Generation Risk Assessment of Main Output Transformers

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Abstract

The loss of large power transformers may have major implications for plant operation, performance, safety, and economics. This paper examines the generation risk associated with main output transformers (MOTs) at a large nuclear station using the Monte Carlo simulation approach. The developed methodology is used for spare inventory optimization and making transformer replacement projections, while taking into account the specific demographics and condition of the transformer population. The transformer reliability is described using a flexible, three parameter mixed Expontial/Weibull lifetime distribution. The results of the study indicate that, due to the long procurement time for large transformers, at least 1 or 2 spare transformers are needed immediately to minimize the risk to the station. Delaying the investment, even for a single year, would increase the risk significantly.

1. Introduction

Large power transformers are important contributors to power plant production and reliability. They range in size from a few MVA to several hundred MVA, depending on the service requirements [1]. Large transformers are also important for the safe operation of nuclear power plants, since they provide power to the station safety systems and safety-related buses for the safe shutdown of the reactor.

A reactor unit typically consists of three large transformers. The main output transformer (MOT), also referred to as the generator step-up (GSU) or unit transformer (UT) [1], steps up the output from the main generator (e.g., 22 kV) to the high voltage (e.g., 500 kV) in the local transmission system or grid. The unit service transformer (UST), also referred to as the unit auxiliary (UAT) or normal station service transformer [1], supplies power from the main generator to auxiliary equipment at the plant during normal (at-power) plant operation. Finally, the system service transformer (SST), also referred to as start-up auxiliary (SAT) or reserve auxiliary (RAT) transformer [1], operates in reverse of the MOT by stepping down the power from the external transmission grid to provide power for the unit during shutdown and start-up (i.e., when the plant itself is not producing any power).

Large power transformers consist of a main tank containing the transformer cooling oil, magnetic core, and insulated copper windings. The condition of the cooling oil is critical as it transfers the heat from the windings to external cooling equipment and also maintains the dielectric properties of the insulating paper. Transformers are supported by many sub-systems which provide phase isolation, electromagnetic current, voltage regulation, cooling, and structural support and physical containment for the transformer. The transformer interfaces with other equipment through sets of bushings. Large transformers are typically custom designed to meet local grid voltage, current and other plant specific requirements.

Large power transformers have generally been very reliable, with 30 to 40 year design lives [1 - 4]. However, the general transformer population is aging, resulting in an increased risk of failure. The risk of failure is further compounded by a decrease in routine maintenance due to economic constraints, increased loading from unit power upgrades, and higher load fluctuations in the transmission grid as a result of deregulation and the increase in intermittent power sources, such as wind [1].

Because large transformers are an assembly of many electrical and mechanical components, failures are often repairable with minimal downtime (and hence outage cost). However, the aging degradation of the insulating paper will eventually require the complete replacement or overhaul of the transformer unit. The replacement of large transformers is costly, with planned replacement costs ranging from 4 million (EUR) per unit [5] to $ 87 million (USD) for the replacement of six main power transformers [6].

Although the planned replacement of large transformers may involve a high capital cost, the unplanned replacement of a large transformer is typically orders of magnitude higher. Large transformers are complex and often custom made units that require potentially long manufacturing and installation times. Procuring a new transformer may take from one year up to 18 months or more [5, 7, 8]. As a result, guarding against the unplanned critical (i.e., non-repairable) failure and the subsequent long outage is the most important aspect of transformer life-cycle management (LCM).

The main objective of this study is to develop a general methodology for making transformer replacement projections, which also takes into account the specific demographics and condition of the transformer population. The procurement and stocking of spares is a central part of the assessment as it provides a means to mitigate against the potentially long unplanned replacement outage. The methodology is based on Monte Carlo simulation, which is the only way to solve repairable system reliability problems with time-dependent failure rates (due to aging degradation) and complex replacement and spare strategies.

An example application is used to demonstrate how the methodology can be used in risk-informed decision making with respect to a population of MOT transformers at a large power station.

