Incorporating Multi-Year Asset Replacement Time Into Calculation of Asset's Expected Annual Unavailability Due to End-of-Life Failure

Miodrag Kandic, *Member, IEEE*, Ioni Fernando, *Senior Member, IEEE*, Aniruddha Gole, *Fellow, IEEE*, and Liqun Wang

***Abstract*—Aging asset management requires careful consideration of end-of-life of any asset. This is particularly serious with aging infrastructure which may require complete replacement of a large asset which has a long lead time. In many current End-of-Life analysis approaches to calculate unavailability, the period of interest is sub-divided into yearly cycles with the assumption that the asset is available at the start of the year. Although this assumption is adequate if the replacement time for the asset occurs within the year, with longer lead times this can create excessively optimistic availabilities. This paper presents an improved probabilistic tool for risk assessment due to End-of-Life failure unavailability which overcomes this deficiency. The End-of-Life methodology proposed in this paper is required when aging assets have long lead times to replacement and so the capital investment decision must be made several years ahead. The method is applied to evaluate the End-of-Life unavailability of Manitoba Hydro Bipole II HVdc converters. The results are corroborated using Monte Carlo simulation. Finally, the risk of End-of-Life is incorporated into an economic cost-benefit analysis corresponding to the presented unavailability evaluation method.**

***Index Terms*—End-of-Life (EOL), EOL failure, aging failure, repairable failure, LCC (Line Commutated Converter), HVdc, Bipole (BP), Pole, Valve Groups (VGs), Probability, Probability Density Function (PDF), Cumulative Distribution Function (CDF), Conditional PDF.**

I. Introduction

Electric utilities all over the world see the need for replacement and upgrades to the aging critical assets. The regulatory and public pressure to achieve two contradictory fiscal goals, of minimizing capital investment and minimizing risk of unavailability of aging assets have mandated the utilities to scrutinize the capital-intensive replacement projects to avoid premature asset replacement. This work is motivated by Manitoba Hydro's project justification process, which is based on both deterministic and probabilistic methods of evaluation for a critical HVdc asset. The asset considered for replacement is the Nelson River Bipole II which is an LCC Bipolar HVdc Link where each pole consists of two series Valve Groups (VGs). Bipole II commissioned in stages between 1978 and 1985, is the only HVdc scheme in the world from that era, with a power rating greater than 1,000MW that has to date not received any major refurbishment work.

Manitoba Hydro's three Bipole HVdc system forms its transmission backbone that delivers a large percentage of Manitoba's generation from the northern Nelson River system to the southern load center.

An existing approach to EOL failure analysis [1] provides methods of computing EOL probability of failure and the unavailability of an asset for a single future year, assuming the asset has survived until the beginning of that year. It assumes outages to only last till the end of that year and ignores the possibility that outages in the year of observation could prolong to multiple years. Such an assumption is practical to make for assets with a short (less than a year) replacement time, since if it had failed the asset would have been reactively replaced prior to considered year. Alternatively, such an assumption can also be made if the risk of EOL unavailability of an asset is not very high. The unavailability then must be evaluated repeatedly at the beginning of each year for effective decision making. Using the approach in [2], the probability of EOL failure and ensuing unavailability for a multiple year period ahead, can be assessed assuming the known present age [2]. However, this methodology does not provide an annualized unavailability for future years, which is required for the annualized economic assessment.

This work introduces an improved approach to determine End-of-Life (EOL) probability of failure, and thereby the expected annual unavailability of the asset in future years. The novelty in the proposed methodology lies in its ability to assess the EOL unavailability for multiple future year period, but on an annual basis, without ignoring the possibility of prolonged multi-year outages (see Appendix II for details). Such annual evaluation is mandatory for the risk analysis in justifying replacement projects of long lead time. In an environment with competing capital investments, the proposed economic

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evaluation framework with EOL unavailability incorporated, allows a planner a method for deciding on the optimal timing for investment. It also indicates whether the replacement should take place reactively upon the asset's EOL failure; or proactively. The approach is demonstrated with the example of Manitoba Hydro's Bipole II HVdc modernization project. However, the methodology is applicable to any asset reaching EOL, and specifically is suited when the replacement project has a long lead time. It should be noted that the presented analysis is meant for those assets that have reached the wear-out stage of its life on the bathtub curve, as this is the situation where utilities would usually estimate the future EOL failure of an asset to determine the risk of failure over a long lead time to replacement. It is true that EOL failures could theoretically occur in early useful life, but this situation is not considered here. The proposed method addresses the gaps in the state-of-the-art in EOL probabilistic failure and unavailability evaluation for risk assessment by providing the annualized unavailability in future years based on the current age. This is particularly useful when the replacement project under consideration has a long lead time. The proposed method which has the focus on evaluating the annual unavailability of the future years, has been corroborated using the Monte Carlo simulation method. The paper also presents an accurate, computationally efficient unavailability evaluation of a multi-component system without approximations.

II. Analytical Computation of End-of-Life (EOL) Failure and Unavailability

A. Unavailability Calculation

Let $f(t)$ and $F(t)$ be the probability density function (PDF) and cumulative distribution function (CDF), respectively, of the EOL failure time of an asset. The conditional PDF $f_{c,T}(t)$ for an asset that is known to have survived until age T, defined over $t \geq 0$ where $t=0$ corresponds to the moment in time when the asset reaches age T, is a scaled version of the original PDF:

$$f_{c,T}\left(t\right) = \frac{f\left(T+t\right)}{R\left(T\right)},\ \ t \geq 0 \tag{1}$$

where $R(T) = 1\text{-}F(T)$ is the survival function evaluated at known survived age T. Here $f(T+t)$ is the probability density function that models EOL failure in t years past the current age of survival T. In the examples showcased in this paper, the Weibull distribution is used for $f(t)$ as in Appendix I, although any other applicable function can be used if desired. Expression (1) is a scaled version of the overall PDF, with the scaling factor being the reciprocal of the reliability function evaluated at survived age T. Such scaling ensures that the integral of the conditional PDF over the entire domain ($0 \leq t < \infty$) equals 1, as evident from the associated CDF expression given by:

$$F_{c,T}\left(t\right) = \int_0^t f_{c,T}\left(s\right) \cdot ds = 1 - \frac{R\left(T+t\right)}{R\left(T\right)},\ \ t \geq 0 \tag{2}$$

For a single asset that has survived to present age T, with its EOL failure described by $f_{c,\,T}(t)$, let the time duration spent in the unavailable state within an arbitrary time interval (t_a, t_b) be described by $\tau_{Ua,b}(t)$, which is a function of failure time t. The mathematical expectation of unavailability duration within time interval (t_a, t_b) as a fraction of that interval is then given by:

$$U_{c,T}\left(t_a, t_b\right) = \frac{1}{t_b - t_a} \int_0^{\infty} f_{c,T}\left(t\right) \cdot \tau_{Ua,b}\left(t\right) \cdot dt \tag{3a}$$

