Losses in xlpe insulated cables engineering essay

Power cables, mainly underground power cables form a bulk part of electrical power systems network. Accordingly, when medium voltage XLPE cables were first installed in the late 1960's, cable manufacturers and electric utilities expected them to perform reliably for 20 to 30 years. However, history has shown that these cables had high percentage of life losses whereby the service life of some of these cables was far shorter than expected. Many cables failed after only 10 to 15 years in service. The failure of XLPE cables was happened due to the aging process. Aging of XLPE cables is related to the temperature of the insulation. For XLPE cables, the normal maximum operating temperature is 90 °C. At this maximum value, the consumption rate of anti-oxidant has been calculated to afford a cable life of 30 years. Increasing the XLPE cables operating temperature will increase the rate which the anti-oxidant is used up. Subsequently, it will reduce the service life of XLPE cables. The reaction follows the Arrhenius relationship which is an exponential function. From this, even a small increase in temperature, it will hence give significant impact on the aging process of XLPE cables. Once the anti-oxidant in the cables is used up, the cables will start to oxidize and become easily broken. Then, the cables will be subject to stress cracking and electrical failure at positions of mechanical stress. In addition, the presence of harmonics in power system causes a conductor to overheat. This overheating process makes the cable to increase in term of temperature to its insulation. Therefore, cable will soften and the mechanical performances will reduce which is called as premature aging. Thus, it is important to investigate the presence of harmonic in any electrical equipment. From this we could know the temperature due to the overheating process and evaluate the life losses of any associated cables.

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Background

By means of the discovery of electricity in the early 19th Century, all countries in the world nowadays have virtually utilized electricity as a source of light and energy. This has led to the existence of distribution-transmission line system carrying current, even if at different voltages and transporting it over long distances till the end users or customers. For the distribution-transmission line system, engineers had thought critically in finding the suitable power cables for power system.

Mainly, most of the bulk electrical energy generated from the generation centers is being transported to major load centers within a large geographical area by the transmission systems using overhead lines [1]. In the other words, the distribution system delivers the electrical energy from these load centers to customers who are within a smaller geographical area. For safety, reliability and aesthetics, the electric circuits used to transport energy to such customers are usually underground power cables, though this kind of arrangement is expensive but has more advantages than the overhead lines [2].

Over the years, high demand of reliable electricity power supply has led the electricity markets to be highly competitive. Electric utility companies now have to develop means of maintaining, enhance the safety and reliability of their expensive power system components to operate advantageously and meet the demands of their customers.

One of power system component that constitutes a bulk part of the distribution and transmission line systems in urban areas is the underground power cable. For instance, in the United Kingdom there are about 93000 km of 11 kV cable and more than 13000 km of 33 kV [6]. In Malaysia with rush of development has led to increasing demands of electrical energy. Doing this, underground cable distribution is increasing significantly. It is estimated that there are about 180000 km of underground cables in Malaysia, forming about 80 % of the underground power distribution system. This shows that, the technology of underground power cables has grown up very fast by the time as the world is moving extremely in science and technology.

However, lately the presence of harmonic in electrical energy systems is well known [3]. The harmonics are due to nonlinear loads such as static converter and can damage the system components [6]. In the case of the cables, harmonics can cause relevant additional losses in the conducting and in the insulating materials which cannot be neglected. From the economical point of view, the presence of harmonics can cause economical damage which increasing the operating costs and decreasing the useful life of the system components.

The economical damage due to harmonic losses can be defined as the summation of the operating costs and the aging costs. As stated in [13], the operating costs are referred to the costs of the incremental energy losses caused by the harmonic flow in the component, where the term ' incremental' means that these losses are superimposed to the ones at the fundamental while the aging costs are referred to the incremental investment costs caused by the premature aging of the components caused by the harmonic pollution.

Premature Aging due to Harmonic

Aging failures have become a major and urgent concern in many utilities since many power system components are approaching the turning point to the end of life. For the case of power cables, the premature aging occurs due to harmonic pollution. The harmonic flow can lead to additional heating in power cables. Subsequently, temperature will rise and premature aging may result.

Development of Power Cables [1]

Power cable technology had its beginnings in the 1880s when the need for power distribution cables became pressing. With urban growth, it became increasingly necessary to replace some of the overhead lines for power transmission and distribution system with underground cables. The illumination of the larger cities proceeded at such a rapid pace that under some circumstances it was impossible to accommodate the number and size of feeders required for distribution, using the overhead line system approach.

