International Journal of Enhanced Research in Science Technology & Engineering, ISSN: 2319-7463
Vol. 2 Issue 5, May-2013, pp: (12-17), Available online at: www.erpublications.com

# A comparative analysis on life cycle operation and maintenance cost of EHV new generation XLPE insulated cable versus conventional overhead lines

Preet Khandelwal[1], Arun Pachori[2]
[1]preet_27sep@yahoo.co.in

**Abstract: This papers shows after effect caused due to continuous improvement in Extra High Voltage (EHV) AC Underground Cables (UTC) Technology like real time monitoring, improved XLPE insulation, which cause change in the Lifecycle Operation And Maintenance (OAM) cost including cost of fixing failure of EHV and HV cross-linked polyethylene (XLPE) UTCs and EHV Overhead Lines (OTL). Due to improvement in manufacturing technology and long term technical experiences of cable manufacturers with EHV XLPE cable systems, there is increase in reliability of cable. Frequency of internal failure in XLPE insulated UTC is very low of value 0.088 as compared to failure in 230 kV Overhead line (OTL) =0.7997. Here failure rate for complete lifecycle of a transmission line can only be obtained on deterministic basis & predicted on a probabilistic basis. This paper is based on the recent Service Experience & statistical data obtained from TSO, Working Groups, and EHV XLPE UTC manufactures.**

**Keywords: Underground Power Transmission Lines, Power cables, Power Transmission economics, Power transmission maintenance, Power transmission reliability.**

## I. INTRODUCTION

The first 400 kV XLPE UTC and accessories with silicone rubber insulation bodies were installed in the network at the beginning of the year 1990 in switzerland. These systems is doing well up to the date. All tests and many years of practical experiences have shown that solid XLPE insulation for high voltage and extra high voltage UTCs and silicone rubber insulation for their accessories are characterized by long electrical lifecycle [1]. To keep the potential of a long-term reliability, it is very important for the EHV XLPE UTCs and accessories to be free from any Partial Discharges. The partial discharge measurements as routine tests for EHV XLPE UTCs and accessories are therefore an important step for the quality of the EHV XLPE UTCs and accessories. Recent developments supported by the cleanness of the polyethylene material and experiences in EHV UTCs resulted in a mature technology with proven benefits i.e., lower TCO and high design flexibility that allowed the use up to 380/400 kV networks as well. Based on all these positive experiences with EHV XLPE UTCs and accessories in service and in prequalification tests for 420 kV, the article also reports on the continuing development of UTC design due to optimization of wall thickness and field strengths. Generally lifecycle of UTC can only be depicted when some large volumes of EHV UTCs installed in a wide range of conditions. The paper shows the comparison between operation and maintenance (OAM) cost of the UTC and OTL including the cost of failure. Generally (OAM) operation and maintenance is a fixed percentage of capital cost of the equipment. In this paper there is continuous decrease in the (OAM) cost due to improve in UTC manufacturing and monitoring process in the recent years taken place. This can be proved in former part of the paper and the effect of reduction of (OAM) cost is proved in later part. With the improvement in the UTC manufacturing technology there is small (about 10%) increase in capital cost of UTC system mainly due better partial discharge monitoring system and better manufacturing system. Also with service experiences of EHV lines for last two decade reduces the (OAM) cost and improve the reliability of whole UTCs system. Here failure rate of UTC is obtained for recent statistical survey and comparison is done for UTC and OTL. Third generation UTCs have less thicker and less capacitance value compared with previous generation XLPE UTC. Recent statistical trends shows that failure in XLPE UTC occurs only after few years of commissioning of UTC system, after that failure rate is very low. Mostly cause of failure is defect in workmanships & manufacturing defect.

## II. COMPARISON OF OPERATION, MAINTENANCE & FAILURE COST

All the discounted cost arises from operation and maintenance of UTCs and overhead lines including failure cost is given on next page of paper:

**TABLE I** shows Present value ( (OAM)) of the sum of the annual costs for periodic maintenance (OAM) over the circuit lifetime EHV AC Transmission Lines [4]; S.C refer shunt compensation; (OAM) refer Annual operation and maintenance cost; (IE) = Equipment cost

