A Technique for Evaluating the Reliability Improvement due to Energy Storage Systems

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***Abstract*—Energy Storage Systems (ESS) can be employed to improve the reliability of power supply at isolated rural locations supplied by long radial networks. This study presents a Monte Carlo simulation based method for assessing the reliability improvement potential of such an ESS. The proposed methodology can be used to establish the proper power rating and storage duration to achieve a given reliability objective. The paper examines a case study for a rural community in Manitoba and establishes the relationship between the expected values of reliability indices and the energy storage duration. The results of the simulation demonstrate the improvement of reliability of power supply with the addition of an ESS located at the remote substation. However, according to ESS cost data published in literature, the proposed option may not still be economically feasible.**

Keywords- Energy Storage System; Supply reliability

I. INTRODUCTION

Some rural customers supplied by long radial sub-transmission lines in Manitoba experience a higher frequency and longer duration of interruptions as compared to customers on other parts of the integrated grid. The electricity interruptions arise from the outages on the long sub-transmission lines supplying isolated rural substations. Some of theses sub-transmission lines run through terrains that are accessible only through air or seasonal roads, and therefore repair is difficult and time consuming. Improving the reliability of power supply at these remote locations by strengthening the distribution grid, for example by constructing alternative lines is expensive and often subjected to opposition due to environmental concerns. Diesel based back-up power generation may be attractive despite fuel transportation and maintenance problems due to low capital cost (C$3.5 million for 10 MW). An alternative to this would be to introduce Energy Storage Systems (ESSs) at remote load centers.

Technology for electrical energy storage is rapidly maturing. Several energy storage technologies such as Battery Energy Storage Systems (BESS) and Flywheel Energy Storage Systems [FESS] are now commercially available. Also a number of large-scale ESSs have been practically implemented [1]. In addition to reliability improvement, ESSs can contribute to improve the dynamic stability, transient stability, voltage stability, frequency regulation and power quality [2] [3].

The technical planning of an ESS involves the selection of optimal power rating and storage duration to achieve a given reliability objective. The process often requires a method to quantify the reliability improvement resulting from a given ESS. This study presents a Monte Carlo simulation based method for assessing the reliability improvement potential of an ESS located at the remote end of a sub-transmission line. The following sections of this paper present the proposed approach through a case study. The simulation results and references [1], [3] and [4] were used to identify energy storage technologies suitable for the application. The scope of this paper is limited to establish a method for sizing the energy storage system. The viability of using ESS for reliability improvement applications is ultimately determined by the associated cost, which is not discussed in this paper.

II. RELIABILITY ASSESSMENT METHODOLOGY

The approach used in this paper involves four steps. The first step is to analyze the historical records of line operation to extract the Cumulative Distribution Functions (CDFs) of "Time between Outages" (TbO) and "Repair Time" (RT). These CDFs are used to create a simple two-state, state transition model for the line availability. The next step is to analyze the historical records of load demand and forecast the future load growth over the considered planning period. The third step is to consider various amounts of ESS. The last step is to run an hour by hour Monte Carlo simulation over the planning period and calculate the reliability indices.

In this paper, System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) are used to quantify the reliability. These are the indices used by the Manitoba Hydro, the utility serving the studied area. Currently Manitoba Hydro attempts to maintain SAIDI below 92 minutes/customer/year and SAIFI below 1.3 events/customer/year [5]. Although the term "System" in SAIFI and SAIDI refers to the entire customer base of the utility, the same indices can be used to express the reliability of a given feeder or subsystem, when calculated over the customer base served by the feeder [6].

III. REMOTE SUBSTATION

The substation considered in the study has a 9 MVA capacity and is fed by a 275 km long, 66 kV, radial sub-transmission system. The overhead lines run through dense forest, many swamp lands, rivers and lakes. The major causes of line outages are fallen trees, lightning, and faulty insulators.