2. Transformer reliability

Despite industry's increased attention to transformer maintenance, transformer failures are on a general increase [1]. Most frequent trips occur as a result of bushing failures, spurious pressure relay activation, lightning strikes, loss of cooling, gas-in-oil generation, and tap changer failures [1]. Among Canadian utilities, the leading cause of failure is insulation degradation and aging [9]. Other types of failure events and industry experience are summarized, for example, in [1, 3, 4, 10, 11].

It is important to note that there are two types of failure events for large transformers: repairable and non-repairable. Distinguishing between the two types is critical for the proper assessment and prediction of transformer risk and reliability.

2.1 Repairable vs. non-repairable (critical) failures

Large transformers consist of many sub-components and equipment whose failure will render the transformer unit unavailable for service. These failures are typically repairable (e.g., the failure of a bushing or cooling system), allowing the transformer to continue in-service following a brief downtime for repairs. The occurrence of these types of events by themselves does not result in the end-of-life (EOL) of the transformer, although their frequency and severity may have a negative impact on the transformer lifetime.

Ultimately, the service life or EOL of a transformer is governed by the life of the paper insulation [12]. As transformers age, their insulation strength degrades until they are unable to withstand system events such as short-circuit faults or transient overvoltages, resulting in a critical (non-repairable) failure. This type of failure will require the replacement (or overhaul) of the transformer and cause a potentially long outage, unless a spare transformer is readily available in stock.

2.2 Lifetime distribution modelling

Aging of the paper insulation implies that the chance of critical transformer failure is also increasing with time. This wearout phenomenon corresponds to the increasing hazard rate in the classic "bathtub" curve, which is often modelled using the Weibull lifetime distribution.

The main challenge in lifetime modelling is the availability of data [13]. Many industry sources [e.g., 1, 3, 14] report transformer failure rates, which correspond to *repairable* (hence, repeat) failures. The occurrence of these events (e.g., the failure of pressure relays) may also be increasing with time, however, their impact on the actual transformer lifetime (i.e., *critical* transformer failure) is unknown and difficult to quantify.

In general, there is very limited data on critical transformer failures. Many utilities replace degraded transformers before they fail critically. Even with existing critical failure data, relating industry experience to a particular plant is very difficult, because transformers are often unique, custom made units, subject to specific local loading and insulation system conditions (i.e., thermal and voltage stresses, contamination, etc.) during their lifetimes.

Once an appropriate lifetime distribution has been chosen or fitted for a particular group of transformers, it must also be "conditioned" to account for the specific demographics within the group. That is, truncating the lifetime distribution at the current age of each transformer to account for the survival up to the present time [15].

Another approach for modelling the transformer lifetime is to construct a physically based model for the insulation degradation directly. This involves formulating a mathematical relationship between the condition of the insulation (e.g., degree of polymerization) and all the important contributing factors (load conditions, temperature, oil quality, etc.). Various types of models have been developed [16], however, in addition to the requirement of very specific and often costly condition monitoring data, applying and calibrating these models to transformers at a particular plant is subject to potentially large uncertainty and error.

3. Probabilistic modelling

Various methods have been used to model the lifetime of large transformers and to determine optimal spare strategies [8, 13, 14, 17-19]. Both the Poisson and Markov processes [8, 17, 18] are based on the constant failure rate assumption, and therefore cannot be used to model aging degradation of the insulating paper in large transformers. Monte Carlo simulation is the most versatile, flexible and widely used method for solving many problems in engineering. It allows the solution of large and complex problems that cannot be described using analytical methods [7, 8, 20, 21]. It is therefore well suited not only for the analysis of repairable system reliability, but also for risk analysis in general.

The main advantage of Monte Carlo simulation is that it allows the consideration of general failure and repair distributions, and the inclusion of various intervention and repair strategies, including imperfect repair. The analysis can also include various maintenance strategies as well as diverse resource data, such as the availability of spare parts and maintenance resources. It is also well suited for risk-informed decision making applications, because reliability and costs are computed in "real" time, taking into account factors such as escalation, electricity costs, etc. Furthermore, there is great flexibility with respect to the decision variables that are involved, as uncertainty distributions can be prescribed to any parameter of interest, such as costs, durations, etc.

