Power system equipment aging

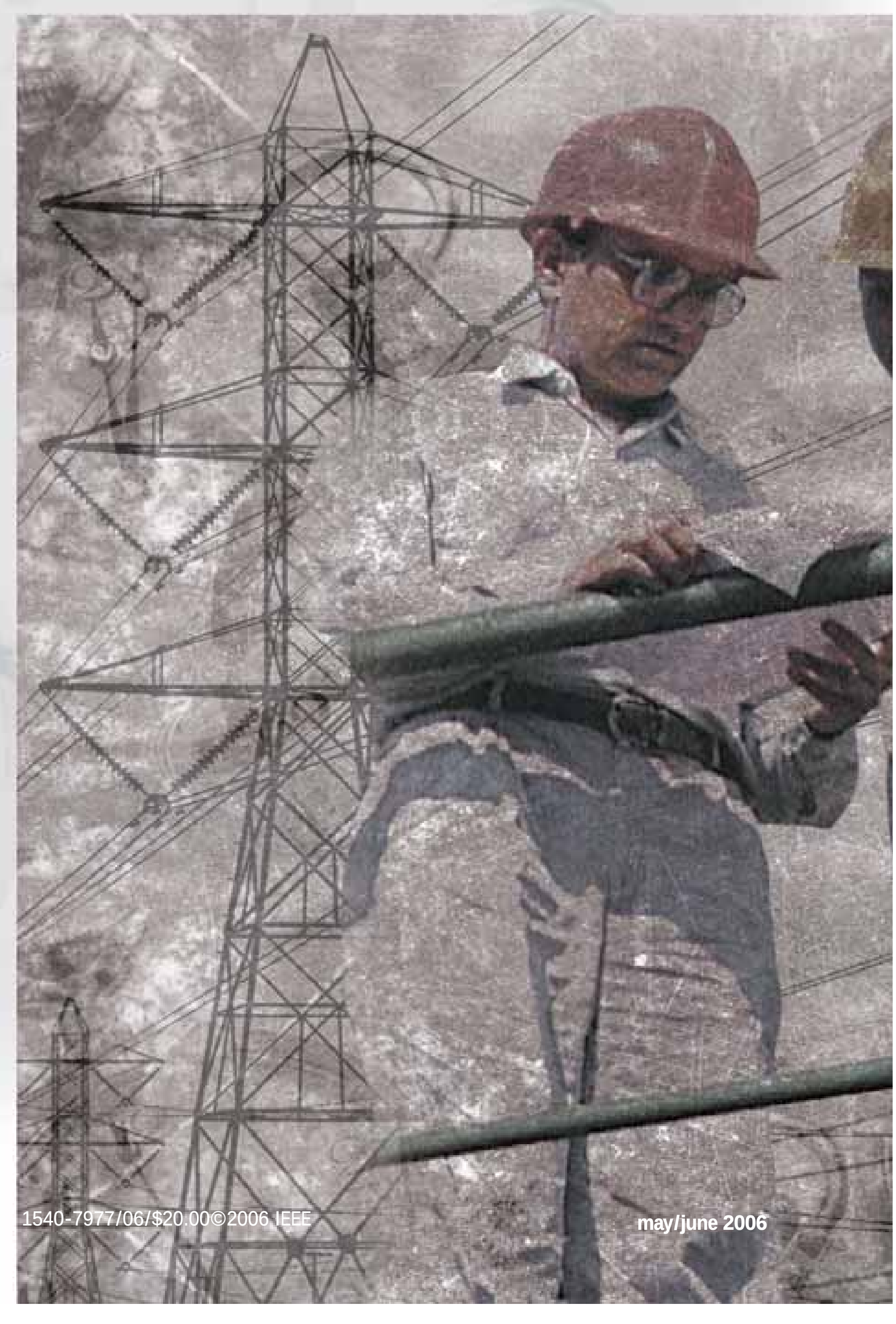
Article *in* IEEE Power and Energy Magazine · June 2006