A. Analysis of Line Outages

Information gathered from the Breaker Operations Reports for the sub-transmission lines during the last nine years (1997-

2005) were analyzed to extract the CDFs of TbO and RT for the system being studied. Fig. 1 shows the distribution of outage events over different months of the year. Two distinct seasons in terms of the frequency of outages were clearly visible: the period from May to September ('summer period') where there were an abundance of outages and the period from October to April ('winter period') where there were few outages. Since the differences were significant, different CDFs were studied for the summer and winter seasons.

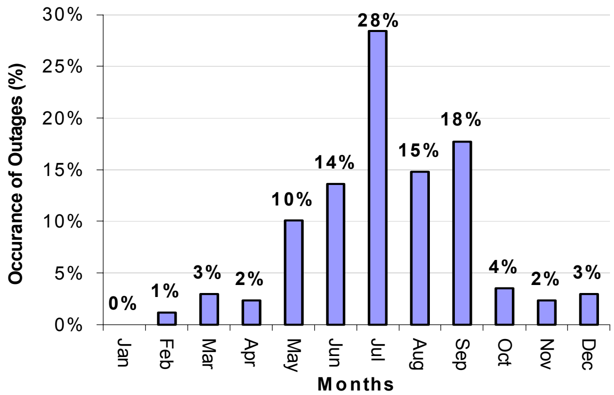

Figure 1. Outages for the period 1997 – 2005

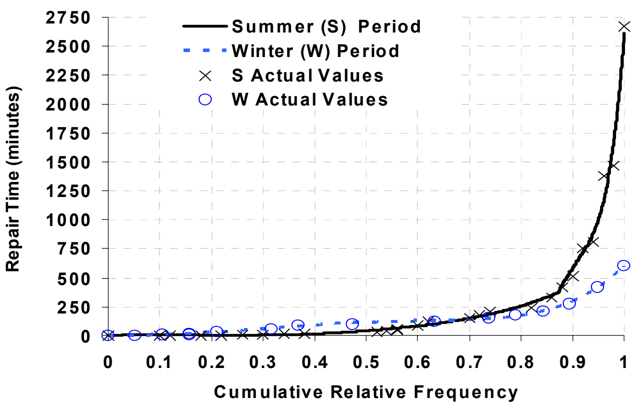

Figure 2. Repair Time (RT)

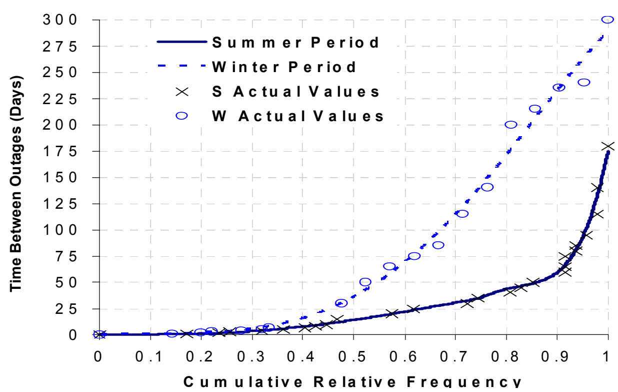

Figure 3. Time btween Outages (TbO)

Figs. 2 and 3 show the cumulative relative frequency distributions obtained for RT and TbO respectively. Polynomial equations fitted to these curves were used to represent these CDFs in Monte Carlo simulations.