3.1 Simulation approach

Consider a group of large transformers at a power station. Each transformer is described by a particular parametric lifetime distribution (e.g., Weibull), which must also be "conditioned" to account for the current age of each unit. Other important elements or decision criteria that must be specified include the reliability of the replacements/spares, the number of spares, and the stock-policy for ordering new spares.

Each simulation trial begins by drawing a time to critical failure for each transformer from its conditional lifetime distribution. The first failed transformer is then replaced with a spare, if one is available, while a new spare is ordered according to the spare stock-policy. If a spare is not available, the unit remains shutdown (i.e., unavailable) until a spare does become available, or a replacement transformer is procured and installed in-service. The critical failure time for the replacement/spare transformer is then simulated and the whole process is repeated until all failure times exceed the end of the study period. The next simulation trial is then started, while keeping track of unavailability, frequency of failures/replacements and spare orders, along with all associated costs. The net present value (NPV) or risk associated with each scenario or trial is computed using a specified discount rate.

In addition to the previous decision criteria, other parameters (deterministic or distributions) that must be specified in the analysis include the outage lengths when a spare is available and unavailable, cost of each spare, cost of (replacement) power, length of the planning period, inventory holding costs, escalation factors, etc. The key aspect of Monte Carlo simulation is that it allows the consideration of highly realistic and complex planning scenarios that could not be analyzed using any other methods.

4. Model application

Consider a large nuclear power station consisting of four reactors, each having a power output of 880 MW. The main generator in each reactor unit is connected to three large main output transformers (MOTs), one for each phase, rated at 990 MVA each, for a total of 12 MOTs for the station. The objective of this example application is to estimate the risk associated with the MOT operation under various planning scenarios until the estimated station end-of-life (EOL) in year 2045.

The analysis is strictly limited to the risk associated with critical MOT failures requiring the replacement of the transformer with a spare or a replacement transformer. Repairable failures of transformer sub-components, such as bushings, tap changers, pressure relays, etc., also contribute to the overall risk, however, their impact is generally much smaller, and hence will not be considered in this study.

4.1 MOT lifetime distribution

Rather than the standard Weibull distribution, which has been used to describe the non-critical or repairable failures of large transformers [3], we use a more flexible three parameter mixed Exponential/Weibull lifetime distribution model to describe the critical MOT failures. Our approach is similar to [19], except that we use the lifetime distribution for critical failures only. The three parameter mixed Exponential/Weibull lifetime distribution is given as.

$$F(t) = 1 - \exp\left[-\lambda t - \left(\frac{t}{\beta}\right)^{\alpha}\right] \tag{1}$$

where λ is the constant parameter of the Exponential distribution, and α and β are the shape and scale parameters of the Weibull distribution, respectively. The time-dependent hazard rate is expressed as

$$h(t) = \lambda + \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{\alpha-1} \tag{2}$$

There is very little plant specific or industry generic data regarding the critical failure of large MOT transformers. Therefore, we use the flexibility of the above lifetime distribution to construct four separate cases to represent the critical failure of the MOTs. The four distributions are described in Table 1, with the corresponding hazard rate plots shown in Figure 1.

As shown in Table 1 and Figure 1, we assume a low constant hazard rate equal to 0.005 critical failures/year similar to [14] for all cases to represent critical failures from (random) causes other than aging. The mean lifetimes range from 38 to 200 years, depending on the assumed severity of the aging degradation process. The failure times for each transformer in the simulation are generated using the inverse transformation method with Newton-Rhapson iteration to solve the non-linear quantile function.

Table 1 Mixed Exponential/Weibull lifetime distribution parameters for MOT failure.

