DOI: http://dx.doi.org/10.4314/gjpas.v18i3-4.8

GLOBAL JOURNAL OF PURE AND APPLIED SCIENCES VOL. 18, NO. 3&4, 2012: 169-177

www.globaljournalseries.com, Email: info@globaljournalseries.com

TOWARDS SOLVING THE PROBLEM OF TRANSMISSION AND DISTRIBUTION OF ELECTRIC POWER IN NIGERIA VIA SUPERCONDUCTOR POWER CABLES

MICHAEL U. ONUU AND UKO OFE

(Received 19 July 2011; Revision Accepted 24 March 2012)

ABSTRACT

Data on transmission and distribution losses in some African countries on conventional cables show that Nigeria experiences the highest transmission and distribution losses (=6.81 x 10^{15} kWh) among African countries and, certainly, among the highest in the world with per capita consumption of 0.03 kWh/person. The total installation cost comparison between conventional and superconducting cables (SC) has been done and the comparison of the losses in SC cables and the conventional ones has also been analyzed. Some of the parametric properties of superconducting materials and benefits of high temperature superconducting (HTS) cables are discussed. Transmission lines in Nigeria have been found to experience high voltages and very low voltages under light loading and high loading, respectively. It has also been found that with the use of HTS cables, these losses, which are mainly the I^2R losses, are negligibly small and almost zero. It is also found that HTS cables would be panacea for these high transmission and distribution losses in Nigeria.

KEYWORDS: Transmission, distribution and superconducting cables.

1. INTRODUCTION

A look at the World energy demand clearly shows that unless a radical energy policy is taken and implemented by every country of the world there will be a serious problem of energy crisis in the near future (Onuu, 1998). Onuu (1998) re-examined existing data on World energy demand and found that the rate at which the World energy demand, $E(t)$ is increasing is exponential and of the form $E(t) = E_0 \exp(bt)$, where t is time in years and E_0 and b are constants with values 433.3 and 0.024, respectively. However, the next serious challenges next to generation are transmission and distribution of electrical energy.

Transmission is the moving of electrical energy from the generating plants to bulk delivery point called the substation, from where it is delivered to consumers (distribution). The choice of transmission voltage depends on the amount of power to be transmitted and transmission distance.

Electricity can only be used after it has been generated, transmitted and distributed. If, therefore, there were inadequate distribution and transmission, even generated electric power would simply amount to wasted efforts. Onohaebi (2009) and Uchenna (2009) observed that Nigerian power transmission network is characterized by prolonged and frequent outages. A summary of outages in Nigeria recorded for 2003, 2004 and 2005 is presented in Table 1.

TABLE 1: Summary of outages in Nigeria for 2003, 2004 and 2005
(PHCN, 2005; NCC, 2006).

Year	Network (kV)	Forced outage	Planned outage	Urgent outage	Emergency outage	Total
2003	330	252	90	69	48	459
2004	330	227	190	139	179	785
2005	330	225	181	59	64	529
2003	132	884	169	321	1361	2735
2004	132	759	130	240	752	1881
2005	132	731	200	296	296	3585

Michael U. Onuu, Department of Physics, University of Calabar, Calabar, Cross River State, Nigeria.
Uko Ofe, Department of Physics, University of Calabar, Calabar, Cross River State, Nigeria.

A total of 3585 outages were recorded in 2005 in Nigeria in the 132 kV network, out of which 296 (65.78%) were emergency outages. The outages constitute 225 representing 42.53% compared to 2004 value 277 (35.1%) and 2003 of 252 (54.47%) for 330 kV Network. Figure 1 shows the different types of outages in Nigeria for 132 and 330 kV networks.

From Table 1 it is also observed that the planned outages on the 132 kV network recorded the highest value of only 7% while the remaining 93% were due to either forced outages or emergency/urgent outages. From Fig. 1 (Uchenna, 2009), it is also clear that more outages were experienced in 2003-2005 along the 132kV network than along the 330kV network.