DOI: 10.1109/MPAE.2006.1632454 · Source: IEEE Xplore

E. Vaahedi
BC Hydro

Power System Equipment Aging

by Wenyuan Li,
Ebrahim Vaahedi,
and Paul Choudhury



1540-7977/06/$20.00©2006 IEEE

Assessment, Maintenance, and Retirement

EQUIPMENT AGING IS A FACT OF LIFE IN POWER SYSTEMS ALTHOUGH THERE may be different causes of aging for different types of equipment. Aging can be caused by insulation deterioration of electrical components (such as transformers and reactors), fatigue damage of mechanical parts (such as generators and motors), or erosion of metal structures (such as underground cable sheathing). Like human beings, any equipment will experience its infancy, normal operation, and wear-out stages. As a piece of equipment ages, it fails more frequently, needs longer times to repair, and eventually reaches its end of life. The direct consequence of equipment aging is higher system risk due to higher failure probability and possible system damage following the end-of-life failure. Utilities normally carry out preventative overhauls and regular inspections. Maintenance activities can, to some extent, extend the life of equipment but could be very costly for equipment at their end-of-life stage. A compromise between maintenance and replacement must be carefully considered.

Concepts of Lifetime

Equipment performs both technical and economic functions in power systems. There are three different concepts of lifetime for power system equipments:

- ✔ *Physical lifetime*: A piece of equipment starts to operate from its brand-new condition to a status in which it can no longer be used in the normal operating state and must be retired. Preventative maintenance can prolong its physical lifetime.
- ✔ *Technical lifetime*: A piece of equipment may have to be replaced due to technical reasons although it may still be physically used. For example, a new technology is developed for a type of equipment and manufacturers no longer produce spare parts. This may result in a situation in which utilities cannot obtain necessary parts or parts become too expensive for maintenance. Mechanical protection relays and mercury arc converters in high-voltage direct current (HVDC) systems are examples of the technical lifetime category.
- ✔ *Economic lifetime*: A piece of equipment is no longer valuable economically, although it still may be usable physically. There are two methods for estimating the economic lifetime:
  1) The capital value of any power equipment is depreciated every year. Once the remaining capital value approaches zero, the equipment reaches the end of its economic lifetime.
  2) In addition to depreciating the capital cost of the equipment, operating and maintenance costs are considered. Operating and maintenance costs usually increase over time as equipment ages and may become excessive. They may even exceed the depreciated value of the equipment. It could be cost effective to retire and replace the equipment before its capital value reaches zero rather than continue to face high operating and maintenance costs.

In the following discussion, the focus is placed on the physical lifetime of power system equipment, although the economic lifetime may have to be considered sometimes in assessing the maintenance and retirement strategy.

table 1. Data of 500-kV reactors.

Number	In-Service Year	Retired Year	Number	In-Service Year	Retired Year
1	1979		51	1976	
2	1979		52	1976	
3	1979		53	1976	
4	1981		54	1970	
5	1981		55	1970	
6	1981		56	1970	
7	1985		57	1981	
8	1985		58	1981	
9	1985		59	1981	
10	1979		60	1983	
11	1979		61	1983	
12	1979		62	1983	
13	1969		63	1984	
14	1969		64	1984	
15	1969		65	1984	
16	1969		66	1983	
17	1969		67	1983	
18	1969		68	1983	
19	1970	1996	69	1984	
20	1996		70	1984	
21	1970		71	1984	
22	1970		72	1983	
23	1970	1989	73	1983	
24	1989		74	1983	
25	1970		75	1984	
26	1970		76	1984	
27	1970		77	1984	
28	1970		78	1978	
29	1970		79	1978	
30	1970		80	1978	
31	1970		81	1969	1996
32	1970		82	1996	
33	1976		83	1969	
34	1976		84	1969	
35	1976		85	1969	
36	1976		86	1969	
37	1976		87	1969	
38	1976		88	1969	
39	1976		89	1969	
40	1976		90	1969	
41	1976		91	1969	
42	1976		92	1969	
43	1976		93	1969	
44	1976		94	1969	
45	1976		95	1969	1997
46	1976		96	1997	
47	1976		97	1969	
48	1976		98	1969	
49	1976		99	1969	
50	1976		100	1969	

Estimating the Mean Life and Age

When we judge whether a man or woman is an old person, we must know his or her age and compare that age with the average life of men or women. Similarly, we have to know the mean life and the age of a piece of equipment in order to make a judgment of its aging status.