Severity of Degradation	**MTTF** (years)	**Distribution Parameters**		
		λ	α	β
No aging	200	1.005	1	-1
Low	64.9	0.005	3.0	90.2
Moderate	43.7	0.005	3.5	55.4
High	38.1	0.005	4.0	47.0

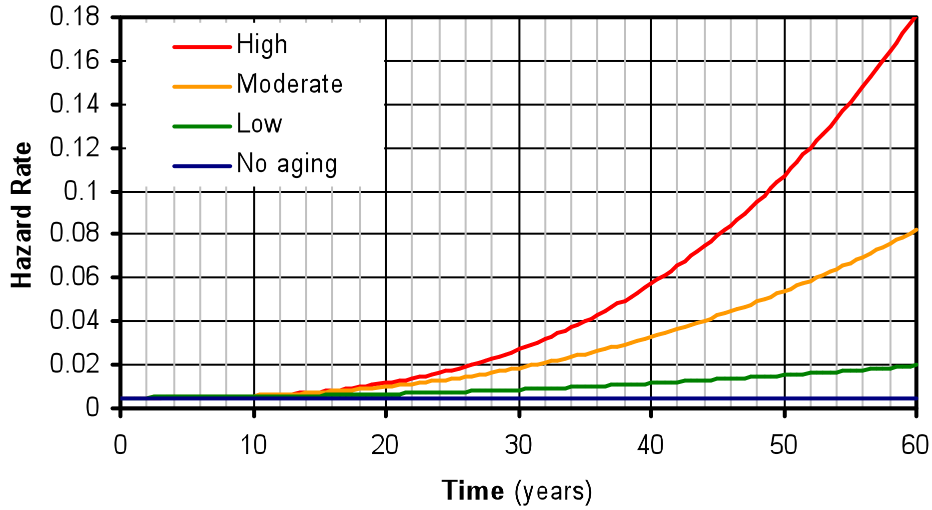

Figure 1 Hazard rates for the four different cases of critical failure of MOTs.

As shown in Figure 1, the hazard rate begins to increase after about 12 to 15 years in service for the three cases with aging degradation (i.e., low, moderate, and high). After 35 years of operation, the hazard rates are equal to 1 %/year, 2.5 %/year and 4 %/year for the low, moderate, and high cases, respectively.

4.2 Other assumptions

The planning period for the study is from year 2011 to year 2045. The current age of the MOT transformers is assumed to be 20 years. Hence, the lifetime of the existing MOTs follows a conditional distribution, while the lifetime of all new replacement and spare transformers follows the original distribution, as shown in Eq. (1). It is assumed that for each case, the spare or replacement transformer has the same reliability (i.e., lifetime distribution with the same intensity of aging degradation) as the original transformer.

A new transformer will require 12 months to be procured and delivered to the site, while a failed transformer can be replaced in 15 days during a forced outage, if a spare is available. The cost (including installation) of a new transformer is assumed to be \$ 5 million. Other factors, such as depreciation of spares or inventory holding costs are not considered in the analysis. The price of electricity is assumed to be constant over the study period and equal to \$ 0.55 / kWh. The discount rate is assumed to be 7 % for the present value calculations.

5. Results and discussion

Several planning scenarios are considered and presented in the following. All results are based on a minimum of 10^7 simulation trials, with each simulation taking a matter a minutes on a standard desktop computer.

5.1 Base case

There are currently no serviceable spare MOTs available at the station, therefore, the Base case assumption is that the station will continue operating without any spares until the station end-of-life (EOL) in 2045. This implies a 12 month forced outage whenever there is a critical MOT failure.

Figure 2 shows the average annual MOT failure/replacement frequency for the various cases of aging degradation. The corresponding average annual unavailabilities are essentially the same (not shown), because of the 12 month (i.e., one year) forced outage duration.

As shown by Figure 2, the replacement frequency (and unavailability) are quite high in all cases, mainly due to the large number of transformers and the lack of spares. In case of aging degradation, the replacement frequency and unavailability increase over time.

Table 2 illustrates how the average or expected number of replacements by year 2045 may be as high as 11 (depending on the severity of aging degradation), resulting in substantial generation and economic risk to the station. Nearly all of the risk is due to the long forced outage following a critical transformer failure, therefore, considering investment in spare transformers would appear to be a prudent and logical LCM planning strategy for the station.