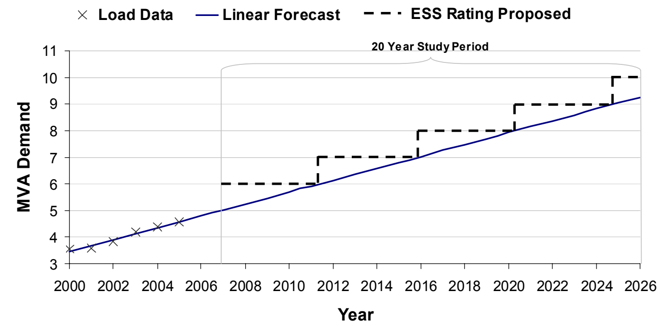

Figure 4. Forecast of Annual Peak Load Demand

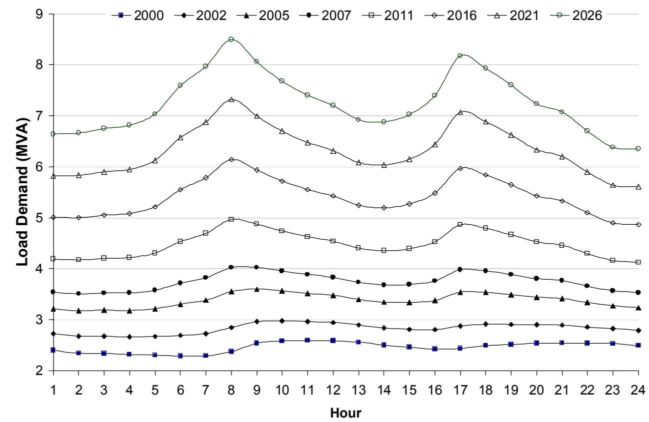

Figure 5. Forecast of Daily Load Profile for January

B. *Load Forecast*

Historical load data for the period from 2000 to 2005 was used to forecast the annual peak demand and the hourly load demands over the 20 year planning period. The load forecast assumed a linear load growth as it seemed to be the most reasonable fit for the historical data. Fig. 4 shows the forecast of peak demand and Fig. 5 shows the change of the daily load curve for the month of January. Similar forecasts were made for all other months.

IV. ENERGY STORAGE SYSTEM

A. *ESS Power Rating*

The ESS considered in this application was to support the total load supplied by the substation when the grid power is lost. Thus its power rating should always be greater than the forecasted peak load demand. Most ESSs are available in modular form and therefore it is possible to increase the capacity of ESS incrementally as the load grows. As illustrated in Fig. 4, the ESS capacity can be added in steps. The intervals at which the capacity is added can be decided based on the type of energy storage technology used. For example, if battery energy storage is used, the capacity expansion can be timed to coincide with the replacement of the existing batteries. Since different energy storage technologies have different life cycles, several expansion plans were considered. Fig. 6 illustrates four plans.

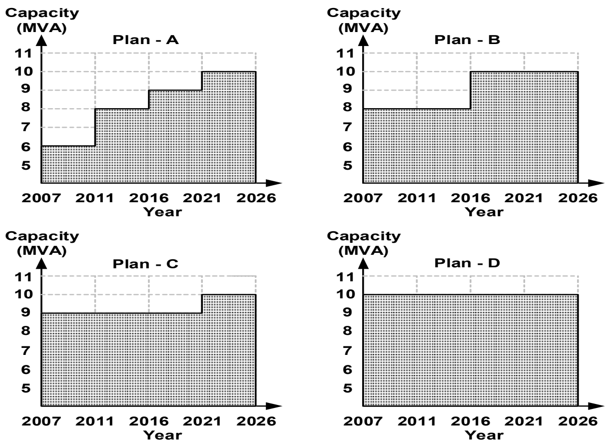

Figure 6. Different ESS Expansion Plans

According to the load forecast, the capacity of ESS required at the end of the 20 year period is 10 MVA. The expansion plan-A shows that the initial size of the ESS needed is 6 MVA. Five years later 2 MVA will be added to the ESS capacity. Similarly, in the 10th and 15th years, the ESS power rating will be expanded by 1 MVA. Likewise, in expansion plan-B, the desired initial ESS power rating is 8 MVA. After ten years, its power rating will be increased by another 2 MVA. In expansion plan-C, the ESS starts with a 9 MVA rating and will increase by 1 MVA in the 15th year. Expansions plan-D represents the case of placing the full ESS capacity at once with no modular design.