In general, a manufacturer provides an estimated mean life of equipment, which is based on theoretical calculations and many assumptions. The manufacturer's estimate is usually inadequate since it does not and cannot include actual operating and environmental conditions of the equipment. Statistically, the sample mean (or the average age method) is often used to estimate a mean life if there is a big population. For instance, we can obtain a meaningful mean life estimate for different groups of human beings by calculating an average age at death. Unfortunately, this method is not suitable for power system components. Major power system components such as generators, transformers, reactors, cables, etc. have a relatively long life, and, therefore, there is very limited end-of-life failure data available in a utility. It is possible to use end-of-life failure records of the same type of equipment across utilities. However, this still may not result in sufficient failure data. Besides, operating conditions, even for the same type of equipment, may vary largely at different utilities, which may be geographically spread apart and have different operation and maintenance rules.

The essential weakness of the sample mean is that it only uses information of components that have died. For an equipment group with very few dead members, surviving components, as well as dead, make contributions to the mean life. The approaches that are based on the Weibull or normal probability distribution have been developed to estimate the mean life and its standard deviation. The merit of the probability-distribution-based approaches is due to contributions of both dead and surviving components to the mean life being taken into consideration. Even with limited data of components that have died, the models can also produce a relatively accurate estimate. Tables 1 and 2 give an example of estimating the mean life for a 500-kV reactor group at the British Columbia Transmission Corporation (BCTC) using the sample mean method, Weibull, and normal-distribution-based approaches. The data and the estimated results are shown in Tables 1 and 2, respectively. In this example, there are only four retired samples in the total of 100 reactors. The estimates of the mean life (37 or 38 years) obtained using the two probability-distribution-based approaches are close and much longer than the estimate of 25 years obtained using the sample mean method. Table 1 indicates that 35 reactors exceed 30 years,

table 2. Estimated mean life for the 500-kV reactors.

	Normal	Weibull	Sample Mean
Mean life (years)	37.628	38.363	25.0
Standard Deviation (years)	6.896	6.293	

confirming that the estimated mean life of 37 or 38 years should be much more reasonable than the 25 years.

There are two concepts related to measuring the age of power system equipment: natural age and functional age. The natural age is the difference between the in-service date and the present date, which is easy to calculate. For the purpose of system planning, a rough estimate is generally sufficient and the natural age can be used. In maintenance, however, we often focus on a specific piece of equipment. In this case, it is better to obtain an estimate of the functional age, which depends on the deterioration status associated with usage history and operating and environmental conditions. The functional age can be estimated through a field assessment in some cases. For example, an oil sampling can be performed for a transformer to test the insulation state. The insulation damage depends on several factors including water, oxygen, and weather. Formulas have been derived to estimate the degree of polymerization of insulation and thus the functional age associated with insulation deterioration. However, it is worthy to note that not all types of equipment can be tested using a sampling approach. For instance, it is difficult to estimate the functional age of an underground cable using a sampling approach. A cable is geographically spread and a section of cable cannot represent the status of the whole cable. Also typically, aging of cables is not caused by insulation deterioration because of their well-sealed structure but due to sheathing erosion or other reasons.

Assessing End-of-Life Failure Probability

With the estimated mean life and age of a specific piece of equipment, its aging status can be qualitatively judged since we know how far away it is from the mean life. The reason we are concerned about the aging status is because we are concerned about the risk caused by end-of-life failure of aged equipment. In order to quantify the risk of aging failures, it is necessary to assess the end-of-life failure probability of aged equipment.

As is well known, the relationship between the failure rate or failure probability and the age can be graphically expressed using a so-called basin curve, as shown in Figure 1. It can be seen from the figure that the failure rate at the wear-out stage increases dramatically with the age. In fact, the basin curve can be mathematically modeled using a Weibull or normal distribution. Figure 2 shows the relationship between the failure rate and age for a normal distribution failure density function; Figure 3 provides the same relationship for a Weibull distribution failure density function. The μ and σ in Figure 2 are the mean and standard deviation of the normal distribution, whereas β and α in Figure 3 are the shape and scale parameters of the Weibull distribution. It can be seen that the relationship shown in the two figures is consistent with that expressed in the wear-out stage of the life basin curve. Note that the Weibull distribution can be used to model all the three portions of the basin curve: $\beta < 1$ for the infancy stage, $\beta = 1$ for the normal operating stage, and $\beta > 1$ for the wear-out stage.