| S.No. | System component HVAC | Power rating MVA | Min value k€/km | Max value k€/km | Average value k€/km(capex) | CALCULATED ((OAM)), n=40 year, k€/km | CALCULATED ((OAM)), n=40 year, k€/km | CALCULATED ((OAM)), n=50 year, k€/km |
|---|---|---|---|---|---|---|---|---|
| 1 | UTC XLPE, single circuit. | 1000 | 1000 | 3000 | 2193 (including S.C) | 45.14 (OAM) = 0.3% (IE) | 36.29 (OAM) = 0.2% (IE) | 38.02 (OAM) = 0.2% (IE) |
| 2 | UTC XLPE, double circuit. | 2×1000 | 2000 | 5000 | 3885 (including S.C) | 79.00 (OAM) = 0.3% (IE) | 64.30 (OAM) = 0.2% (IE) | 67.36 (OAM) = 0.2% (IE) |
| 3 | OTL, single circuit | 1500 | 400 | 700 | 550 | 72.409 (OAM) = 1.75% (IE) | | |
| 4 | OTL, double circuit | 2×1500 | 500 | 1000 | 750 | 99.304 (OAM) = 1.75% (IE) | | |
| 5 | OTL, double circuit | 2000 | N.A. | N.A. | 600 | 79 (OAM) = 1.75% (IE) | | |

*A. Computation of Operation and Maintenance Costs (OAM)*

Generally costs for maintenance of OTLs are taken as fixed percentage of the total actual capital cost of the equipment as given in Table II. Generally maintenance is done at the predefine schedules. Trained and experienced personnel are required for proper and effective maintenance. Air/ ground patrolling is required in search for any need for maintenance to the OTL system, whose frequency is inverse proportional to the extent of the inspection [6]. Common preventive maintenance schedule include washing of insulators, replacements of line signage and markings, and Removal of individual trees or snags (hazard trees) that pose a risk of falling into conductors or structures and causing outages or fires. Maintenance cost also depends on type of terrain, suppose in hilly area and mountain cost of maintenance increases.

**TABLE II**

| Table (OAM) cost of UTC & OTL [5] | | |
|---|---|---|
| | OTL | UTC |
| Operation | 0.8 – 1.0% | 0.1 - 0.3% |
| Maintenance | 0.7 – 1.0% | 0.1% |
| Operation & Maintenance cost | 1.5 – 2.0% | 0.2 – 0.4% |

Generally costs for maintenance of UTCs are also taken as fixed percentage of the total actual capital cost of the equipment. Routine maintenance for UTC include route patrols with the main purpose of preventing external failure i.e., damages from third parties, other factors include change in soil conditions (resistivity), monitoring water levels in the near ROWs and cooling fans, if UTC is layed in tunnel also considered. Other Routine maintenance activities require de-energisation of whole or partial UTCs system for checking/fixing of UTC, joints & termination point insulation, it also include inspection of reactor banks protection equipment such as differential protection for UTC system [8]. Partial-discharge detection by means of sensors placed at critical points of the circuit (e.g., joints, termination, etc) determines online detection discharge phenomena in UTC insulation [9]. An online monitoring system reduces planned outages frequency and downtime of circuit. General for discounted ((OAM)) cost is given below [10]. Taken (interest rate) i = 6% through out in this paper, & shunt reactor compensation 17.5 k€/MVAR, taking 11 MVAR/km required compensation. Present value ((OAM)) of the sum of the annual costs for periodic maintenance (OAM) over the circuit lifetime is given by:

$$((OAM)) = \frac{(1+i)^n - 1}{i(1+i)^n}\ (\text{OAM})$$

Where (OAM) is total operation and maintenance amount required at the end of life taking interest rate 6% per annum for whole lifecycle completion & ((OAM)) is discounted values at present. Hence, for the examined OTL case, with $(IE)_o = 0.5(I_o)$, whereas for the sensor less UTC case, with $(IE)_u = 0.5(I_u)$ & new UTC with sensors it is $(IE)_u = 0.55(I_u)$.

Where $(IE)_u$ = UTC Equipment cost; $(IE)_o$ = OTL Equipment cost; $(I_u)$ = UTC capex; $(I_o)$ = OTL capex. The values presented in Table I refer to the Average values of capital cost throughout Europe, wherein the installation of these equipments applies in standard environmental conditions (over flat land and in sparsely populated areas). The lower limit (min. value) refers to countries with low labour costs and the upper limit (max. value) concerns countries with higher labour costs. It is worth noting that the total investment cost (I) was apportioned among equipment, civil works, and other minor cost components on the basis of the line features. These correspond to average installation conditions: the circuits run through flat suburban areas with few directional changes; moreover, it is assumed that no remarkable geotechnical/ topographic obstacles are present along the route. Also (OAM) percent = 0.2% taken for UTCs for calculation of ((OAM)) due to increase of reliability of UTC system.