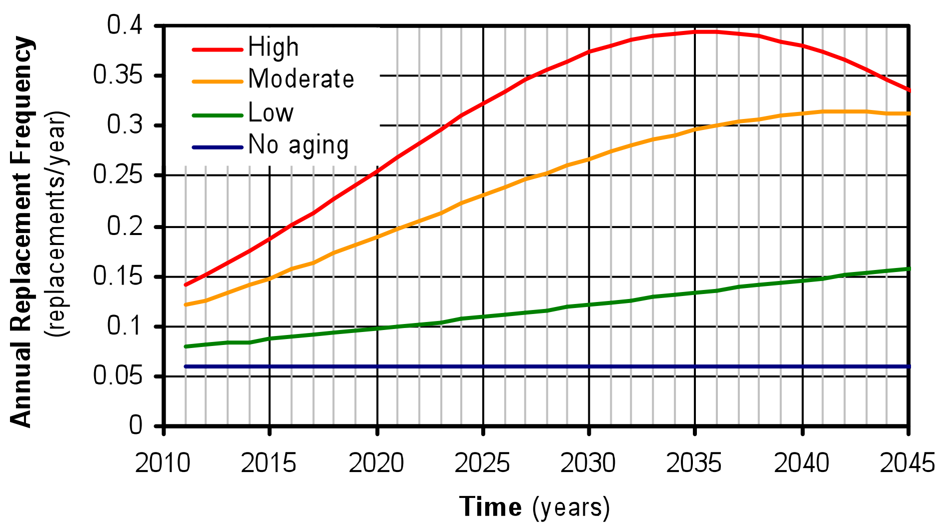

Figure 2 Average annual MOT failure/replacement frequency.

Table 2 Base case risk assessment results.

Severity of Degradation	**Average Number of Replacements by year 2045**	**Total Risk*** ($ Million)
No aging	2.1	320
Low	4.1	547
Moderate	8.4	1,059
High	10.9	1,389

* Total risk is in terms of net present value (NPV) using a discount rate of 7 %.

5.2 Optimal number of spares

The Monte Carlo simulation approach can be readily adopted for assessing the optimal spare strategy for the station. Assuming the stock-policy is always to maintain a specific number of spare transformers in stock over the entire planning period, Figure 3 illustrates the impact of number of spares on the replacement frequency for the case of *moderate* aging degradation.

Figure 3 shows a curious result, in that the replacement frequency appears to increase with the number of spares. Again, the case of, for example, 1 spare here implies that a single spare is always maintained in stock (i.e., a new one is always ordered upon failure). The reason for the increased frequency observed in Figure 3 is that more replacements can be performed in a shorter period of time when spares are available. In the case of no spares, a unit must be shutdown for 12 months upon MOT failure while a replacement is being procured. This means that the other two MOTs in the unit cannot fail during this time (i.e., their failure is delayed) because the unit is shutdown. When spares are available, the unit can be restored to service in a much shorter period of time (i.e., 15 days), resulting in more critical failures. This also occurs because the replacement transformers have the same lifetime distribution as the failed units (i.e., their reliability is assumed to be the same as the existing transformers).