There are two failure probability concepts for end-of-life failures of equipment. One is the probability of an end-of-life failure occurring in a given period (usually one year). The other is unavailability, which is the probability of the equipment being unavailable due to its end-of-life failure

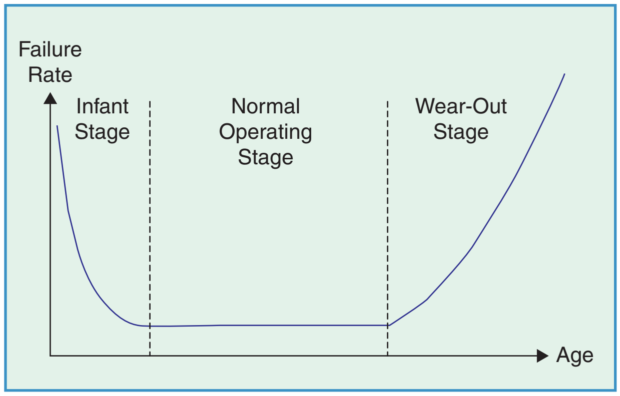


figure 1. Basin curve for failure rate of equipment.

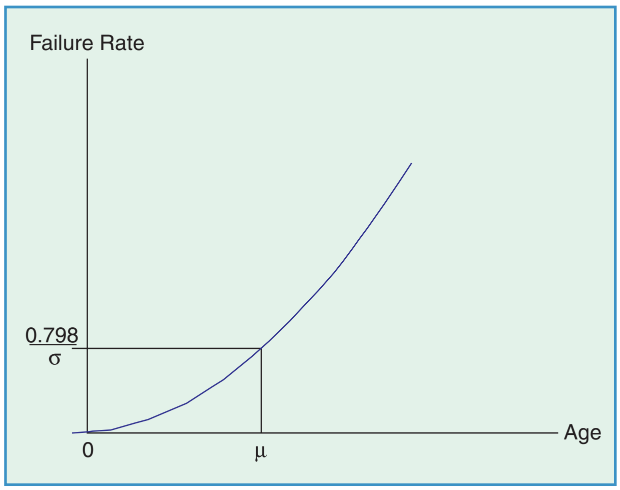


figure 2. Relationship between failure rate and age for a normal probability distribution.

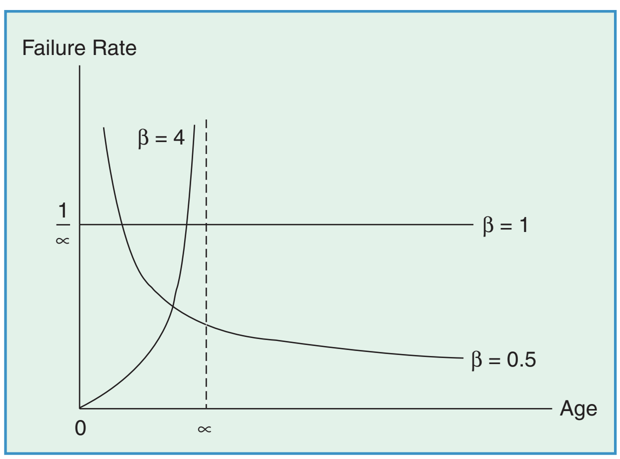


figure 3. Relationship between failure rate and age for a Weibull probability distribution.

Equipment aging is a fact of life in power systems, and dealing with aged equipment has challenged the utility industry for years

during a given period. Both probabilities are used to quantify the likelihood of equipment's end-of-life failure, although they are conceptually somewhat different. The unavailability due to end-of-life failure is consistent with the concept of the unavailability due to repairable failure of equipment. The end-of-life and repairable failures are two basic failure modes in system risk assessment.