Note that depending on whether the EOL failure happens before the interval $[t_a, t_b]$, in the interval $[t_a, t_b]$ or after t_b, one gets unavailability duration $\tau_{Ua,b}(t)$ as given by (3b).

$$\tau_{Ua,b}(t) = \begin{cases} t_b - t_a, & t \leq t_a \\ t_b - t, & t_a < t \leq t_b \\ 0, & t_b < t \end{cases} \tag{3b}$$

If annualization of unavailability is ignored as in [2] one obtains (3c), which is a special case of (3a). For a specific time interval of k years immediately following the survived age T, t_a=0, t_b=k and the unavailability duration becomes $\tau_{Ua,b}(t) = (k-t)$.

$$U_{c,T}\left(0, k\right) = \frac{1}{k} \int_0^k f_{c,T}\left(t\right) \cdot \left(k-t\right) \cdot dt \tag{3c}$$

Note that if only a single year immediately after T is considered, one obtains, by setting k =1 in (3c), the annual unavailability for that one year as reported in [1]. Integration by parts of Expression (3c) yields (3d), which is a form expressed via conditional CDF. This is a more convenient form for the purposes of this paper, as discussed in Section II-B.

$$U_{c,T}\left(0, k\right) = \frac{1}{k} \int_0^k F_{c,T}\left(t\right) \cdot dt \tag{3d}$$

As proposed in this work, the annualized unavailability in the k^{th} year from T is a special case of formulation (3a). Note that from (3b), for failure prior to year $k-1$, $\tau_{Ua,b}(t) = \tau_{Uk-1,k}(t) = 1$. For failures within year $[k-1,\ k]$ itself, it is $\tau_{Ua,b}(t) = \tau_{Uk-1,k}(t) = (k-t)$ and zero otherwise, thus yielding (4a):

$$\begin{aligned} U_{c,T}\left(k^{th}\, yr\right) &= \frac{1}{k-(k-1)} \int_0^{\infty} f_{c,T}\left(t\right) \cdot \tau_{Uk-1,k}\left(t\right) \cdot dt \\ &= \int_0^{k-1} f_{c,T}\left(t\right) \cdot 1 \cdot dt + \int_{k-1}^{k} f_{c,T}\left(t\right) \cdot \left(k-t\right) \cdot dt \end{aligned} \tag{4a}$$

The two terms in (4a) associated with k^{th} year analysis can be treated differently based on the needs. In rare circumstances it may be necessary to evaluate economic sensitivities to when exactly the EOL failure occurs, in which case the two terms of the k^{th} year unavailability should be kept separate for the economic analysis. Often such sensitivities are negligible and the two terms of k^{th} year in (4a) can be added up as is done in this paper.

Integrating (4a) by parts yields (4b), a more convenient form for unavailability in the k^{th} year in terms of the cumulative probability function $F_{c,T}(t)$:

$$\begin{aligned} &U_{c,T}\left(k^{th}\, yr\right) \\ &= F_{c,T}\left(k-1\right) + \left(-F_{c,T}\left(k-1\right) + \int_{k-1}^{k} F_{c,T}\left(t\right) dt\right) \\ &= \int_{k-1}^{k} F_{c,T}\left(t\right) \cdot dt \end{aligned} \tag{4b}$$

Because $F_{c,T}(t)$ is a cumulative probability, at first glance it may appear that earlier failures are being counted multiple times. However (4b) directly follows from (4a), and is the correct expected value of unavailability for the year *k*. Using the PDF formulation instead, can be more challenging when dealing with multiple components, as discussed in the next section.

It is worth noting that equations (4a) and (4b) can be used for evaluating the unavailability for the k^{th} month in the future, instead of the k^{th} year in the future. Any other period of choice (weeks, days, etc.) can also be used with the appropriate scaling of time units in the expected unavailability equations, and in the economic evaluation equations thereafter in Section V.

B. Unavailability for Multi-Component System

To calculate the annualized unavailability for a multi-component system, another form of the unavailability formula (4a) or (4b) is given first. Let *X* be the random variable that the system is in the unavailable state at time *t*. Since $F_{c,T}(t) = P(X \leq t)$, (*i.e.*, the probability of failure before time *t*), equation (4b) can be rewritten as in (5a) to give the expected unavailability in the interval [$k-1$, k]:

$$U_{c,T}\left(k^{th}\ yr\right) = \int_{k-1}^{k} \left[P\left(X \leq t\right)\right] \cdot dt \tag{5a}$$

This alternative form is better suited for the multi-component analysis below.

A system of 4 components like Manitoba Hydro's Bipole II has 4 VGs, which are assumed to fail independently resulting in $2^4 = 16$ states. Let the component ages be T_j, failure times be X_j with conditional CDFs $F_{c,Tj}, j = 1, 2, 3, 4$. Further, binary digits 0 and 1 are used to denote the unavailable and available states of a component, respectively, e.g., U_{0101} means that components 1 and 3 are unavailable due to EOL. Then:

$$\begin{aligned} U_{0101}\left(k^{th}\ yr\right) &= \int_{k-1}^{k} \left[P\left(X_1 \leq t\right) \cdot P\left(X_2 > t\right)\right. \\ &\quad \left. \cdot\, P\left(X_3 \leq t\right) \cdot P\left(X_4 > t\right)\right] \cdot dt \\ &= \int_{k-1}^{k} F_{c,T1}\left(t\right) \cdot \left(1 - F_{c,T2}\left(t\right)\right) \\ &\quad \cdot F_{c,T3}\left(t\right) \cdot \left(1 - F_{c,T4}\left(t\right)\right) \cdot dt \end{aligned} \tag{5b}$$

$$\begin{aligned} U_{0000}\left(k^{th}\ yr\right) &= \int_{k-1}^{k} F_{c,T1}\left(t\right) \cdot F_{c,T2}\left(t\right) \\ &\quad \cdot F_{c,T3}\left(t\right) \cdot F_{c,T4}\left(t\right) \cdot dt \end{aligned} \tag{5c}$$

etc. It should be noted that the expected annual durations of states computed in (5b) and (5c) are in the form of an integral of the product of conditional CDF, and/or conditional Reliability (1-CDF), functions. In contrast, earlier work [2],[4] use an approximation with individual components' unavailability functions [4].

$$U_{0000}\left(k^{th}\ yr\right) \approx U_1\left(k^{th}\ yr\right) \cdot U_2\left(k^{th}\ yr\right) \cdot U_3\left(k^{th}\ yr\right) \cdot U_4\left(k^{th}\ yr\right) \tag{5d}$$

This form in (5d) is reasonably accurate when the individual conditional cumulative functions, $F_{c,T}(t)$, are nearly constant over the year in question, i.e., for components with their survived age past their expected life, and for the year in question at least several years from survived age. Otherwise, the percentage error produced by (5d) can be substantial. In this paper, the exact analytical integral expressions such as (5b) and (5c) are used for combinations of VGs, as presented above. Hence, this CDF based formulation is exact in comparison to the existing methods, and unlike the PDF based formulation, is simpler when applied to multiple components.