In fact this situation deteriorated so notably in New York City that, in addition to the technical and aesthetic considerations, the overhead line system began to pose a safety hazard to the line workers themselves, the firemen, and the public. As a result, the city passed an ordinance law in 1884 requires removing the overhead line structures and replacing them with underground power cables. Similar laws and public pressure were applied in other cities, with the consequence that by the early 1900s, underground electrification via insulated cables was on its way to becoming a well-established practice [14].

A practical lead press was invented in 1879 and subsequently employed to manufacture 2kV cables for Vienna in 1885. During the same period, vulcanized rubber was used to produce cables on a commercial scale, although use of guttapercha had already been made as early as 1846.

Impregnated-paper power cables were first put on the market in 1894 by Callender Cables of England, using impregnant mixtures of rosin oil, rosin and castor oil and only in 1918 were these replaced by mineral oils. In North America, impregnated-paper cables were first supplied by the Norwich Wire Company. Varnished cambric cables were introduced by the General Electric Company in 1902. The behavior of these cables with hightemperature was subsequently improved the addition of black asphalt.

Some of the more common early solid and liquid insulating employed in various underground cable installations were natural rubber, gutta-percha, oil and wax, rosin and asphalt, jute, hemp, and cotton. In 1890, Ferranti developed the first oil-impregnated-paper power cable. By following their manufacture, his cables were installed in London in 1891 for 10 kV operations. In addition, the cables were made in 20 ft lengths as the total circuit was 30 miles in length about splicing joints were four required. Nevertheless, these cables performed so well that the last cable length was removed from service only in 1933. Cable installation continued to proceed at a rapid pace, so that by the turn of the 20th century many major cities throughout the world had many miles of underground power cables. For example, already by the end of 1909, the Commonwealth Edison Company in Chicago had 400 miles of underground cable operated in the voltage range between 9 to 20 kV. Montreal had some 4500 ft circuits of three-conductor cables installed in ducts under the Lachine canal for 25

kV operations; the same voltage was used for cable traversing the St. Lawrence River in 1906. With some experiences behind them, cable manufacturers were increasingly gaining confidence and during the St. Louis

Exposition in 1904 power cables developed for voltages as high as 50 kV were put on display [14].

Oil-Impregnated Paper Power Cables [14]

During the period prior to World War I, extensive use was made of oilimpregnated paper cables of the three-conductor belted type for voltages up to 25 kV. Due to non-uniform stress distribution in the cable construction, the belted cable proved to be highly partial discharge susceptible when attempts were made to extend the operating voltage range with larger wall thickness to approximately 35 kV, to meet the increased power demand following World War I [18]. This problem was resolved by shielding the individual conductors, using 3-mil-thick copper tapes. The outside of the shielded conductors was thus maintained at the same ground potential.

Figure 1. 3. 1 Cross-section of an Oil-impregnated Paper Insulated Cable

In addition, the belt insulation was replaced with a binder consisting of fabric tapes and strands of interwoven copper wire. The purpose of the latter was again to maintain the shields of the three cables at the same potential. Over the years, the conductor shapes of the three-conductor shielded paper insulated cables have evolved into three forms, namely circular, oval, and sectoral.

In many utilities a substantial portion of the present-day distribution load is still carried at 35 kV via three-phase oil-impregnated paper belted cables, with the three conductors individually grounded. There is little inducement to replace these cables with solid extruded dielectric cables, whose outer diameter for an equivalent power rating would exceed that of the ducts accommodating the more compact threephase oil-paper belted cables. Moreover, the oil-paper belted cables have been characterized by remarkably long in-service lifetimes that often exceed 65 years. Belted cables with unshielded conductors are still deployed but only for working voltages equal to or less than 15 kV.

With the individual conductors shielded, it was possible to extend the use of the three-phase belted cables for voltages as high as 69 kV, though on the average their application has been confined to voltages below 35 kV. The main reason for this upper limit has again been associated with the occurrence of partial discharges, which had in numerous instances led to the deterioration and failure of the dielectric at the elevated voltages. The partial discharges were found to take place in voids, which were formed either during the manufacturing process or during the load cycling while in service.

Solid-Dielectric-Extruded Power Cables [1, 14]

With the discovery of the hydrocarbon thermoplastic polyethylene (PE) in England in 1933, polyethylene became rapidly, the insulant of choice for RF coaxial cables. PE was first used as an insulant for power cables in the 1950s. In the mid 1960s, conventional PE became the material of choice for the rapidly expanding URD systems in the United States. It was known to be superior to butyl rubber for moisture resistance, and could be readily extruded. It was used with tape shields, which achieved their semi-conducting properties because of carbon black. By 1968, virtually all of the URD installations consisted of polyethylene-insulated medium voltage cables.