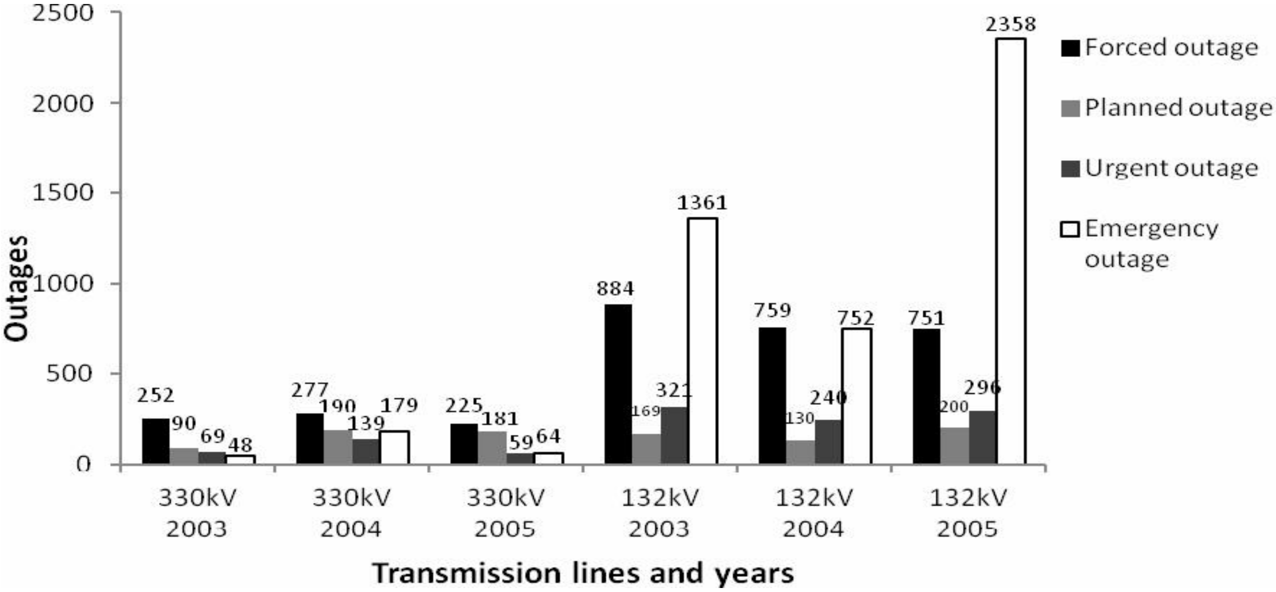

Fig. 1: Number of various types of outages on the 330 and 132 kV for 2003-2005 (Uchenna, 2009)

Adeleye (1977) also stated that one of the problems associated with transmission and distribution of electricity in Nigeria was that transmission lines were unusually long with insufficient substations for control of voltages. Table 2 shows typical links in Nigeria and their respective networks. He proffered a solution that the 11kV lines should be limited to about 12km instead of 45km resulting in low voltage. The same observation was also made about the 33kV lines. However, this proffered solution might not be a panacea for the problem.

Table 2: Some links in Nigeria and respective network

S/No.	Link	Network (kV)	Distance apart (km)
1.	Onitsha to Enugu (New Haven)	330	96
2.	Onitsha to Alaoji	330	138
3.	Alaoji to Afam	132	25
4.	Benin to Onitsha	330	137
5.	Benin to Ikeja West	330	280
6.	Osogbo to Benin	330	251
7.	Osogbo to Jebba	330	249
8.	Jebba to Shiroro	330	244
9.	Benin Kebbi to Kanji	330	310
10.	Jos to Gombe	330	265
11.	Kaduna to Kano	330	230

According to Akin (2008), Nigeria's electricity market dominated by the state-owned Power Holdings Company of Nigeria (PCHN), formally called National Electric Power Authority (NEPA), has been incapable of providing minimum acceptable international standards of electricity service, reliability, accessibility and availability for the past three decades. The nature of the poor record in electricity supply in the Nigerian network is clear in the trend in the transmission and distribution losses depicted in Fig. 2.