III. EOL Failure and Unavailability Using Monte Carlo (MC) Simulation

The analytically computed probability of failure, as well as unavailability are corroborated using two approaches of Monte Carlo simulations [5]–[7], [13].

1) MC1 – focuses on advancing the age of the asset by checking for the simulated survival of the asset every small-time advancement of the way, until the asset fails. One day of time advancing is used in this work. In the procedure, a very large number of candidate values are explored for each random failure time of a component, which then is repeated for a large sample of components.
2) MC2 – is an alternative faster approach. Here the one-day increments in time are not used in the Monte Carlo simulations. Instead it directly simulates the time of failure using the conditional CDF for each component. Then the process is repeated for a large sample of components.

The faster MC2 is equivalent to MC1, if sufficiently small time-increments are used in MC1. For MC1, uniformly distributed random number between 0 and 1 is compared to the probability value to decide if the asset survived the time interval or not. If the asset survives, the age is updated to the next time interval, and process is repeated. If the asset fails in a given time interval, the instance of failure is recorded. In approach MC2 for each simulation run, the CDF of the Weibull distribution is set to a uniformly generated random number in [0,1] and the failure time *t* is solved for, using (6) yielding $t_{fail\text{-}sim}$ as in (7).

$$F_{c,T}\left(t\right) = 1 - \frac{R\left(T+t\right)}{R\left(T\right)} = 1 - \frac{e^{-((T+t)/\alpha)^{\beta}}}{e^{-(T/\alpha)^{\beta}}} = rnd_{num} \tag{6}$$

$$t_{fail-sim} = \alpha \cdot \left[(T/\alpha)^{\beta} - \ln\left(1 - rnd_{num}\right)\right]^{1/\beta} - T \tag{7}$$

In this paper, the process is repeated over a sample size of *N*=10000 to determine the instances of EOL failure that result in the corresponding annual unavailability.

A. Analytical Versus Monte Carlo Evaluation

In this Paper Monte Carlo Simulation was used to corroborate the analytical results and was not intended as the primary method for unavailability calculations. Analytical evaluation is exact for the probabilistic model used and when a closed form of the unavailability and other quantities of interest can be obtained,

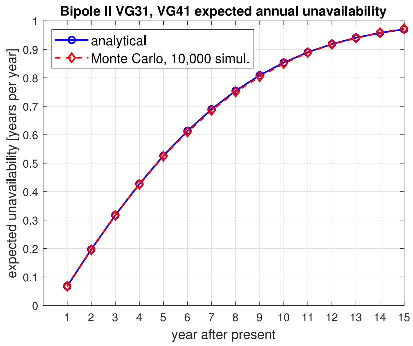

Fig. 1. Comparison of expected annual unavailability of VG31, obtained analytically and by Monte Carlo simulation.

which is the case here. On the other hand, accuracy of Monte Carlo results is a function of the number of cases simulated, distribution of parameters etc. Most importantly, the direct analytical method discussed in the paper is an exact method and can be used with any asset or system without any need for intervention to monitor convergence and accuracy. Its greatest advantage is in its computational efficiency when it comes to dealing with large interconnected systems, where the need to enumerate large numbers of states is avoided in arriving at the annual unavailabilities as shown in Appendix II. It is thus well suited for implementation in algorithms computing energy unserved or bottled generation due to unavailabilities resulting from not only EOL failures, but also repairable failures in larger interconnected systems [11]. It also offers more mathematical insight into computationally complex scenarios, like ‘reactive replacement’ option discussed in Section V-C.

IV. Analytical vs. Monte Carlo Simulation of Unavailability

Manitoba Hydro’s HVdc Bipole II is comprised of 4 VGs: VG31 and VG32 in Pole 3, and VG41 and VG42 in Pole 4, with present ages: $T_{31}=T_{41}=41$ years old, and $T_{32}=T_{42}=35$ years. All individual VGs EOL failure times are represented by a Weibull distribution (given in Appendix I) with characteristic life $\alpha=23.679$ years, shape parameter $\beta=3.108$ and time-shift (wear-out stage starting time) $\gamma=16.8$ years, which yields $\mu=37.979$ years and $\sigma=7.457$ years. The Weibull parameters were estimated for this asset class as described in Section VII.

A. Unavailability of Individual Valve Groups

Analytical and Monte Carlo generated plots are shown in Fig. 1 for annual unavailability of VGs 31 and 41, which have the same survived age of 41 years. The analytical results are obtained using (8), which is obtained from (4b) and (A3).

$$U_{VG31}\left(k^{th}\ yr\right) = \int_{k-1}^{k} F_{c,T31}\left(t\right)\cdot dt$$
$$= \int_{k-1}^{k}\left(1-\exp\left(\left(\frac{T_{31}-\gamma}{\alpha}\right)^{\beta}-\left(\frac{t+T_{31}-\gamma}{\alpha}\right)^{\beta}\right)\right)\cdot dt \quad (8)$$

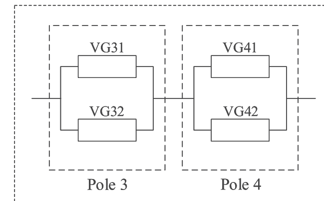

Fig. 2. Reliability connection diagram of Bipole II components, showing that failure of a Pole requires both VGs within the Pole to fail, while the failure of entire Bipole requires either of the two Poles to fail (no monopolar operation is permitted in this case).

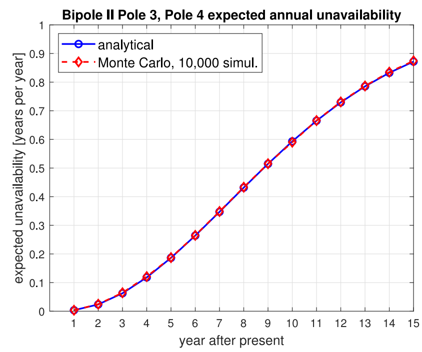

Fig. 3. Comparison of expected annual unavailability of Pole 3 (Pole 4 has same results) obtained analytically and by Monte Carlo simulation.

Both results are essentially identical, corroborating the analytical approach.

The failure times obtained from the MC simulation are post-processed by scanning through each year using an interval of 1 day (Δt=1/365 year). For a failure at a time t_{fail} in the simulation, all Δt intervals past t_{fail} are added to the unavailability. These annual unavailability values are averaged over N=10000 simulations, and an excellent match to analytical results is observed in Fig. 1. Similarly, well matched MC results were observed for VG32 and VG42 both of which have an age of 35 years but are not shown here.