The polyethylene was referred to as HMWPE; this simply meant that the insulation used had a very high " average" molecular weight. The higher the molecular weight, the better the electrical properties. The highest molecular weight PE that could be readily extruded was adopted. Jacketed construction was seldom employed at that time. Extruded thermoplastic shields were introduced between 1965 and 1975 leading both to easier processing and better reliability of the cable [19].

XLPE was first patented in 1959 for a filled compound and in 1963 for unfilled by Dr. Frank Precopio. It was not widely used because of the tremendous pressure to keep the cost of URD down near the cost of an overhead system. This higher cost was caused by the need for additives (cross linking agents) and the cost of manufacturing based on the need for massive, continuous vulcanizing (CV) tubes. EPR was introduced at about the same time. The significantly higher initial cost of these cables slowed their acceptance for utility purposes until the 1980s. The superior operating and allowable emergency temperatures of XLPE and EPR made them the choice for feeder cables in commercial and industrial applications. These

materials do not melt and flow like HMWPE.

The emergence of power distribution cables insulated with PE have replaced a significant portion of the oil-impregnated-paper insulated power cables used at operating voltages up to 35 kV. But lower voltage PILC cables are still being manufactured, due to their in-service longevity and reliability. In spite the long record of service and reliability of PILC cables, they are being gradually replaced by the less hygroscopic polymeric insulated cables, XLPE.

XLPE cables have distinct advantages which are lighter weight, better electrical and thermal properties, less maintenance, and easier terminating and jointing procedure etc. Today, XLPE cables are being extensively used in many countries all over the world. In 1959, Japan and USA commercialized XLPE cables up to medium voltage rating. Since then a fast development of XLPE cables has taken place. Presently, XLPE cable of 500 kV class has been installed in Japan.

The introduction of XLPE has increased the capability of polymeric insulated cables because of their higher temperature ratings. XLPE insulations perform well at elevated temperatures. Their normal operating temperature is about 90 °C and designed to withstand an emergency overload and short circuit ratings of 130 °C and 250 °C, respectively.

Technology of XLPE Cables

XLPE has become the most favored insulant. Germany, USA, Asian and Scandinavian countries have installed gigantic quantities of such cables. Japan has developed XLPE cables up to 500 kV which is the highest voltage rating of XLPE cables manufactured so far. The basic material for XLPE cable is polyethylene (PE). PE has very good electrical properties. However, its mechanical strength decreases significantly above 75 °C restricting its continuous operating temperature to 70 °C only.

The improved thermal characteristics of PE are obtained by establishing a large number of cross-links between its liner molecular chains employing suitable techniques. The introduction of XLPE has increased the capability of polymeric insulated cables because of their higher temperature ratings. The processes for converting PE to XLPE are electron irradiation, chemical cross linking, and organic silane method.

Electron irradiation is a slow process and it is difficult to ensure an even degree of cross linking throughout the thick insulation required for power cables. Therefore this process is usually restricted to thin insulation of 1 to 2 mm thickness only. Chemical cross linking process is the process by which cross-linking of PE is established using organic peroxide such as dicumyl peroxide (DCP) at high temperature in the range 250 to 350 °C and pressure 15-20 kg/cm2. This method is employed in the production of XLPE cables of all voltage range, from LV to EHV. Sioplas technique is a relatively new method of cross linking PE into XLPE. Cross linking is achieved by mixing suitable silane to PE and exposing this to ambient conditions. This method has the distinct advantage of lower capital expenditure as no special arrangements to maintain high pressure and temperature are required. But the process is very slow for thick insulation and hence restricted to low voltage and medium voltage XLPE cables.

The general construction of XLPE cable consists of copper or aluminium conductor, extruded layer of semi conducting material over conductor (for voltage class above 3. 3 kV), extruded XLPE insulation, extruded layer of semi-conducting material (for cables of voltage rating above 3. 3 kV), copper wire or tape as metallic screen, armour, inner sheath and outer sheath, usually made of PVC etc. Three core XLPE cables are generally used up to maximum 33 kV. Cables of 66 kV and above voltage rating are of single core construction.