Table 3 shows an example of end-of-life failure probabilities for three representative transformers. Both the unavailability due to repairable and end-of-life failures and probability of an end-of-life failure occurring in one year are shown in the table. The transformers are of the same type and at the voltage level of 230/12 kV. Based on 15 years of historical records in the BCTC reliability database, this type of transformer has the following average repairable failure data: the failure frequency is 0.0834 failures/year and the repair time is 59.06 h. An a posteriori normal distribution was used to model end-of-life failures. The mean life of transformers was estimated to be 45 years with a standard deviation of ten years. The ages of T1, T2, and T3 were ten, 32, and 48 years, respectively. This indicates that T1 was young, T2 in its middle age, and T3 quite old (beyond the mean life).

Table 4 and Figure 4 show the unavailability due to end-of-life failures for three representative 230-kV underground cables in a six-year period. The mean life for the cables was estimated to be 45 years with a standard deviation of 15 years. In this case, the Weibull distribution model was used. The ages of Cables 1, 2, and 3 were 16, 28, and 44 years, respectively. It can be seen that the unavailability for Cables 1 and 2, which are not aged yet, only has a marginal increase as the age increases whereas the unavailability for Cable 3, which reached the mean life, has a large increase with its age.

Aging Process and Maintenance

The probability of end-of-life failure increases with equipment aging. On the other hand, the aging process can be slowed through maintenance activities. Conceptually, there are two types of maintenance: corrective and preventative. Corrective maintenance is a repairing activity after a failure of equipment and deals with a repairable failure. Preventative maintenance is an overhaul or inspection activity before a piece of equipment fails. The major goal of preventative maintenance is to reduce deterioration and prolong the lifetime of equipment, and it addresses both repairable and end-of-life failures. The usable or economic value of equipment is reduced as it ages, and preventative maintenance activities delay the aging process. The relationship between the value, time, and preventative maintenance is shown in Figure 5. It can be seen from the figure that maintenance can recover part of the lost value caused by deterioration in the aging process. However, although maintenance can slow aging, it cannot fully stop it.

There are two strategies for implementing preventative maintenance: regular and predictive. Regular maintenance is carried out at fixed intervals whereas predictive maintenance is undertaken as needed. Regular maintenance is the policy most widely used by utilities and is based on the manufacturer's specification or the experience of maintenance personnel. This strategy is simple and easy to perform but may result in either higher costs (doing unnecessary maintenance activities) or relatively high system risk (not doing necessary maintenance activities in time). Predictive maintenance has been addressed in the power industry and implemented in some utilities in the past 10–15 years. This strategy needs an assessment process including mathematical modeling and calculations, condition monitoring, and appropriate criteria.

table 3. Unavailability due to repairable and end-of-life failures and probability of an end-of-life failure occurring in one year for three transformers (normal distribution model).

ID	Unavailability (Repairable)	Unavailability (End-of-Life)	Total Unavailability	Probability of End-of-Life Failure Occurring
T1	0.000562	0.000049	0.000611	0.000104
T2	0.000562	0.009905	0.010462	0.020227
T3	0.000562	0.049369	0.049904	0.098172

table 4. Unavailability due to end-of-life failure for three cables in a six-year period (Weibull distribution model).

Cable	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Cable 1	0.00039	0.00051	0.00066	0.00084	0.00106	0.00132
Cable 2	0.00479	0.00560	0.00652	0.00756	0.00871	0.01000
Cable 3	0.03605	0.03981	0.04385	0.04818	0.05283	0.05779

Reliability centered maintenance (RCM) is a powerful approach in predictive maintenance activities. It has a wide range of interpretations and may be defined differently in various publications. In our opinion, RCM should include at the minimum the following components:

- ✔ collecting statistical data such as operation history, failure records, aging status tests or assessments
- ✔ estimating failure probabilities due to repairable and end-of-life failures of equipment
- ✔ evaluating impacts of individual equipment failures on the system
- ✔ quantifying the effects of maintenance activities on improving equipment failure frequencies/repair times and whole system reliability
- ✔ applying economic or reliability criteria to determine the best maintenance scheme, which may be an optimal maintenance alternative (range and sequence in maintenance) or lowest-risk maintenance scheduling (timing) or most cost-efficient workforce planning.