*B. Failure rate of XLPE AC UTCs*

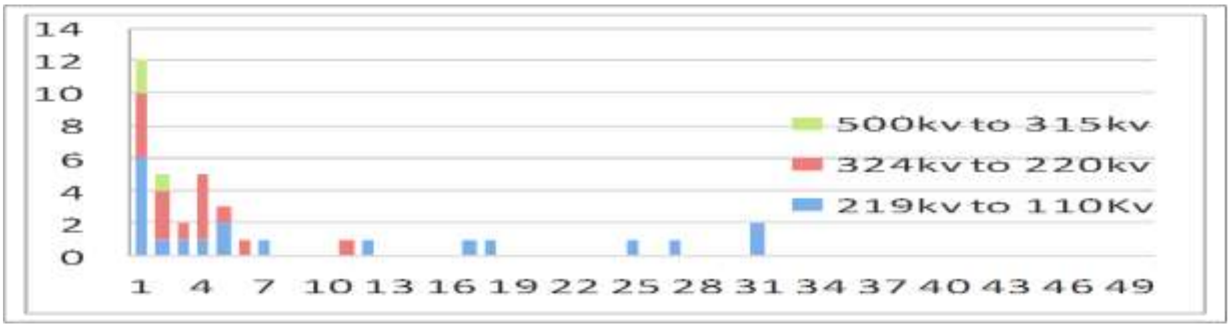
According to the statics available between 2000 to 2005, more than 90% of the installed XLPE UTCs had water barriers. For voltages range 220 kV to 500 kV extruded or welded metallic barrier has been used and still is the preferred solution. However, laminated barrier has now been introduced even at the highest voltage levels, generally where UTCs are installed in air. The use of pre moulded straight joints is increasing for XLPE UTCs. For the highest voltage levels the trend towards using pre moulded joints is very clear and more than 80% of the joints installed were pre-molded at 220kV. Based on the reported faults, it can be concluded that direct buried UTC systems are about 10 times more likely to be damaged by external conditions than UTC systems installed in ducts or tunnels. Comparing the recent data with that published previously and considering internal UTC failures only, the new information appears to indicate that XLPE has a lower failure rate than SCOF. Failure rates resulting from external failures appear to be tending to increase. Based on the data collected, it has been possible to estimate the outage times associated in carrying out repairs following a fault. Repairs on SCOF UTCs take on average 29 days whilst XLPE UTC systems require 20 days. Chart I shows that maximum fault occurs during initial service life of cable.

**TABLE III**

Comparison of fault between XLPE UTC and OTL [2], [3]

| S. No. | Type of Transmission conductor | **Failure Rate** (No. of failure/100 ct.km year) | | |
|---|---|---|---|---|
| | | Internal | External | Total |
| 1 | XLPE cable (220kv to 500kv) | 0.067 | 0.067 | 0.133 |
| 2 | XLPE cable (60kv to 500kv) | 0.030 | 0.058 | 0.088 |
| 3 | Splice (No. / year.100 splices) | | | 0.048 |
| 4 | Termination (No. / year.100 terminations) | | | 0.050 |
| 5 | HPOF, GC, EPR, & PE CABLE (60kv to 500kv) | 0.208 | 0.462 | 0.67 |
| 6 | HPOF, GC, EPR, & PE CABLE (220kv to 500kv) | 0.020 | 0.279 | 0.299 |
| 7 | All AC cables in service up to 2005 (220kv to 500kv) Excluding PILC) | .2743 | .2059 | 0.4802 |
| 8 | Over Head Line (230kv to 500kv) | N.A. | | 0.5314 |
| 9 | Over Head Line (230kv) | N.A. | | 0.7997 |

**CHART I**
**Trend in AC EHV XLPE Internal Failure; horizontal axis represents years while vertical axis represent number of faults**




Based on the cable failure data reported in Table III and considering a circuit length of 40 km the number of cable failures to be expected during the nominal 40 year life would be approximately four for SCFF cables or one failure every 10 years while for XLPE UTCs the expected failure rate would be one failure every 20 years. Expected failure rates for (six) terminations over 40 years are negligible for both SCFF and XLPE UTC systems. For UTC splices, on the other hand, expected failures (assuming splices every 500 m) during the nominal life would be one and two failures, respectively, for SCFF and XLPE UTC systems. In addition to above, Table III Shows that comparing the between OTL (S.No. 6) & internal fault of UTC (S.No. 2) gives the surprising ratio 17.71 and when including the external fault it becomes 6.038. Therefore it is clear from the above information that internal fault becomes very low as compared to external fault in the recent year. Also when comparing with internal fault rate of UTC (220kV - 500kV) with total fault rate on 230 kV line ratios becomes 11.94. In addition to above, after few years of commissioning of XLPE UTC, failure rate of XLPE UTC is rare as shown in below. This shows that after successful commissioning of UTC, fault occurs only few times in the starting year of lifecycle of the UTC system.