B. *ESS Energy Rating*

The ESS energy rating (the storage duration) is the main factor affecting the extent of reliability improvement. The strategy used here is to evaluate the expected reliability (in terms of reliability indices) for different storage durations and to select the suitable storage duration based on the obtained reliability-storage duration relationship. The reliability of the remote substation was calculated taking into account only the interruptions to customers supplied by it. In this study, only the interruptions due to failures on the primary side of the sub-transmission system are considered. In order to examine the effect of the duration of energy storage, τ (hours), the two indices, SAIDI and SAIFI for the customers served by the remote substation are evaluated for different values of τ. Evaluation of the expected values of indices is carried out using a Monte Carlo simulation. Once the relationships between the reliability indices and the storage duration is established, it is possible to select the appropriate energy rating for the ESS to achieve a given reliability level that is determined by the economic factors.

V. MONTE CARLO SIMULATION

A computer algorithm was developed in MATLAB® to perform Monte Carlo simulations to determine the expected reliability improvement due to the installation of an ESS at the remote substation. The substation is assumed to be in two possible states: (i) grid supplies the load (as well as the ESS), (ii) grid out but ESS supplies the load. The frequency of outages and the durations of outages in the simulation are governed by the CDFs of 'time between outages' and 'repair time' found in Section III-A.

The simulation starts with the grid in operation and the ESS fully charged. The time until the first outage is determined by generating a random number between 0 and 1, and then finding the corresponding time from the CDF of TbO. The simulation is progressed on an hourly basis. For a given day, load MVA demand for each hour is computed using the load forecast equations developed in Section III-B. If there is no outage on that day, the total load is supplied by the grid. On the other hand, if the there is an outage in the day, the outage duration is determined using the CDF for RT. It is assumed that during the grid outage, ESS supplies the total load for as long as it can. State of the storage (i.e. remaining energy in the storage) is accounted in each hour, and if the energy stored in the ESS drops below a specified minimum limit, the load is interrupted. At the end of each day, the variables storing the important details are updated. The recorded information include such quantities as the total number of outages so far, total duration of ESS operation, total duration when the load was interrupted, total energy supplied by the grid, total energy supplied by the ESS, total energy demand not supplied, etc. The hour by hour simulation continues for the 20 year planning period. At the end of the simulation, these recorded data can be used to determine the reliability indices and obtain useful information pertaining to the operation of the ESS.

The SAIFI and SAIDI, which are calculated for each year, are averaged over the 20 year period to obtain a single reliability figure. As the SAIFI and SAIDI values so obtained are dependent on the random number sequence used, the simulation is repeated many times with different random number sequences. Monte Carlo simulation is considered converged when the average values SAIFI and SAIDI obtained, after repeated simulations, become stable.

VI. RESULTS AND DISSCUSSION

Fig. 7 shows the evolution of the mean value for the 20 year average of SAIFI during a simulation. The mean value of SAIFI converges after around 3000 repeated simulation runs. Similar trend was observed in respect of duration index SAIDI.

In order to obtain the relationship between the reliability and storage duration, Monte Carlo simulations were performed for different ESS durations. For each of the expansion plans, storage duration τ, was varied from 0 to 4 hours. It was assumed that maximum Depth of Discharge (DoD) allowed is 70% based on the DoD of batteries. Figs. 8 and 9 demonstrate the variations of SAIFI and SAIDI values with τ.

According to Fig. 8, without any ESS the SAIFI value is around 6.6 events/customer/year. With increasing ESS duration, the SAIFI values decrease for all expansion plans. In order to achieve Manitoba Hydro targets, storage duration between 1.5 to 2 hours is required depending on the expansion plan.