B. Unavailability of Individual Poles

The reliability model [4] of Bipole II (with the VGs arranged in Poles 3 and 4) is shown in Fig. 2. For a Pole to fail, both VGs within that Pole are required to fail. Conditional CDFs for Pole 3 and Pole 4 failures are then given by (9), where t denotes the time from their respective survived ages:

$$F_{c,Pj}\left(t\right) = F_{c,Tj1}\left(t\right)\cdot F_{c,Tj2}\left(t\right), \quad \text{for } j=3,4 \quad (9)$$

Using (9), the Pole unavailability before the observed time t, in the k^{th} year from the present is calculated from (4b) giving an unavailability as in (10). Similarly, Pole 4 yields the same results as Pole 3 due to the identical ages of VG31 and VG41, as well as of VG32 and VG42.

$$U_{Pj}\left(k^{th}\ yr\right) = \int_{k-1}^{k} F_{c,Pj}\left(t\right)\cdot dt,\ j=3,4 \quad (10)$$

Fig. 3 shows the analytical result for the unavailability of the Poles from (10) as well as the results from MC simulation. MC uses the same post-processing logic as described earlier, only difference being that Δt intervals for $t > \max(t_{fail-j1}, t_{fail-j2})$ are accumulated into the unavailability duration for that year. This is because the Pole is considered to have failed if both VGs within it have failed.

C. Unavailability of the Entire Bipole

In this section the scenario of the entire Bipole replacement is considered. The decision to replace the Bipole is made reactively immediately following the event of a failure of the Bipole. Extended monopolar operation is not permitted for Manitoba Hydro's Bipole II, and so the Bipole is deemed to have failed if any one Pole has failed (see Fig. 2). In other words, Bipole failure occurs unless both Pole 3 and Pole 4 are operational, i.e., the conditional CDF of Bipole II failure, is then given by (11), where $(1 - F_{c,P3}(t))$ and $(1 - F_{c,P4}(t))$ are the probabilities of Pole 3 and Pole 4 being available at time *t*.

$$\begin{aligned} F_{BPII}(t) &= 1 - (1 - F_{c,P3}(t)) \cdot (1 - F_{c,P4}(t)) \\ &= F_{c,P3}(t) + F_{c,P4}(t) - F_{c,P3}(t) \cdot F_{c,P4}(t) \end{aligned} \tag{11}$$

Now, it takes a time T_{repl} to replace the Bipole, assuming a 'reactive replacement' approach where the replacement decision is made immediately following the first of the two Poles failing.

For the first $k \leq T_{repl}$ years after the present time, the unavailability of the Bipole is given by (12a) as there is no chance of it being replaced in the k^{th} year:

$$U_{BPII}\left(k^{th}\ yr \leq T_{repl}\right) = \int_{k-1}^{k} F_{BPII}(t) \cdot dt \tag{12a}$$

Otherwise, if the replacement was initiated more than T_{repl} years ago i.e., observed year $k > T_{repl}$, the Bipole would be back in service in the k^{th} year (assuming infancy failures are ignorable). Therefore, the EOL unavailability contribution only comes from failures in the period $[(t - T_{repl}),\ t]$ as shown in (12b).

$$U_{BPII}\left(k^{th}\ yr > T_{repl}\right) = \int_{k-1}^{k} \left(F_{BPII}(t) - F_{BPII}(t - T_{repl})\right) \cdot dt \tag{12b}$$

Fig. 4 shows the annual expected unavailability for $T_{repl} = 4$ years and $T_{repl} = 6$ years. It also shows the unavailability if 'no replacement' was made (i.e., $T_{repl} \to \infty$), which naturally has an asymptotic limit of 1.0 indicating eventual total unavailability. The graph shows analytically calculated values, and for $T_{repl} =$ 6 years, it also shows a plot obtained by MC simulation, which is in excellent agreement with the analytical result. The logic expression used in MC simulation for accounting failure times into the unavailability, is given in (13):

$$\begin{aligned} &BP\ II\ is\ unavaibale\ at\ t\ \ if: \\ &\min\left[\max\left(t_{fail-31}, t_{fail-32}\right),\right. \\ &\quad \left.\max\left(t_{fail-41}, t_{fail-42}\right)\right] < t < \\ &\min\left[\max\left(t_{fail-31}, t_{fail-32}\right),\right. \\ &\quad \left.\max\left(t_{fail-41}, t_{fail-42}\right)\right] + T_{repl} \end{aligned} \tag{13}$$

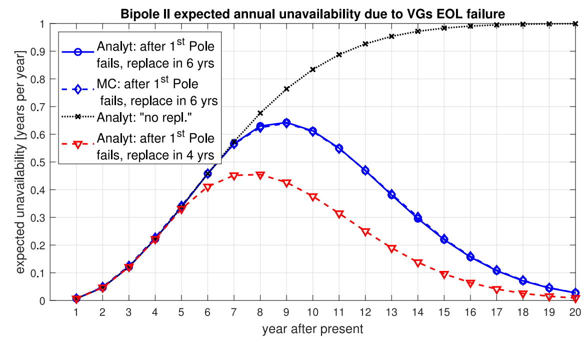

Fig. 4. Comparison of expected annual unavailability of the Bipole II system obtained analytically and by Monte Carlo simulation, for a 4 or 6-year replacement time consideration, and with no monopolar operation permitted.

V. Economic Analysis

In this section the economics of an asset replacement project is discussed, by taking into consideration the cost penalty of unavailability. In contrast to earlier approaches, the unavailability cost associated with the replacement time being greater than a year is taken into consideration.

As a demonstration of concept, economic analysis of the Manitoba Hydro's Bipole II asset replacement project is presented. In this analysis the annual EOL unavailability calculations for the asset over the multi-year lead time shown in Section II-B, are utilized to evaluate the Net Present Value (NPV) and Net Present Costs (NPC) over the project life cycle. The financial model of NPV analysis considers only simplified cost of replacement and benefit of avoidance of outage and is adequate for demonstrating the method. However, if desired, any other energy and capacity cost model can be substituted.

Economic comparisons with the following project alternatives are:

Base Case- 'No replacement' of the asset (shown in Section V-A) is used as a reference to compare different replacement options against, due to its simplicity. Other options may also be used as the base case if desired.

Option 1- 'No deferral', immediate approval of the replacement project, with a lead time to in-service. (Section V-B).

Option 2- 'Reactive replacement', approval upon EOL failure of the asset, with a lead time to in-service (Section V-C).

Option 3- 'N_d-year deferral', for initiation of the replacement project, with a lead time to in-service (Section V-D).

A. Base Case- Cost of 'No replacement' of the Asset

Using (12a) with $T_{repl} \to \infty$ to calculate $U_{BPII-no-repl}$, the NPC of the 'no replacement' becomes (14). To calculate NPC, future costs are discounted to the present year using the interest rate.