*C. Corrective maintenance Repair Costs (F) after Failures*

XLPE UTCs the expected failure rate would be one failure every 20 years and failure rate of splices is also one or two for nominal life on deterministic basis. Corrective maintenance is needed for OTLs and UTCs. The estimation of costs for the repair of components failing at random is of probabilistic nature. Ғ represents the costs associated with the circuit risk-of-failure in year y. Hence, the amount of these costs over the whole life of a given circuit, (F), is meant as expected value. Focus of this method is only monetary risk of failure at the circuit operation only, it only focuses on costs for repair/replacement of faulted components and return of the circuit into service, it does not include economic losses caused to system, and third party loses arises from outage. When failure (permanent fault) occurs, circuit requires service and a repair process starts to resume circuit operation as soon as possible. Generally for reducing downtime of circuit, some spares of circuits whose frequency of replacement is high in case of failure is usually held by operators at an offsite located store. If the faulted item is not repairable, new spare of required type must be purchased. Otherwise, all repairable items are transported to a repair shop. After repairing of faulted item, it held as spares at the store. Therefore, for non repairable items, the cost for supplying the spares consists of the expenditure for the initial set and of the expenditure for replacing the consumed spares at the time failures occurs for the corresponding installed components.

For repairable items, the costs for workshop-based refurbishment required. Also the expenses for components substitution $c$ or refurbishment $r$ include the costs of electrical and civil work costs for the removal of failed component and the installation of spares as well as costs for the transportation of materials to the site which is collectively referred to as $\omega$. Generally any circuit contain $m$ components of different types, and there are $n_a$ components of the "a" type, whose cost is, the total original capital cost of circuit equipment (excluding civil costs and equipment installation costs) is: [7]

$$((IE)) = \sum_{a=1}^{m} n_a c_a$$

Where,

$m$ = Number of component types;

$c_a$ = Capital cost of one component of type a.

(i). All of the components belonging to the examined circuits are assumed to operate in the useful region of their "bathtub" curve: the distribution of their time to failure is assumed exponential and, consequently, their failure rates are constant. The expected annual cost (€s/year) of failing equipment (by assuming, as first approximation, the need for substitution of each faulted item with a new one) is [7]

$$(F) = \sum_{a=1}^{m} n_a c_a \lambda_a$$

$\lambda_a$ Where is the failure rate (failures/year) of components of type "a".

(ii). It is worth noting that $n_a$ is the total number either of OTL spans or of UTC minor sections. Suppose, for single circuit 75(Km) = 3L = $\sum n_a \ell_a$ , where $\ell_a$ is the length ( in kilometers) either of a span between two consecutive towers ($\ell_a \cong 0.3$ km) or of a minor UTC section between two joints ($\ell_a \cong 0.7$ km). Likewise, $c_a$ and $\lambda_a$ are expressed as values per kilometer, when referred to conductors. The cost component for the works at site $\omega_a$ must be added to the capital cost $c_a$ in the case of replacement of the failed item of type "a" with a new spare, while if the failed item is repairable to its refurbishment cost $r_a$ .

(iii). The work cost $\omega_a$, consisting of civil and electrical installation costs plus transportation costs is assumed, both in the non repairable and in the repairable case, equal to a given percentage of $c_a$. The extent of this percentage depends upon the component type "a", and the features of its installation. The values of $\omega_a$ ranging between (0.25% - 0.50%) of $c_a$, for XLPE-insulated items laying underground, and (0.02% - 0.15%) of $c_a$ , for all other OTL and UTC items laying above the ground surface, have been assumed. Hence, the whole expected annual cost for repair after failures is

$$(F) = \sum_{a=1}^{m} n_a \lambda_a (c_a + \omega_a)$$

(iv). Non repairable faulted items is replaced with new items, while repairable items carried to the central workshop, then repaired, & held as spares at the central store. In the former case, the cost of purchasing a new spare $c_a$ must be sustained while, in the latter, the (usually lower) cost for refurbishment of the failed component $r_a$. The refurbishment cost $r_a$ is assumed to be a variable percentage of the corresponding capital cost $c_a$, depending on the component design characteristics and the failure mode occurring. In the present case studies, ratio $r_a/c_a$ has been assumed ranging in the interval (0.1% - 0.25%) for all repairable failure modes of components.