Figure 1. 3. 2 Solid dielectric extruded power cable [14]

The manufacturing process of XLPE cables consists of mixing of PE with cross-linking agent (DCP) and antioxidants, extrusion of semiconducting layers and insulation over the conductor, crosslinking the PE compound in curing lines at high temperature and pressure and cooling the core to ambient temperature. All these processes are carried out in one step employing catenaries lines for curing and cooling, hence the name continuous catenaries vulcanization. Semiconducting layers and insulation are extruded using triple extrusion technique.

The curing process was initially carried out with steam at high temperature and pressure. This resulted in the formation of microvoids within the insulation and restricted the application of steam curing process up to 33 kV. To achieve reliable HV cables, it was therefore necessary to employ curing in the absence of steam. For this reason, dry curing methods were developed, where PE was crosslinked under nitrogen pressure in silicone oil, in molten salt and also in long dies. The numbers of microvoids were drastically reduced. A new curing process has recently appeared namely silane process which is more economical.

Losses in Power Cables

Losses in power cables include losses in conductor, insulation, sheath, and screens armors. Conductor losses (I2Rac losses) depend upon the rms current I effective AC resistance of the cable conductor. Dielectric losses comprise of losses due to leakage through the cable insulation and caused by dielectric polarization under AC stresses. It includes the net dielectric losses depend upon cable voltage, its frequency as well as the permittivity and loss tangent of the cable dielectric material, as shown by the equation below:

Power loss = Ï‰CoV2Îµr tan Î´ [2] (1)

Generally, tan Î´, which partially controls the dielectric losses, is significantly

higher for oil-paper insulation as compared to XLPE insulation. For most of the dielectric materials used in cables, tan Î´ depends upon temperature, applied stress and supply frequency. For oil-paper insulation tan Î´ is also strongly influenced by moisture content. Therefore, in voltage cables, a moisture level of less than 0. 05 % is desirable in order keep dielectric losses within acceptable limits. The presence of voids and microcracks can also influence dielectric losses. These voids are formed in the insulation or at the screens/insulation interfaces during manufacture, installation or operation.

In polymeric cables, they are formed during the extrusion process while in paper-insulated cables, during the impregnation cycle. Voids may also form in cables by the differential expansion contraction of cable materials due to cyclic loading or short circuit conditions. These voids have a higher electric stress as compared to the bulk insulation. However, the gas inside a void usually has lower breakdown strength as compared to the main insulation. When the electric stress in void exceeds the breakdown strength of gas within the void, PD occurs.

Any partial discharge in such voids increases the effective tan Î´ value for insulation. Consequently, when the applied voltage is raised above the charge inception threshold, the dielectric losses exhibit a distinct increase. Similarly, impurities in the cable insulation and screening materials also increase dielectric losses.

The AC current flowing along each cable conductor induces emf the metallic sheaths of the cable. Without grounding, such sheaths would operate at a potential above the ground potential and can pose a hazard. Furthermore, it will accelerate degradation of the jacket and materials, thereby affecting the cable's life and reliability. When the sheaths are bonded, circulating current flows in them causing power losses. However, for three-core cables such losses are negligible. In addition to circulating currents, eddy currents are also induced in sheaths of both single and multi-core cables causing additional losses which usually are of small magnitudes.

1. 5 Objectives of Study

This project is conducted to evaluate the expected value of aging cost due to harmonic losses in XLPE cables. Therefore, this project is conducted regarding to these objectives:

To investigate the effects of harmonics losses on XLPE cables from

economical point of view.

To evaluate the expected value of the aging cost due to harmonics losses

in XLPE insulated cables.

1. 6 Scope of study

This study will focus on XLPE insulated cables

This study will use the characteristics of single core underground cables.

The effect of harmonics losses on XLPE cable will be investigated

A program will be developed to evaluate the expected value of aging cost

due to harmonic losses.

The economical damage due to harmonic losses is quantified by means of the expected values of the operating costs and of the aging costs. For this, it will focus only for the calculation of the expected values of the aging costs.

CHAPTER 2

LITERATURE REVIEW

2. 1 Introduction

We design power systems to function at the fundamental frequency [1]. In Malaysia, the fundamental frequency is standardized at 50 Hz. This design is prone to unsatisfactory operation. At the same time, failure will happen when subjected to voltages and currents those contain substantial harmonic frequency elements. Frequently, the electrical equipment may seem operate normally. However, when they operate under a certain combination of conditions it might enhance the impact of harmonics which cause results to damage [20].