Assuming a project life cycle of 40 years from the in-service date representing the project life, an annual interest rate of $i = 5\%$ and the cost of one full year outage of Bipole II of $UC(k) = \$100$M, assumed constant over the years for simplicity, (14) computes to a net 'no replacement' costs of \$1280.8M, \$1290.9M, and \$1300.5M, for the various N_{hor}=46, 47 and

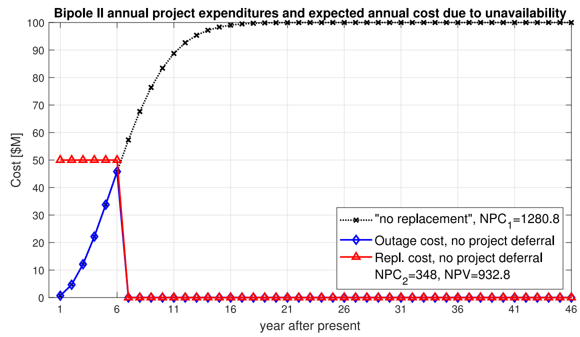

Fig. 5. Annual expected costs of unavailability and replacement project expenses, for the 'no deferral' option with a 6-year lead time to in-service.

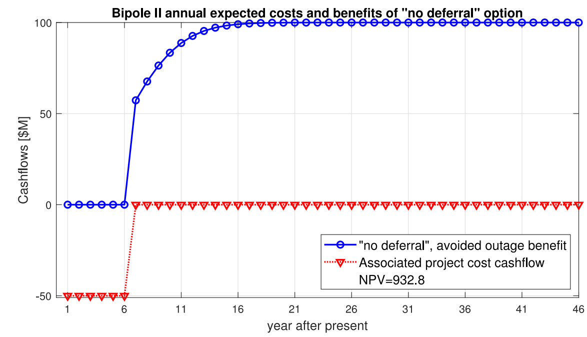

Fig. 6. Annual expected costs and benefits associated with Bipole II unavailability and replacement project expenses, for the 'no deferral' option of the project with a 6-year lead time to in-service.

48 year evaluation periods, respectively, used in the options described.

$$NPC\left('no\ replacement'\right) = \sum_{k=1}^{N_{hor}} \frac{U_{BPII-no-repl}\left(k\right) \cdot UC\left(k\right)}{\left(1+i\right)^k} \quad (14)$$

B. Option 1- 'No deferral' Option for Project Approval – with a Project Lead Time to In-service

Assume a project replacement cost $PC(k)$ in the k^{th} year, where k ranges over [1, T_{repl}]. The total project replacement cost is then $\sum_{k=1}^{Trepl} PC(k)$. Equation (14) can be extended with an additional term, $PC(k)$ to give the NPC with the 'no deferral' option as in (15). For demonstration of the concept, the $\$300M$ project replacement cost is assumed to be uniformly distributed over a replacement period $T_{repl} = 6$ years, i.e., $PC(k) = \$50M$ for all k. For the 'no deferral' option, the NPC is a discounted sum of the combined costs, i.e., the cost of EOL unavailability over the first 6 years of project lead time and the cost due to project expenses, as given in (15). Note that the cost of unavailability is zero after replacement, and therefore the cost components only exist till the replacement project is in service, that is till T_{repl}.

$$NPC\left('no\ deferral'\right) = \sum_{k=1}^{T_{repl}} \frac{U_{BPII-no-repl}\left(k\right) \cdot UC\left(k\right) + PC\left(k\right)}{\left(1+i\right)^k} = \$348M \quad (15)$$

The net present value (NPV) can be defined as the saving in cost resulting from the option being considered over the 'no replacement' option, over a 46-year period, as given in (16).

$$NPV\left('no\ deferral'\right) = NPC\left('no\ replacement'\right) - NPC\left('no\ deferral'\right) = \$932.8M \quad (16)$$

The positive NPV shows that replacement with no deferral results in a saving of $\$932.8M$ over the no replacement option. Fig. 5 shows the annual expected costs of unavailability for Option 1 and the annual replacement project expenditures.

An alternative approach to cost evaluation is a cost-benefit analysis where the avoided outage costs are evaluated as benefits in the cash flows over the project life cycle. The annual benefits for such an approach are captured in Fig. 6, and can be calculated by taking the difference in the annual costs between the options of 'no replacement' and 'no deferral', which are shown in Fig. 5. Benefits due to avoided outages result in positive cashflows in the years following the replacement completion, and project expenditures are negative cashflows. The NPV obtained by the sum of discounted costs and benefits is equivalent to the NPV given in (16).

C. Option 2- 'Reactive replacement', Approval Upon End-of-Life Failure of the Asset, with a Lead Time to In-Service

The expected unavailability $U_{BPII-reac-repl}$ of Bipole II with reactive replacement is obtained from (12a) and (12b) with $T_{repl} = 6$. Then the NPC of Option 2 becomes (17). It is worth emphasizing that in this option the distribution of these costs follows the probabilistic nature of replacement project initiation because the decision to replace is governed by the probabilistic occurrence of the EOL failure.

$$NPC\left('reactive\ replacement'\right) = \sum_{k=1}^{N_{hor}} \frac{U_{BPII-reac-repl}\left(k\right) \cdot UC\left(k\right) + PC_{reac}\left(k\right)}{\left(1+i\right)^k} = \$572.9M \quad (17)$$

For evaluating (17) $UC(k) = \$100M$ is used as before, but as project replacement is only initiated after a failure, the expected project replacement cost $PC_{reac}(k)$ follows a distribution as in (18a). Of course, the summation of all $PC_{reac}(k)$ values asymptotically becomes the total replacement cost of $\$300M$.

Fig. 7 shows the expected annual costs of unavailability for Option 2 and the annual replacement project expenditures. The annual project expenditures due to reactive replacement $PC_{reac}(k)$ are given by (18a), and depends on:

1) the probability of failure $P_{fail}(j)$ in year j where j varies over the $T_{repl} = 6$ year period, i.e., between $(k - T_{repl} + 1)$ and k, prior to the observed year k (note

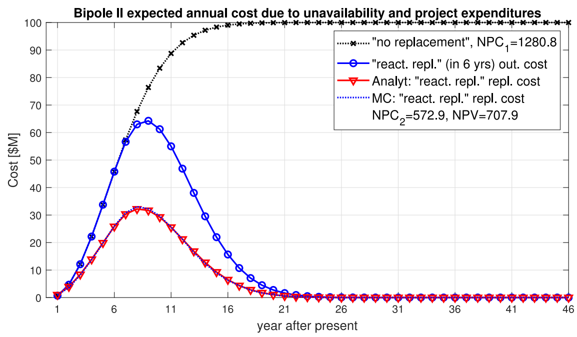

Fig. 7. Annual expected costs associated with Bipole II unavailability and replacement project expenses, for 'reactive replacement' option of the project with a 6-year lead time to in-service.