Also, for every component "a", it is easy to determine the probability $z_a$ of not-being repairable after a failure. An estimate $z_a$ of can be obtained from appropriate fault statistics by specifying component failure and repair modes. Whenever suitable information reporting system lacks, likely values of $z_a$ may be guessed on the basis of engineering judgment. Finally, having taken into account also the chance for reparability of the failed item, the whole expected annual cost for repair can be more precisely expressed as

$$(F) = \sum_{a=1}^{m} n_a \lambda_a (c_a z_a + (1 - z_a) r_a + \omega_a)$$

Hence, the present value of the sum of the expected annual repair costs over the n years of the circuit life is

$$((F)) = \sum_{a=1}^{m} n_a \lambda_a (c_a z_a + (1 - z_a) r_a + \omega_a) \times \frac{(1+i)^n - 1}{i(1+i)^n}$$

**Table IV**

| TABLE SHOWS VALUES OF KILOMETRIC REPAIR COSTS | | | |
|---|---|---|---|
| | OTL | Double-Circuit UTC | |
| | All Equipment | UTC | Shunt compensation Equipment |
| (F) (€/km) | 704 | 680 | 1070 |
| | OTL | Double-Circuit UTC | |
| ((F)) (€/km) | 10592.6 | 26331.0 | |

Table IV reports the expected values of ((F)) for the OTL and the UTC case. The annual kilometric cost (F) of UTC is split into two terms: the former refers to the pieces of equipment making up the UTC assembly, whereas the latter refers to the shunt compensation equipment only. The relatively low expected value of the repair costs, exclusively pertaining to the UTC assembly, reflects the high reliability of EHV XLPE UTCs and accessories. Conversely, since a higher total failure rate characterizes the series of conventional and electromechanical components, making up the compensation equipment (above all, reactors and circuit breakers contributing to its value), and the corresponding cost component has prevailing weight on the total annual repair cost of the UTC. Comparing the predictive & deterministic model of fault rate of EHV XLPE UTCs with EHV OTLs. Failure rate of EHV XLPE UTC complete system excluding shunt compensation on deterministic basis is 0.231 per 100ct.km.year & cost of probabilistic failure value is 680 €/km.year. Therefore cost of UTC fault is 588,744 €/fault. Similarly, cost of OTL fault is 132,480 €/fault. In the above case shunt compensation for UTC is not included.

**TABLE V**

| TABLE SHOWS COMPOSITION OF ((OAM)) & ((F)) | | | |
|---|---|---|---|
| | OTL<br>40 year life | XLPE UTC<br>40 year life | XLPE UTC<br>50 year life |
| ((OAM)) €/km | 79,000 | 79,000 | 67,360 |
| ((F)) (€/km) | 10,593 | 26,331.0 | 27,583 |
| Total: | 89,593 | 105,331 | 94,943 |
| Ratio: | $^{105,331}/_{89,593} = 1.1756$ | | $^{94,943}/_{89,593} = 1.0597$ |

Table V shows that lifecycle discounted cost ratio for 40 year life of cable have 1.176 times compare to the OTL cost of similar capacity, also when life of cable is consider for 50 year, then lifecycle discounted cost ratio becomes 1.06. In addition to above there is decrease in the total discounted cost of approximately 9.86% with increase in life of cable of 50 years.

## III. CONCLUSION

This article shows after effect due to continuous improvement on EHV XLPE UTCs 380/400kV technology. Its effect on the (OAM) cost and failure cost (F). With the improvement in the XLPE cable system technology, number of failure in the XLPE UTCs system reduces & therefore, reliability & lifecycle of the whole system increases. From the Table II it is clear that ((OAM)) cost for 40 year life of cable is similar for delivering same power at rated voltage for UTCs & OTL. With the increase of cable life there is reduction in ((OAM)) cost, also burden of capital cost of development of new transmission line extends for 10 year (expected additional lifecycle increase of EHV XLPE UTCs). Failure rate shows that mostly UTCs fault are of external type, i.e. third party failure which can be controlled by proper maintenance especially patrolling. Failure cost (F) of UTCs is based on deterministic & probability approach. The factor for accurate probability assessment of cost require large number of availability of statics of failure events with specification of failure modes and subsequent repair cost for increasing the confidence level of correct assessment. In addition to all above XLPE UTCs once properly commissioned provide hassle free operation for complete lifecycle. From recent survey, it is also concluded that fault generally arises in the starting years of commissioning due to workmanship or manufacturing defect. Once the XLPE UTC system is energized and is subjected to electrical loads at network voltage, an electrical lifecycle of well over 50 years can be expected. Above discussed methodology do not include costs arises due to undelivered energy, it also does not include re-dispatching and congestion costs arises from the differences in UTC and OTL corrective maintenance times.

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