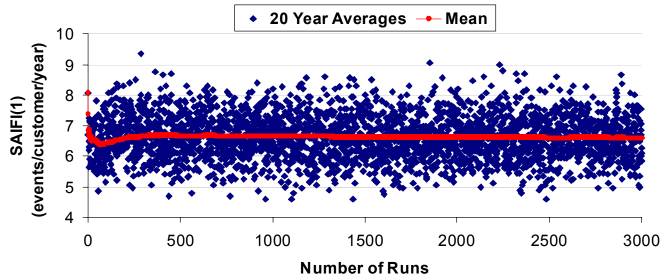

Figure 7. Determining SAIFI(1h) Convergence Value

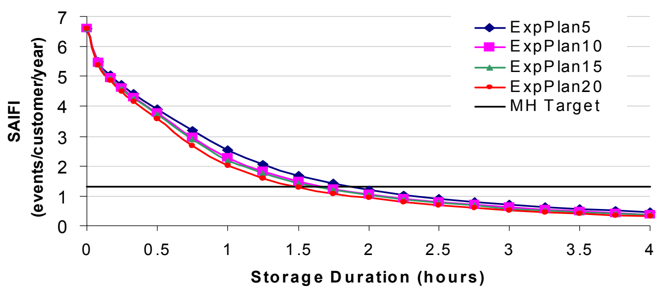

Figure 8. Variation of SAIFI with ESS duration

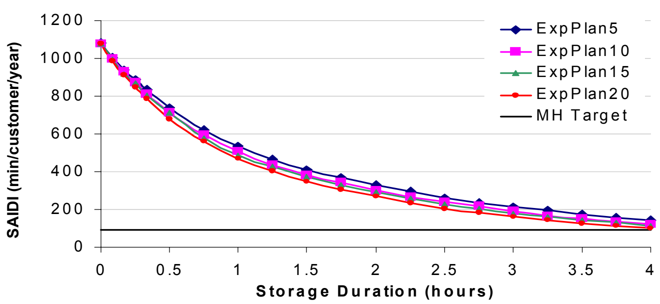

Figure 9. Variation of SAIDI with ESS duration

Very similar relationship was obtained for the variation of SAIDI with the storage duration. As can be seen in Fig. 9, without any ESS the SAIDI for the substation is approximately 1100 minutes/customer/year. The expansion plan that came closest to the Manitoba Hydro target value was the plan where total capacity of the storage is installed at the very beginning of the project. A 2 hour ESS would reduce the value of SAIDI to 250-300 minutes/customer/year. Although this is still higher than the system wide average, it is justifiable considering the remote nature of the location.

A. Energy Storage Technology

The energy storage technology is chosen based on power and energy rating of the ESS. The ESS rating require for this location was around 6 – 10 MVA, 12 – 20 MWh. The ESS for this location required the operation of an uninterruptible power supply (UPS) as well as providing long durations of energy. According to [3], such an application can be categorized as Long Duration Power Quality (LPQ) application. References [3] and [1] have stated that BESSs are the most promising of the different ESSs based on the power level and discharge time.

Among commercially available battery technologies for this application are lead acid and sodium sulphur (NaS) [3], [4]. Reference [3] shows many examples of areas throughout Japan that uses the NaS battery systems with features similar to this application. Other technologies that have possibilities are redox flow cells such as zinc bromine, vanadium, and polysulfide bromide [3], [4]. Castle Valley, Utah is a situation similar to this case study in Manitoba that uses vanadium redox flow cells for a smaller 250kW peak shifting ESS.

References [1], [3] and [4] go on to demonstrate the life cycle cost comparisons of the different technologies being used. According to the estimates given in [1] and [3], the cost of an ESS based on the above mentioned technologies range from C$21 to C$40 million. The cost of ESS is a major factor affecting the viability of the proposed approach for improving the reliability at isolated locations. The total cost can be reduced if the rating of the ESS can be reduced. This is achievable, for example, by introducing a scheme for shedding certain types of loads such as water and space heaters during the outages. By removing such loads having a large thermal capacity, the peak demand of the substation may be reduced by as much as 50% of the current level without adversely affecting the customers. The Monte Carlo simulation proposed in this can be easily extended to analyze such scenarios.

VII. CONCLUSION

The paper presented a Monte Carlo simulation based method for assessing the reliability improvement potential of an ESS located at the remote end of a sub-transmission line. The method was applied to analyze an ESS located in a substation supplying a remote community in Manitoba. Based on the analysis, an ESS with duration of about two hours would be required for this location. According to surveys of EPRI and DOE [3] battery energy storage appears to be the most suitable option for this type of application. However, detailed cost analysis is needed to determine the economic feasibility of using ESSs for this application. Work on ESS cost evaluation is in progress.

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