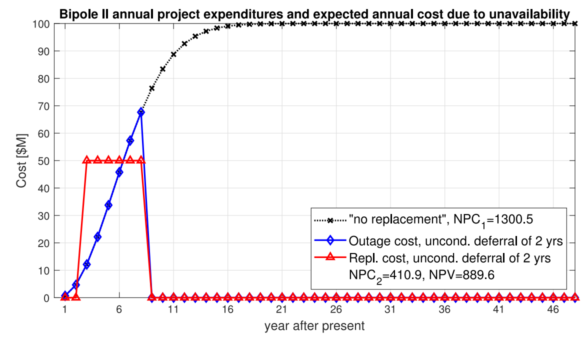

Fig. 8. Annual expected costs associated with Bipole II unavailability and replacement project expenses, for '2-year deferral' option of the project with a 6-year lead time to in-service.

that if this leads to a zero or negative value, start at year 1 is used);

2) the annual project cost $PC(k-j+1)$ reflects the expected project replacement cost in the j^{th} year before the observed year k.

$$PC_{reac}(k) = \sum_{j=\max(1,k-T_{repl}+1)}^{k} \left[P_{fail}(j) \cdot PC(k-j+1)\right] \quad (18a)$$

For demonstration purposes, the project expenditures are assumed equal in all years, and (18a) simplifies to (18b), where $F_{BPII}(k)$ is given in (11).

$$PC_{reac}(k) = PC \cdot \left[F_{BPII}(k) - F_{BPII}(\max(0, k-T_{repl}))\right] \quad (18b)$$

With these assumptions, $NPC('reactive\ replacement')$ evaluates to $\$572.9\text{M}$, giving an NPV of $\$707.9\text{M}$ for a 46 year period of evaluation (*i.e.*, $NPC('reactive\ replacement') - NPC('no\ replacement')$). It should be noted that since the project in-service date in this option is probabilistic, the overall evaluation period specified by 40 years past the in-service date, is also probabilistic beyond the 46-year period. The more accurate NPV considering the probabilistic evaluation period is $715.6M. The NPV of the 'reactive replacement' option is less than the NPV = $\$932.8\text{M}$ of 'no deferral' option.

The reality of the HVdc replacement projects are that they will always have a long lead time. Therefore, even the emergency 'reactive replacement' cannot avoid the 6-year lead time during which the cost of unavailability will be incurred. Since the risk of unavailability of the asset increases as the asset ages, the project delay increases the cost of unavailability in this option where the project in-service occurrence is probabilistic.

D. Option 3- 'Nd -year deferral' for Initiation of the Replacement Project, with a Lead Time to In-Service

This option is similar to Option 1, except that the replacement is initiated N_d-years from the present, rather than immediately, which results in a replacement after $N_d + T_{repl} = N_d + 6$ years. The NPC is given by (19), and for the first N_d years, essentially the unavailability cost of no replacement is similar to (14) and the cost after project initiation is similar to (15).

$$NPC('N_d\ yr\ deferral') = \sum_{k=1}^{N_d} \frac{U_{BPII-no-repl}(k) \cdot UC(k)}{(1+i)^k} + \sum_{k=N_d+1}^{T_{repl}+N_d} \frac{U_{BPII-no-repl}(k) \cdot UC(k) + PC(k)}{(1+i)^k} \quad (19)$$

Fig. 8 shows the annual expected costs of unavailability and replacement project expenditures for Option 3 when $N_d = 2$ years. This option results in an NPV of $\$889.6\text{M}$ ($\$1300.5\text{M} - \$410.9\text{M}$), as evaluated over a 48-year period in this case. Although better than Option 2 ('reactive replacement') it is more expensive than Option 1 ('no deferral').

With no deferral, the NPV is $\$932.8\text{M}$. For deferrals of 1 and 2 years, the NPVs are $\$914.3\text{M}$ and $\$889.6\text{M}$, respectively, i.e., 98% and 95.4% of the 'no deferral' option.

Since the horizon periods for the NPVs in the above three options are different, i.e., N_{hor}=46, 47 and 48, respectively, a more suitable quantity for comparison of the options is their Annual Equivalent Value $AEV = NPV \cdot i/[1-(1+i)^{-N_{hor}}]$, where i is the interest rate. With $i = 5\%$, the AEVs for the three options come out as $\$52.17\text{M}\ (100\%)$, $\$50.85\text{M}\ (97.5\%)$, and $\$49.21\text{M}\ (94.3\%)$, respectively. In this case study, the AEV progressively drops with increasing years of deferral of the project.

Where the EOL unavailability evaluation period is shorter than a year (eg. months, weeks, days etc.), the expected cost of unavailability term in equations (14), (15), (17) and (19) would have to be revised accordingly. For example: the annual risk/cost of unavailability should be made up of the sum of the 12 products over the 12 months: $\sum_{m=12(k-1)}^{12k} U_{asset}(m) \cdot UC(m)$, for monthly EOL unavailability evaluation.

Here the EOL unavailability risk analysis is effectively incorporated to an economic evaluation framework. The proposed framework can be used repeatedly for various sensitivities discussed in Section VII for a comprehensive sensitivity analysis, by which the robustness of the economic decisions can be evaluated.

VI. Incorporating Repairable Failures Into Unavailability Calculations

The expected annual unavailability quantities presented in previous sections of the paper exclusively arise due to EOL failures. However, prior to EOL failure instance, the asset will also experience unavailability due to repairable failures. Let U_r be the expected fraction of time for which the asset is unavailable due to repairable failures. When both EOL and repairable failures are considered, the unavailability duration function generalizes to:

$$\tau_k(t) = \begin{cases} 1, & t \le k-1 \\ (k-t) + U_r \cdot (t-k+1), & k-1 < t \le k \\ U_r, & k < t \end{cases} \tag{20}$$

Where U_r is the average proportion of the unavailable duration due to repairable failures. Here the same U_r is assumed for all years, but if the repairable failure rate changes, U_r can be replaced by $U_r(k)$. Then the expected annual unavailability is given by:

$$\begin{aligned} U_T\left(k^{th}\ yr\right) &= \frac{1}{k-(k-1)}\int_0^{\infty} f_{c,T}(t)\cdot \tau_k(t)\cdot dt \\ &= \int_{k-1}^{k} F_{c,T}(t)\cdot dt + U_r\left[1-\int_{k-1}^{k} F_{c,T}(t)\cdot dt\right] \\ &= \int_{k-1}^{k}\left[F_{c,T}(t) + U_r\cdot R_{c,T}(t)\right]\cdot dt \\ &= U_{EOL}(k) + U_r\cdot(1-U_{EOL}(k)) \qquad (21a) \\ &= U_{EOL}(k) + U_r - U_r\cdot U_{EOL}(k) \qquad (21b) \end{aligned}$$

Note that equation (21a) states that the repairable failure unavailability is applicable only for the portion of the year $(1-U_{EOL}(k))$ before EOL failure. The equivalent form (21b) has been given in literature [1] for the special case of 1-year past survival age only (i.e., $k=1$), whereas (21a) and (21b) are shown to be applicable for all $k \geq 1$.