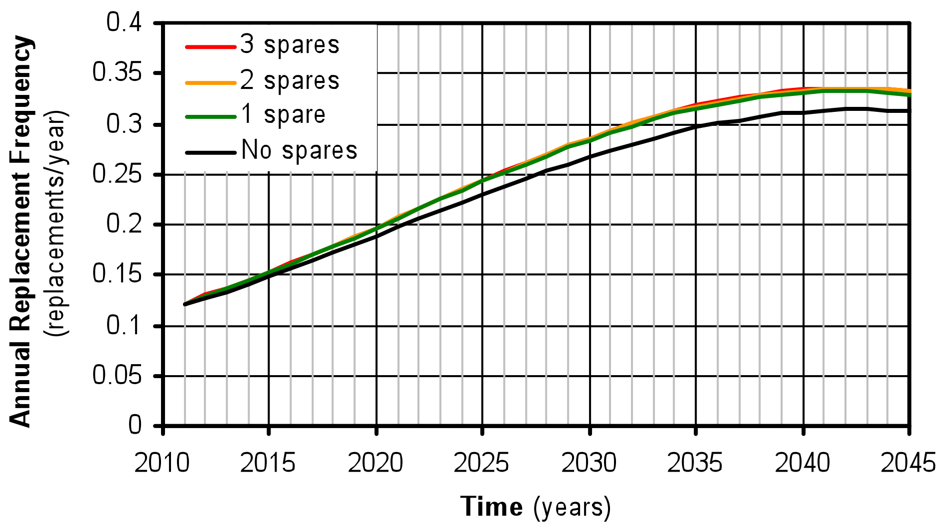

Figure 3 Average annual MOT failure/replacement frequency versus number of spares for the case of moderate aging degradation.

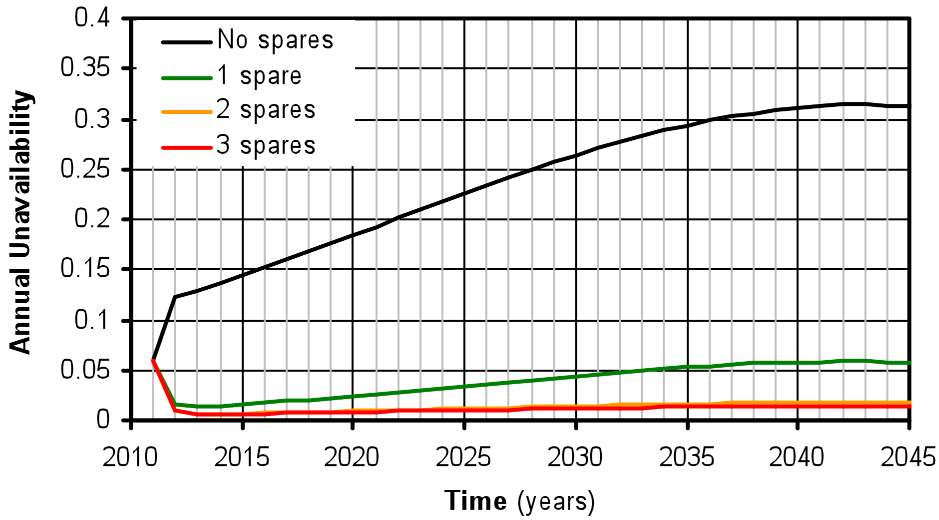

Figure 4   Average annual unit unavailability versus number of spares for the case of moderate aging degradation.

Lost power due to unavailability is typically the highest contributor to generation and economic risk. Figure 4 above shows the impact of spares on the unit unavailability. It is evident that stocking even a single spare can reduce the overall unavailability substantially. Nearly all of the unavailability associated with 3 spares is due to the 15 day replacement time, which means nearly perfect coverage, i.e., a spare is always available in-stock when a critical failure occurs. Therefore, having more than 3 spares will not have any additional impact on unavailability, and hence, overall risk.

Figure 5 shows the impact of number of spares on the total risk for all cases. It is evident that regardless of the severity of aging degradation, maintaining at least a single spare in stock will reduce the overall risk dramatically. In case the transformers are indeed aging over time, Figure 5 illustrates that maintaining an additional spare can reduce the overall risk even further. Again, having more than 3 spares will not have a significant impact on the overall risk.