Retirement of Aged Equipment

Retirement of aged equipment is eventually unavoidable. It is just a matter of retiring earlier or later. Endless maintenance activities on a piece of aged equipment will produce the following problems or concerns:

- ✔ The maintenance cost will increase as equipment ages.
- ✔ Repeated maintenance activities over a very long time cannot assure the original performance of equipment, resulting in increasing operational cost.
- ✔ The failure probability or unavailability due to the end-of-life failure will still continuously increase with the age although maintenance can slow deterioration. This leads to increasing system risk.
- ✔ Economically, the total cost of ownership consisting of investment, maintenance, operation, and system risk costs may be lower if the equipment is replaced. Thanks to innovation and development of new technology in the past decade, prices of many power system components have decreased.
- ✔ Financially, a very low book value of aged equipment may have negative effects on the design of electricity rates, which are associated with asset values and investment return requirements.
- ✔ In a wider sense, an over-maintenance strategy will impede progress of new technology.

The key is to determine when a piece of aged equipment should retire. There are four strategies that have been deployed in the utility industry to establish the retirement date.

1) The aged equipment is continuously used until it dies. The problem with this policy is that for major transmission system equipment (e.g., cables, transformers, reactors, etc.), it will take more than one year to complete the whole replacement process including the purchase, transportation, installation, and commissioning of new equipment. The power system may be exposed to severe risks of being unable to meet security criteria during the replacement period.
2) The aged equipment is continuously used with close field monitoring. The process of purchasing new equipment for replacement starts when phenomena associated with fatal failure are observed. Unfortunately, some equipment cannot be monitored in such a way. As mentioned earlier, it is almost impossible to monitor the aging process of a cable since sampling a section of cable cannot represent the status of the whole cable. There have been many examples in real life where an aged cable suddenly developed multiple leakages simultaneously leading to a fatal failure. For a power transformer, although oil sampling can be performed to partially monitor the status of its wear, the

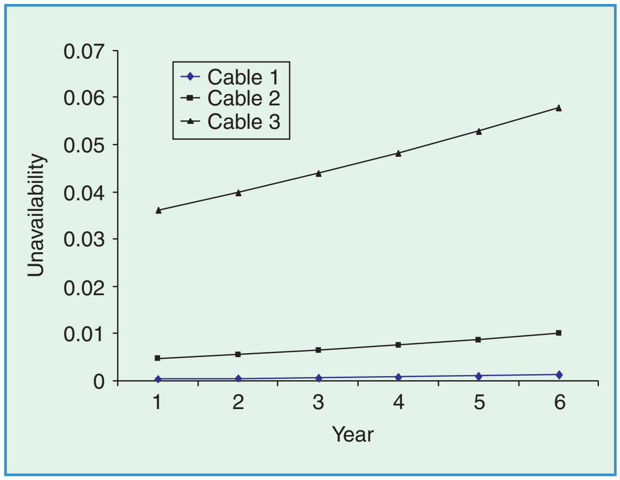


figure 4. Unavailability due to end-of-life failure for three cables in a six-year period.

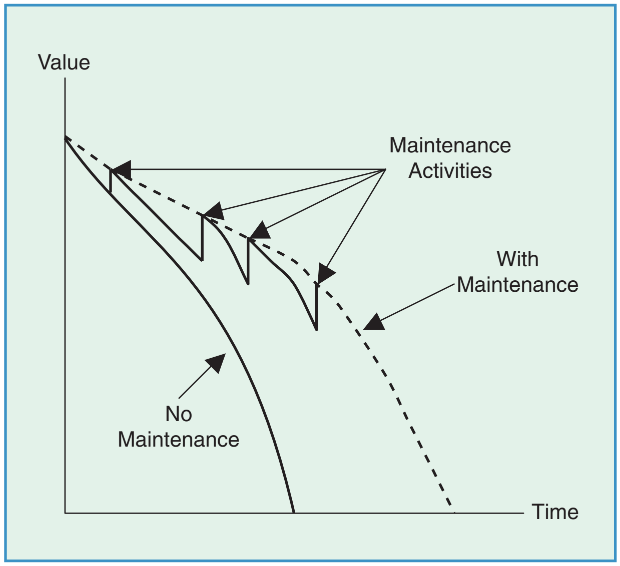


figure 5. Relationship between the value, time, and preventative maintenance for aged equipment.