To incorporate repairable failures into multi-component system, formulation (5b) is combined with (21a). Let Z be the random variable that the system is in the unavailable state (due to both EOL and repairable failures). Assuming that within any year $[k-1, k]$, conditional on the EOL failure $X > t$, the probability of a component being in unavailable state due to repairable failure is U_r, the probability of combined repairable and EOL unavailability at time $k-1 < t < k$ is given by:

$$\begin{aligned} P(Z \le t) &= P(X \le t) + P(Z \le t | X > t)\cdot P(X > t) \\ &= P(X \le t) + U_r \cdot P(X > t) \qquad (22a) \end{aligned}$$

$$P(Z > t) = (1-U_r)\cdot P(X > t) \tag{22b}$$

Then the expected annual unavailability is the expectation of the system being unavailable (i.e., Z) over the interval $[k-1, k]$, and it can be written as in (23):

$$\begin{aligned} U_T\left(k^{th}\ yr\right) &= \int_{k-1}^{k}\left[P(Z \le t)\right]\cdot dt \\ &= \int_{k-1}^{k}\left[F_{c,T}(t) + U_r\cdot(1-F_{c,T}(t))\right]\cdot dt \end{aligned} \tag{23}$$

For a system of two components, the expected annual unavailability is given similarly as in (24):

$$\begin{aligned} U_{01}\left(k^{th}\ yr\right) &= \int_{k-1}^{k} P(Z_1 \le t, Z_2 > t)\cdot dt \\ &= \int_{k-1}^{k}\left(F_{c,T1}(t) + U_{r1}\cdot(1-F_{c,T1}(t))\right)\cdot \\ &\quad \cdot\left((1-F_{c,T2}(t))\cdot(1-U_{r2})\right)\cdot dt \end{aligned} \tag{24}$$

Note that as discussed in Section II-B, if the multi-component unavailability is calculated as a product of individual components' unavailabilities, the result is approximate. Extension to more components is straightforward with additional product terms, as was done in (5b) using CDFs. In the case of the Bipole II example, inclusion of repairable failures did not significantly impact the unavailability results.

VII. Weibull Parameter Estimation and Sensitivity to Uncertainty

A. Data Used in the Case Study

The number of HVdc systems in the world is significantly smaller than widely used ac transmission systems. Therefore, statistical data are inherently more limited, in comparison to assets in ac systems. The data sample includes 15 HVdc schemes which have already experienced EOL failure in their wear-out stage of the bathtub curve, and 27 values of in-service years of HVdc schemes which are still operational around the world. The data of all these 42 HVdc schemes compiled by review of various publications are similar in age and type to Manitoba Hydro's Bipole II. This provides an adequate sample size for estimating the statistical parameters using the Maximum Likelihood Estimation (MLE) method used for the analysis.

B. Estimating Weibull Parameters

A three-parameter Weibull distribution is used to model the data and the MLE method is used to estimate the unknown parameters, which yields the mean life of 37.98 years with standard deviation 7.46 years. These estimated values reasonably agree with the 30-35 year expected lifetime provided by the industry life extension guidelines of existing HVdc systems in EPRI and CIGRE publications [14], [15]. Also, the mean time falls in between the life of the assets of Manitoba Hydro's HVdc valve groups being evaluated, where the condition report of the same assets suggests that the valve groups are experiencing wear-out stage of aging. Therefore, these single set of estimates are considered for the single demonstrative analysis provided in the paper.

Accuracy and uncertainty in the statistical estimation can be assessed by the MLE. However, a key factor is to be able to estimate a range of statistical parameters as required for a sensitivity analysis [12]. Parameter range estimated within an acceptable confidence level (e.g., 90%) fitted to the data sample can provide such a range.

In a complete analysis for decision making, it is typical to repeat the NPV computations with the upper and lower estimate bounds of the statistical parameters to determine the validity of the decision for the variations in the estimated unavailability. In addition, it is typical to test the decision's sensitivities to other factors such as cost of outage, project costs and even interest rates. In this paper the sensitivity analysis is not carried out, however the chosen parameters for the analysis are estimated using real data, the true age of the asset evaluated, and its condition assessment.

Although other probability distributions can be used, this paper uses the Weibull distribution as do the majority of previous works [1]–[3], [8]–[10], [13] on EOL failure probability. The Weibull distribution can readily fit all three regions of the bathtub curve and provides closed form analytical solutions. The Weibull survival function calculated using the MLE method was also compared to the Kaplan-Meier estimate using the same sample of 42 data. The MLE estimate falls within the 90% confidence interval of the Kaplan-Meier estimate, which further justifies the use of Weibull distribution with estimated parameter values. The Weibull parameters corresponding to the mean life of 37.98 years and a standard deviation of 7.46 years are given in Section IV.

VIII. Conclusion

Unlike existing analytical methods, the proposed method can evaluate the risk of EOL failure into multiple future years on an annualized basis. The existing approach assumes survival of the asset to the beginning of each evaluation year, and thus cannot evaluate risk in multiple future years of project lead time on an annualized basis. Without the proposed method the risk of EOL unavailability will be underestimated in replacement projects with long multi-year lead time, and as a result would unduly be screened out in a capital prioritization exercise.

The method's versatility is seen where the unavailability of 2^2 possible states of the 2 VGs are combined to first determine the unavailability of a Pole, and thereafter the 2^4 states of VGs to determine the unavailability of the Bipole as a whole. The multi-component method proposed in this paper based on CDFs is accurate while still being computationally efficient. It is also capable of integrating EOL unavailability and repairable failure unavailability of individual components, which can then be used to evaluate unavailability of a system with multiple components.

The paper shows that the overall system unavailability during the project lead time is significantly impacted by assets which have been retained past their expected life. It is critical that the risks be evaluated as viewed from the current year, where the EOL unavailability is based on a probability calculation conditional to the current age of the asset as proposed. In the event where the presented economic analysis suggests deferral of the project for several years into the future to be economically optimal, instead of immediate project approval, the analysis would have to be revised and repeated in the future years based on new information available, on the status and age of system components.

Appendix I
The Weibull Distribution

The commonly used Weibull distribution is used as the probabilistic model for EOL failure in this work [1].

Weibull distribution Cumulative Distribution Function (CDF) and Probability Density Function (PDF), with a characteristic life parameter α, shape parameter β, optional time-shift parameter γ, specifically defined over the wear-out stage time interval of the bathtub curve ($t \geq \gamma$), are respectively given by:

$$F(t) = 1 - e^{-((t-\gamma)/\alpha)^{\beta}}, \quad t \geq \gamma, \tag{A1}$$

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} \cdot e^{-((t-\gamma)/\alpha)^{\beta}}, \quad t \geq \gamma, \tag{A2}$$

and both functions have value 0 for $t < \gamma$. The wear-out stage is always represented by $\beta>1$. However, γ is sometimes approximated to zero with appropriate adjustments to the other two parameters, without much loss of accuracy in the results.