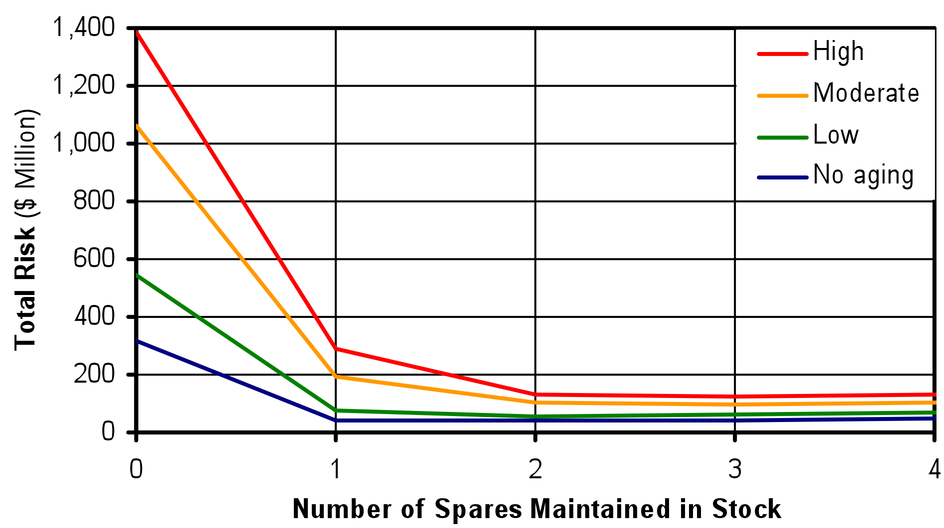

Figure 5   Total risk versus the number of spares maintained in stock.

5.3 Replace all 12 MOTs during a future refurbishment outage

Let us assume that the station is unwilling to consider a \$ 10 million capital investment on two spare transformers because it is considering replacing all 12 MOTs in a refurbishment outage in the near future. Figure 6 illustrates the increase in total risk versus the number of years the initial spare order (of 2 spares) is delayed.

As shown by Figure 6, it is clear that delaying the spare order even for a single year would increase the total risk in the range of \$ 20 - \$ 50 million. Therefore, waiting for several years until refurbishment would clearly be a risky undertaking, even assuming no aging degradation is taking place.

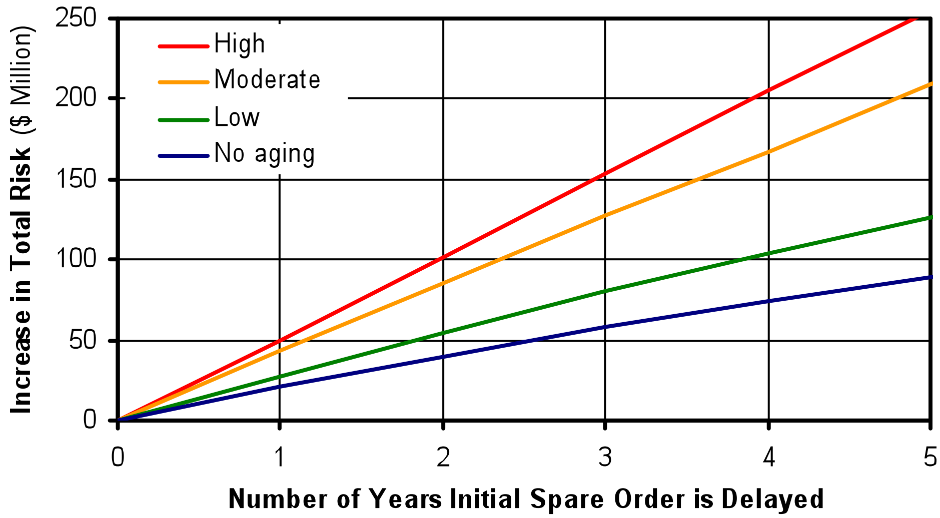

Figure 6 Increase in total risk versus the number of years initial spare order is delayed.

6. Summary

Large power transformers are significant contributors to plant reliability, safety and economics. In this study, the Monte Carlo simulation approach was used to assess the risk associated with a group of 12 MOT transformers at a large power station. The MOT reliability and various intensities of aging degradation were described using a flexible, three parameter Exponential/Weibull distribution. The demographics and condition of the individual transformers were also considered in the analysis.

The example application showed how the developed methodology allows the consideration of highly realistic and complex planning scenarios that could not be effectively analyzed using other methods. The sample results of the simulation study revealed that the station should consider maintaining at least 1 or 2 spare MOT transformers in stock at all times to minimize the risk posed by the potentially long outage to procure a replacement transformer. The study also confirmed that delaying the decision to purchase the spares, even for a single year, would result in a substantial increase in risk to the station.

7. Acknowledgements

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