Most people do not realize that harmonics have been around for a long time. Since the first AC generator began to operate more than 100 years ago (Sankaran, C., 1995), electrical power systems have experienced harmonics. When harmonics present in electrical equipment, it can cause the equipment to malfunction and fail to work. In this case proper design and rating are needed to prevent the presence of harmonics.

2. 2 Power System Harmonics

The objective of the electric utility is to deliver sinusoidal voltage at fairly constant magnitude throughout their system. In fact, in order to achieve this objective is reasonably complicated because there are loads that exist on the power system that will produce harmonic currents. These currents produced may result in distorted voltages and currents that can give negative impact to the system performance in different ways.

As the number of harmonic producing loads has increased over the years, it has become increasingly necessary to address their influence when making any addition or changes to an installation. We should consider two important concepts that have to bear in mind with regard to power system harmonics. The first concept is the nature of harmonic current producing loads (non linear loads) and the second concept is the way in which harmonic currents flow and how the resulting harmonic voltages develop.

Ideally, voltage and current waveforms are perfect sinusoids. However, because of the increased popularity of electronic and other non-linear loads, these waveforms quite often become distorted. This deviation from a perfect sine wave can be represented by harmonics – sinusoidal components having a frequency that is an integral multiple of the fundamental frequency. Thus, a pure voltage or current sine wave has no distortion and no harmonics, and a non-sinusoidal wave has distortion and harmonics. To quantify the distortion, the term total harmonic distortion (THD) is used. The term expresses the distortion as a percentage of the fundamental (pure sine) of voltage and current waveforms. In addition, current harmonics can distort the voltage waveform and cause voltage harmonics. Voltage distortion affects not only sensitive electronic loads but also electric motors and capacitor banks.

2. 2. 1 Definition of Harmonic

Harmonics are defined as current and voltages at frequencies that are integer multiples of the fundamental power frequency [4]. For example, if the fundamental frequency is 50 Hz, then the second harmonic is 100 Hz, the third is 150 Hz, and etc [5]. The presence of harmonics in electrical energy systems is well recognized due to nonlinear loads such as static converters and it can damage the system components [6]. These nonlinear loads will draw current in abrupt pulses rather than in a smooth sinusoidal manner. Then, these pulses cause distorted current wave shapes which in turn and cause harmonic currents to flow back into other parts of the power system. In the case of power cables, harmonics can cause relevant additional losses in the conducting and in the insulating materials which cannot be neglected in the cable size [6].

2. 2. 2 Source of harmonics

Most harmonics originate from the generation of harmonic current caused by nonlinear load signatures [4]. The major sources of power system harmonics include switching operations, power electronic devices and other nonlinear loads and etc [7]. Electronic devices are nonlinear and thus they create distorted currents even when supplied with a purely sinusoidal voltage. As nonlinear currents flow through a facility’s electrical system and the distribution-transmission lines, additional voltage distortions are produced due to the impedance associated with the electrical network. Thus, as electrical power is generated, distributed, and utilized, voltage and current waveform distortions are produced [8].

As the number and ratings of power electronic devices connected to the power systems increase, the harmonic currents injected into power system and the resulting voltage distortions have become a major problem for power quality. This is the current issues that always be taken into account nowadays. Furthermore, the installation of power factor improving capacitors may lead to resonance conditions that amplify specific harmonic currents flowing into transformers and generators. On the other hand, large industrial ac motors may also provide a path for the harmonic currents. These currents can cause overheating problems for the motors, generators, and transformers. Power grid connected electric devices which can generate harmonic currents in the power system include fluorescent light ballast transformers, induction motors, incandescent light dimmers, overexcited transformers, arc welding equipment, AC/DC rotary converters, battery chargers, computers, and any type of device that utilizes rectified AC power to drive DC equipment [9].

2. 2. 3 The Harm of Harmonics

Harmonics only mean trouble if the power system is not well designed to handle them. High harmonic neutral currents are a problem only if the neutral is not properly sized. Current harmonics are not a problem to a transformer if it is derated appropriately. Even some voltage distortion below 8 % THD at the point of utilization is acceptable as long as sensitive equipment is not affected. However, it is always important to be aware of the presence of harmonics and to try to minimize them by purchasing low distortion electronic ballasts and reactors for PWM ASDs. This will not only keep the harmonics in check and improve the power factor in the facility, but will also save energy by reducing losses on power system components. In addition, any time there is a considerable increase of non-linear loads, it is important to check power system components to prevent problems.

2. 2. 4 Effects of Harmonics on Power System

Harmonic currents and voltage distortion are becoming the most severe and complex electrical challenge for th