Conditional probability of failure within additional specified time *t* from an asset's current age *T*, assuming the Weibull distribution above is given by:

$$\begin{aligned} &P((T < X \leq T+t)\,|X > T) \\ &= \frac{F(T+t) - F(T)}{1 - F(T)} \\ &= 1 - \frac{e^{-((t+T-\gamma)/\alpha)^{\beta}}}{e^{-((T-\gamma)/\alpha)^{\beta}}} \end{aligned} \tag{A3}$$

Appendix II
Example Showing Superiority of the Proposed Approach and Limitations of the Existing Method

This Appendix demonstrates the novelty and superiority of the proposed approach by showing that, compared with the existing approach [1], it is accurate, complete and computationally efficient when dealing with a system of multiple aging components in a 'prolonged outage' scenario.

The example below considers a system with two aging components. The work presented in [1] assumes that the asset has survived to the start of the future year *k* under consideration, and the PDF is conditioned accordingly. Then the expected unavailability in year *k* is calculated based on the conditional probability of EOL failure within year *k* only. Accordingly, the state transitions and unavailabilities from EOL failure for a *two-component* system are shown in Fig. 9. Here, (A, A) denotes that both components 1 and 2, are available, (A, U) denotes that component 1 is available and component 2 has EOL failed, and so on.

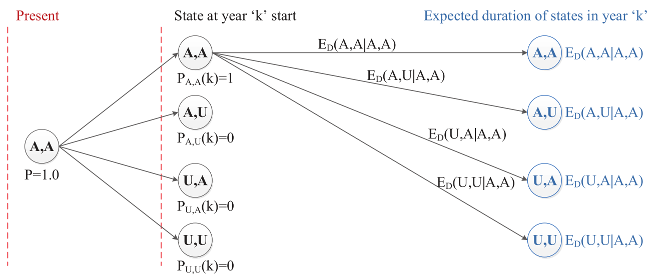

Fig. 9. Expected durations of four states of a two-component system, in a future year with assumed survival of both components to the start of that year.

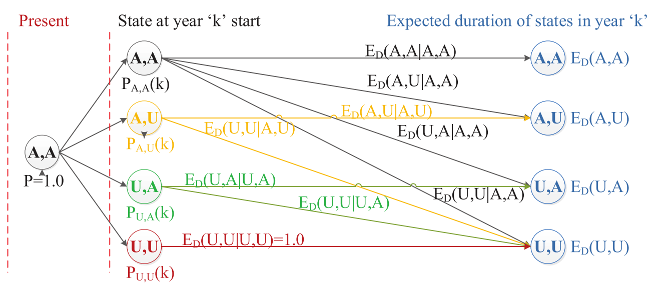

Fig. 10. Expected durations of four states of a two-component system, in a future year with consideration of all possible states at the year-start and the respective contributions to 'expected duration of states'.

Note that both components are assumed available at the beginning of year *k* as per the assumption in [1]. Since the alternative condition that the components have not survived to the observed year *k* is not considered in this method, it fails to capture all possible states as well as the prolonging of the EOL failure to the subsequent year for any of the components. Therefore, the approach in [1] is essentially applicable to replacement projects where evaluating the risk of EOL failure beyond the year following survived age is not necessary for any of the aging components. This would typically apply to projects with a sub-year lead time.

For multi-year lead time replacement projects such as the one discussed in this paper, ignoring all possible year start states and the prolonging of the EOL failure to subsequent years can result in a severe underestimation of expected unavailability. A correct, generalized analysis of the possible "expected duration of states", E_D, should consider *all* remaining possible states at the year-start, their probabilities, and their contributions to the "expected duration of states" (e.g., $E_D(A, U)$ etc.) as shown in Fig 10.

Such state enumeration requires computing probabilities of being in each of the four year-start states (e.g., $P_{A,U}(k)$ etc.). Note that if methodology in [1] was applied, only $P_{A,A}(k)$ would be unity and $P_{A,U}(k)$ etc. would be zero, as per Fig. 9.

Next, the 9 conditional expected duration contributions of the year-start states (e.g., $E_D(A, A|A, A)$, etc.) to the overall expected durations of states, are computed. The overall expected durations of the four states in the k^{th} year are therefore the weighted sum of the intermediate conditional expected durations, as illustrated in Fig 10. For example, $E_D(A, U) = P_{A,A}(k)\cdot\ E_D(A, U|A, A)+\ \mathrm{P}_{A,U}(k)\cdot\ E_D(A, U|A, U)$, etc.

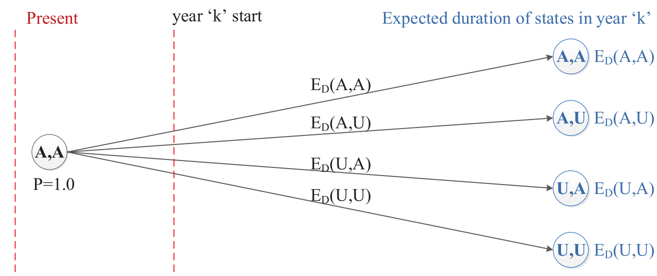

Fig. 11. Expected durations of four states of a two-component system, in a future k^{th} year using proposed method computed directly from present-day state.

$E_D(A, U|A, A)$ etc. can be computed by modifying equations (5b) and (5c), to apply for two components instead of four. Further, the assumed survived ages $T_1 + k - 1$ and $T_2 + k - 1$ would be used in (5b) and (5c) instead of known survived ages T_1 and T_2, respectively, and the integration limits would be from 0 to 1, instead of $k - 1$ and k, respectively. Further, the weighting probabilities $P_{A,A}(k)$ and $P_{A,U}(k)$ can also be obtained by the products of the survival probabilities in the manner of (2). Note that in Fig 10, certain transitions (e.g., $E_D(A, A|A, U)$ are not permissible because, an *end-of-life* failed component does not return to being available again.

For the *two-component* system in Fig. 10, there are $3^2 = 9$ permissible 'transitions', i.e., non-zero contributions of conditional expected state durations. The number of states and transitions grows exponentially if additional components are present. It can be shown that each added component triples the total number of possible transitions. Thus, for a *N-component* system there are 3^N transitions and 2^N states. Hence the state enumeration approach, though accurate would be computationally inefficient as the number of components grows.

These inefficiencies are overcome by the method proposed in this paper, by use of the equations (5b) and (5c), to arrive at the overall expected durations of the k^{th} year states in a single step, using the survived ages of T_1 and T_2 , respectively, as illustrated in Fig 11. Mathematically, the result obtained is accurate and identical to that from state enumeration, but it eliminates the tedious and cumbersome state enumeration process.

The proposed method, unlike the method in [1], is derived from conditioning the PDFs to the known current ages of the N aging components in the system. It eliminates the need to deal with the enumeration of 2^N year-start states and 3^N transitions year after year and is far more computationally efficient for systems with larger number of aging components. It is well suited to be used in software algorithms meant to compute the energy unserved or bottled generation due to unavailabilities resulting from not only EOL failures, but also repairable failures in larger interconnected systems for a prolonged outage period exceeding a year.

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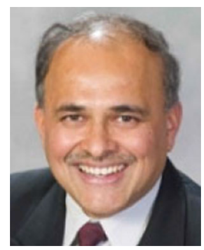

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