numerous substation alternatives can be modeled and evaluated using life cycle cost and intangibles (soft factors) such as environmental impact and substation performance. The methodology helps our customers to select the most suitable substation solution according to their specific economic and technical requirements.

RELIABILITY ASSESSMENT METHODOLOGY

The SubRel™ tool is a computer software application, consisting of graphical user interface (GUI), reliability database, and analytical engines to calculate substation reliability and life cycle cost [1, 2].

The program uses a dynamic state enumeration method for substation reliability assessment. To do this, SubRel™ automatically makes a failure mode and effect analysis (FMEA) by modeling every possible contingency, determine the impact of each contingency, determine the frequency of each contingency, and sums up the impact of all contingencies for an overall reliability assessment. The end result is the expected number of annual interruptions and the expected total annual interruption time for each component in the system.

The first thing that SubRel™ computes is the amount of time that a substation is in its normal operating state (NS). This is equal to the amount of time during one year minus the time spent in Maintenance States (MS):

$$Time\ in\ NS = \frac{8760 - Time\ in\ MS}{8760} 100\%$$

The program then simulates all faults that occur on components (while the system is in its normal operating state). For each faulted component, SubRel™ follows the following sequence of events:

1. The component experiences a fault.
2. The nearest protection devices on all energized paths to the faulted component are tripped (the protection system is assumed to perform as intended).
3. After a delay (determined by the Mean Time To Switch (MTTS) of disconnecting points), the fault is isolated and the system is reconfigured to restore power to as many loads as possible.
4. After the faulted component's Mean Time To Repair (MTTR) is elapsed, the fault is repaired and the system reverts to its normal operating state.

After simulating faults in the normal operating state, SubRel™ simulates all maintenance states and all faults that occur during maintenance states. When a component is maintained, the program automatically isolates the component using disconnecting devices and reconfigures the system to restore power to as many loads as possible. This maintenance state will, of course, cause the component being maintained to experience an outage. It may also cause an outage on nearby loads if they can not be fed via an alternative path during the maintenance.

Once the software determines the substation's maintenance state for a particular component, it will simulate faults during this state for all energized components. This fault simulation is identical to the method used during the normal state except that the system starts off in a different configuration.

SUBSTATION RELIABILITY MODELS AND

ANALYSIS

Our example: A distribution substation is to be built in order to provide a cement plant with electric power. The plant will receive power from two 120 kV overhead lines connected to independent sources. The high voltage will be transformed to 15 kV to supply the loads in the cement plant. It is clear that several substation configurations, implemented using different technologies, can be used for providing the power to the various loads in the plant. Our purpose is not to review each possible alternative but to show a methodology for selecting an optimal configuration and technology based on the specific requirements of various loads in the cement plant and the constraints of the surrounding distribution system.
To build the substation reliability models we use SubRel™ software described above. It allows us to:

- Draw and modify different substation alternatives
- Modeling substation configurations build with conventional equipment and with integrated modules.
- Calculate substation reliability, investment cost, O&M cost, and cost of interruption
- Calculate the total life cycle cost for the substation with user specified interest rate and life cycle time
- Repeat the calculation for different substation alternatives
- Transfer the results to an Excel spreadsheet with graphical interpretation.

Three substation alternatives, 120/15 kV, were modeled for supplying a cement plant using the software described above:

- H-connection with three circuit breakers (CB) and associated disconnectors– GIS technology
- Ring bus with four CBs – GIS technology
- Ring bus with four CBs – AIS technology