> In order to quantify the risk of aging failures, it is necessary to assess the end-of-life failure probability of aged equipment.

replacement may still not be able to be completed in time because of the impossibility of taking oil samples frequently enough to predict its end-of-life failure that may occur one year later.

3) Another option that has been a practice of some utilities is to set a retirement age which is normally around the estimated mean life of equipment. Once a piece of equipment reaches this age, it will be forced to retire. The purchase and transportation can proceed in advance. The problem for this policy is the fact that any specific piece of equipment may die before or after the specified retirement age. If it dies before, this will cause the same problem as described for the previous two strategies. If it can survive longer, its early retirement will result in a waste of capital because of unnecessary earlier investment for replacement.
4) A probabilistic analysis approach for making decisions about retirement of aged equipment has been recently developed. The basic idea is to quantify the expected system risk cost and capital savings due to delaying the retirement of aged equipment. The approach uses the Weibull probability distribution to model the unavailability due to the end-of-life failure of aged equipment as described earlier. The expected system risk cost due to delaying the retirement can be then evaluated using a system risk assessment method. Finally, an economic comparison analysis of the total cost (including system risk cost, maintenance cost, and capital savings) for the different alternatives is conducted to determine timing of retirement. The reliability-based approach should be the best strategy to determine the retirement date of equipment.

Conclusions

Equipment aging is a fact of life in power systems. Dealing with aged equipment has been a challenge in the utility industry for years. This article discussed the issues around power system equipment aging, including concepts of equipment lifetime, approaches to estimating the mean life and age, and Weibull and normal-distribution-based models to assess the end-of-life failure probability. The relationship between aging and maintenance activities, limitations of maintenance in extending equipment life, and determination of timing of retirement were also discussed. A few examples showing actual data of transformers, cables, and reactors at BCTC have been presented. Maintenance activities can extend the life of equipment but could be very costly for equipment at their end-of-life stage. A compromise between maintenance and replacement must be carefully considered. RCM and probabilistic analysis approaches are available for utilities to guide maintenance activities and manage aged assets in a more efficient and economic manner.

For Further Reading

W. Li, *Risk Assessment of Power Systems: Models, Methods, and Applications*. New York: IEEE Press and Wiley & Sons, 2005.

J. Endrenyi, "Reliability and maintenance," in *IEEE Tutorial Text on Electric Delivery Systems Reliability Evaluation*, ch. 5., 2005 IEEE PES General Meeting, San Francisco, CA, June 2005, ch. 5, Tutorial 05TP175.

W. Li and J.K. Korczynski, "A reliability based approach to transmission maintenance planning and its application in BCTC system," *IEEE Trans. Power Delivery*, vol. 19, no. 1, pp. 303–308, Jan. 2004.

W. Li, "Evaluating mean life of power system equipment with limited end-of-life failure data," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 236–242, Feb. 2004.

W. Li, "Incorporating aging failures in power system reliability evaluation," *IEEE Trans. Power Syst.*, vol. 17, no. 3, pp. 918–923, Aug. 2002.

Biographies

Wenyuan Li is currently the principal engineer at British Columbia Transmission Corporation, Vancouver, Canada. He is an IEEE Fellow and an honorable advisory professor at Chongqing University in China. He has authored four books and published a considerable number of papers in power system planning, operation, maintenance, optimization, and reliability. He was the winner of the 1996 Outstanding Engineer award given by the IEEE Canada.

Ebrahim Vaahedi is currently the Chief Technology Officer at British Columbia Transmission Corporation, Vancouver, Canada. He is an IEEE Fellow, the chair of IEEE Power System Operation Method Subcommittee, and an editor of *IEEE Transactions on Power Systems*. In 2004, he received the IEEE Best Paper award.

Paul Choudhury is currently the manager of system planning and performance assessment at British Columbia Transmission Corporation (BCTC), Vancouver, Canada. He was previously the manager of BCTC's System Control Centre and has worked in utility operations at BCTC, B.C. Hydro, and Ontario Hydro for over 15 years. He is a Member of the IEEE.