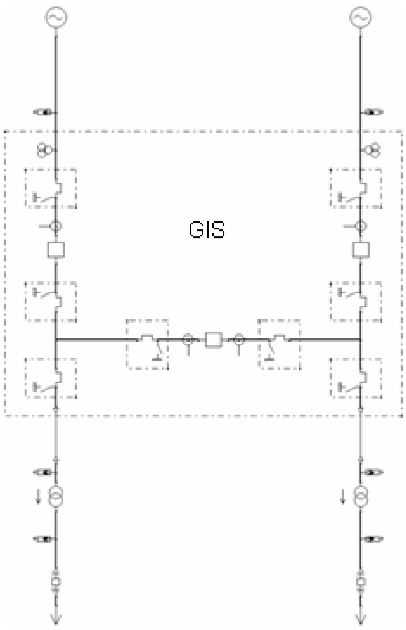

Figure 1. H-connection with 3 CBs – GIS

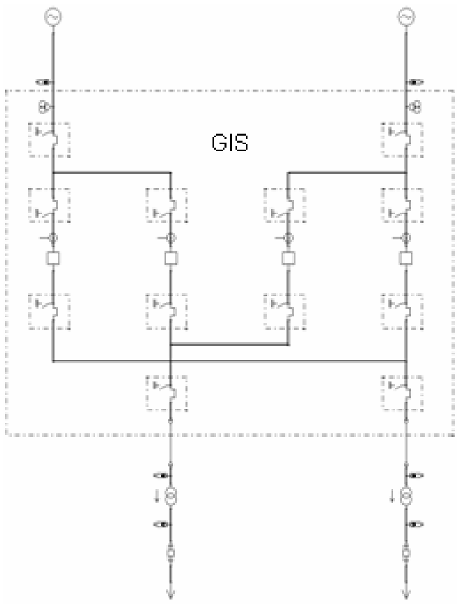

Figure 2. Ring bus with 4 CBs - GIS

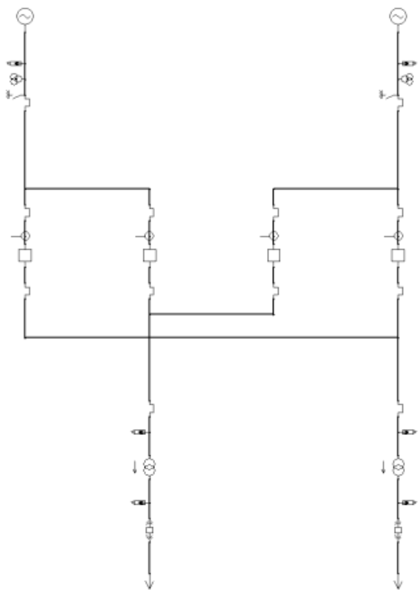

Figure 3. Ring bus with 4 CBs - AIS

On the 15 kV side of the substation we utilize standard metalclad switchgear, which is identical for all three alternatives. For simplicity, the reliability numbers are calculated at the point after the transformer main drawout circuit breaker. On the 120 kV side, we actually present two typical configurations: H-connection and Ring bus. In addition, the Ring bus configuration is implemented with two different technologies – AIS and GIS.
The reliability data used in the models are based upon long-term historic data available from open sources such as IEEE, Canadian Electricity Association (CEA), CIGRE [3-6]. The square around the equipment indicates the components located in one gas compartment for GIS

technology. Any fault of a piece of equipment in any such location will require opening of the entire gas compartment. SubRel™ software is capable of simulating substation reliability calculations with integrated type modules such as GIS, Innovative AIS and others.
The calculated reliability results for the three substation alternative are shown in Table 1 below.

Table 1. Reliability results for 15 kV load feeders

S/S Config.	TOF /yr	TOD hr/yr	OFF /yr	ODF hr/yr	OFM /yr	ODM hr/yr
H 3 CB GIS	0.5135	9.46	0.0635	3.66	0.45	5.80
Ring Bus GIS	0.5130	9.46	0.0630	3.66	0.45	5.80
Ring Bus AIS	1.2544	11.98	0.2044	3.78	1.05	8.20

The reliability results include the following components:

- Total Outage Frequency – TOF = OFF + OFM
- Total Outage Duration – TOD = ODF + ODM
- Outage Frequency due to equipment Failure – OFF
- Outage Duration due to equipment Failure – ODF
- Outage Frequency due to equipment Maintenance – OFM
- Outage Frequency due to equipment Maintenance – ODM

From the reliability results we can make the conclusion that the H-connection and Ring bus configurations with GIS technology both are equal from reliability point of view. Additional criteria should be used to select the right configuration for every specific case. For example, the H-connection includes less equipment, thus the initial investment cost will be lower. On the other hand, the Ring bus configuration is more flexible and allows different substation modifications when a fault occurs.
The Ring bus configuration implemented with AIS technology has lower reliability numbers and requires more frequent maintenance. On the other hand, AIS technology is with 25 to 30% lower initial cost compared to GIS technology.
Overall, to make the right decision for the most suitable substation alternative we should use not only the reliability results but additional criteria that can be different for any specific case. In the next two paragraphs we will review these criteria and include them for economical evaluation and ranking the substation alternatives.

ECONOMIC EVALUATION

Some of the major additional criteria that can be considered to find the most suitable substation configuration are:

- Capital cost for the substation – initial investment cost
- Additional cost due to land acquisition and site preparation
- Operation and maintenance cost (O&M Cost)
- Reliability related cost – due to power supply interruption

For simplicity's sake we will make economic evaluations only for the Ring bus configurations implemented with the GIS (Fig.2) and AIS (Fig. 3) technologies. In reality this analysis can be made for unlimited substation alternatives. It is estimated that the initial investment cost for the AIS Ring bus substation will be $5,000,000. For the GIS substation the total initial capital cost will be $7,000,000. The O&M cost for the AIS substation are estimated to be $25,000 per year for equipment cleaning. The annual routine maintenance costs for AIS equipment are estimated to be $3,000 per breaker position. A GIS substation does not require the cleaning costs since all energized components are enclosed in gas compartments, excluding the connection to the overhead lines. The annual routine maintenance cost for GIS substation is estimated to be about 10% of the cost for AIS equipment maintenance, i.e., $300 per breaker position for this particular case.
The reliability related costs for the cement plant supplied from this substation are due to loss of production, shutdown cost and loss of revenue. In the event in an outage, it is estimated that the facility will require 10 hours to restart and reestablish a normal production rate.
For a cement plant the typical average loss of production and shutdown cost can vary from $500,000 to $1,100,000 per outage depending of the size of the plant and the technology used. For reliability calculation these costs are expressed as summary of the cost of interrupted energy [$/kWh] and cost of interrupted power [$/kW]. The first item is related to the outage duration and the second, to the outage frequency.
To combine all of the variables mentioned above, i.e., capital cost, O&M cost and reliability related cost we can calculated the Life Cycle Cost for every substation alternative [8]:

$$LCC = IC + \left[FC + VC\right] * \left[\frac{(1+p)^n - 1}{p*(1+p)^n}\right]$$

Where:

LCC	=	Life Cycle Cost
IC	=	Investment Cost
FC	=	O&M Cost, i.e., fixed annual cost
VC	=	Interruption Cost, i.e., variable cost
n	=	substation planned life time
p	=	Interest rate

To calculate the LCC we are assuming a 7% discount rate and a 30 year substation life. The investment costs are $5,000,000 and $7,000,000 respectively. O&M costs are $37,000 per year for the AIS substation alternative and $1,200 for the GIS substation alternative.
For reliability related cost we will consider only outages due to equipment failure. Although the outages costs due to planned maintenance are also a factor, it is conservatively assumed that these costs are zero as the cement plant will be able to schedule the substation maintenance during the plant technology process maintenance. Considering the assumptions above we can calculate the LCC for the cost of interruption per outages varying from $500,000 to $1,100,000. The assumed cost of interrupted energy is $0.07/kWh.

Figure 4 shows the calculated LCC for both alternatives depending of the cement plant cost of interruption.

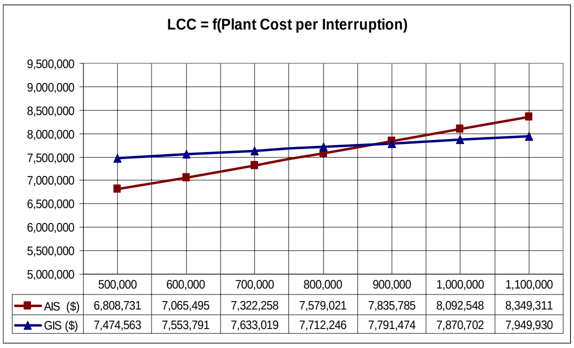

Figure 4. LCC for AIS and GIS Substations

If we compare both substation alternatives, we can conclude that depending of the cost of interruption per outage for the cement plant, either one of the substation alternatives can be more economically effective. When the cement plant cost of interruptions are under $875,000 per event, the AIS configuration is more cost effective from a LCC point of view. Over $875,000, the GIS configuration is becoming more cost effective.

RANKING SUBSTATION ALTERNATIVES

Usually, when the final decision regarding the substation configuration is to be made, the Life Cycle Cost and many additional objectives related to substation performance and its environmental impact should be considered. In reality, it is very difficult to combine attributes that can be expressed in currency and subjective attributes like flexibility, safety and environmental impact. In order to solve this problem we developed a tool called SubRank™ [9]. The tool is based on the idea to apply multi-criteria analysis for substation design [10] and multi-objective decision analysis using value hierarchy [11]. The tool considers the following objectives and their attributes for substation ranking process:

- Life Cycle Cost - Investment Cost, Site Preparation Cost, O&M Cost, Interruption/Failure cost
- Substation Performance – Flexibility, Safety, Automation Level, Technology Vintage
- Environmental Factors - Ecological Impact, Air Pollution Tolerance, Appearance/Aesthetics, Audible Noise Generated, EMF Generated, Radio/Television Interference Generated, Disposal Concerns

The values for the Life Cycle Cost are already calculated in the previous paragraph. The attributes for the substation performance and environmental factors can now be subjectively provided by the industrial customer. The final results can be shown as a graphic and a table. Figure 5 presents an example of the weighted single dimensional values and the total final values generated from SubRank™.

	Weighted Single Dimensional Values and Final Value			
	Life Cycle Cost	Performance	Environmental	Final Value
AIS Ring Bus	0.129	0.034	0.058	0.221
GIS Ring Bus	0.185	0.088	0.083	0.355

Figure 5. SubRank Calculated Values

CONCLUSIONS

The proposed decision making process for distribution type substations, and the tools developed for implementing this process, allows substation customers to select the most suitable configuration depending of their specific requirements. The criteria that can be used for this purpose are divided in two major groups:

- Cost related that are objective and expressed in the substation Life Cycle Cost. They include substation capital cost, site cost, O&M cost, and reliability related cost.
- "Soft" attributes, that are subjective and very difficult to express in numbers.

The proposed methodology implemented with the SubRel™ and SubRank™ tools allows a combination of the criteria in both groups to be applied for selecting feasible and cost effective substation configurations for different types of substation customers.

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