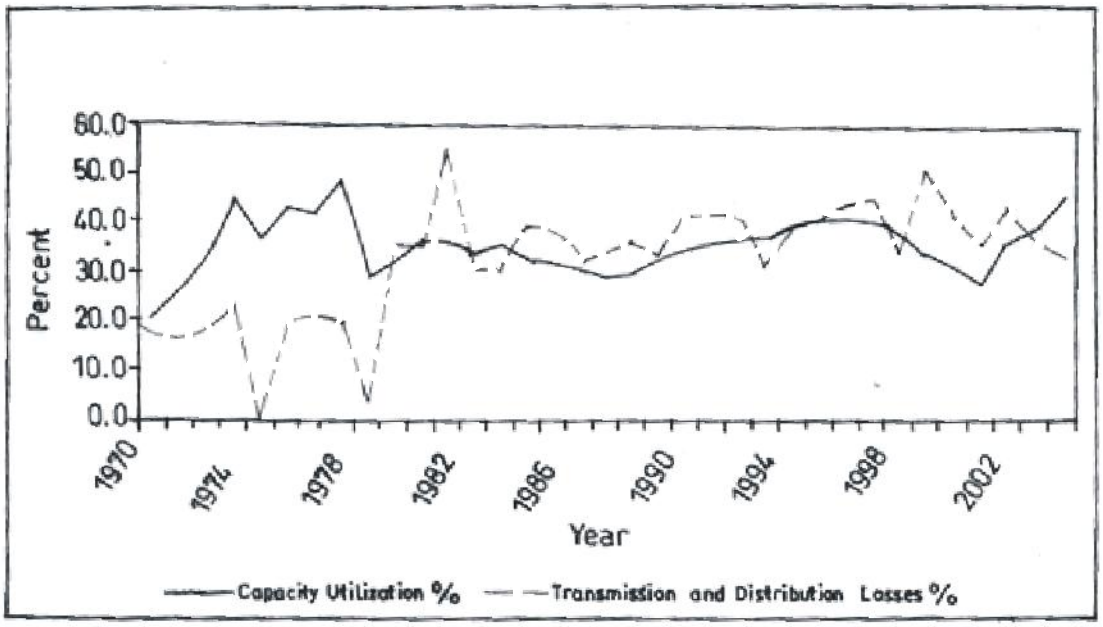

Fig 2: Indicators of electricity crises in Nigeria from 1970 to 2004 (Akin, 2008)

Akin (2008) reiterated that the system losses are five to six times what obtains in well-run power systems. The low and unstable capacity utilization evident in average capacity utilization, of less than 40% for the most of the period, show the large gap between installed and actual operational capacity. Remarkably, despite the size of inoperable capacity, no new plant has been added to the grid since 1990. The installed power generation is 4,600MW, but the operational capacity is less than 3,000MW. This is made up of hydroelectric and gas-fired power generating plants (Akin, 2008).

Electric power transmission and distribution losses in some African countries as at 2004 are shown in Table 3. South Africa and Egypt generate total power of 45,000 and 18,000MW, respectively (Table 4). Since losses are proportional to the quantity generated, it is not surprising that those losses in South Africa and Egypt as are high as 1.47 and 1.23 x 10^{16} kWh, respectively. But Nigeria that generates only 4,600MW has 6.81 x 10^{15} kWh losses. Thus, it is clear that Nigeria ranks first in electric transmission and distribution losses in Africa.

Table 3: Electric power transmission and distribution losses in some African countries as at 2004 (Emeka, 2008)

Countries	**Losses x 10^{12} (kWh)**
South Africa	14,710
Egypt	12,315
Nigeria	6,805
Morocco	3,116
Zimbabwe	1,472
Ghana	890
Cameroon	790
Sudan	607
Tanzania	578
Angola	325
Gabon	273
Ethiopia	254
Botswana	131
Benin	114
Togo	89

Table 4: Comparative analysis of consumption of electricity for some countries of the World (Emeka, 2008).

Country	**Population X 10^6**	**Power Generation (MW)**	**Per Capita Consumption**
United States	250.00	813,000	3.20
Cuba	10.54	4,000	0.38
United Kingdom	57.50	76,000	1.33
Ukraine	49.00	54,000	1.33
Iraq	23.60	10,000	0.42
South Korea	47.00	52,000	1.09
South Africa	44.30	45,000	1.015
Libya	5.50	4,600	1.015
Egypt	67.90	18,000	0.265
Nigeria	140.00	4,600	0.03

Table 4 shows a comparative analysis of consumption of electricity for some countries in the world. From the table, Libya, for instance, with a population of only 5.5 million has generating capacity of 4,600MW. The same is applicable to Nigeria which has a population of 140 million (Emeka, 2008).

1.1. High Temperature Superconducting Cables: Technology and Development Trend

According to Takato *et al.* (2005), superconducting cables are expected as one of the solutions for the shortage of transmission capacity in metropolitan areas. Its merits, they stated, being large transmission capacity in compact dimension; small transmissions loss; no leakage of electromagnetic field to the outside of the cable; small impedance. Obviously, these features are effective for the improvement of reliability and economical competitiveness of electrical networks.

The interest in the field of superconducting power cables dates back to the 1960s, but because conventional metallic superconductor requires helium as cooling medium, the cable system designs were unduly complex and cost prohibitive (Takato *et al.*, 2005). The interest in this field, however, was renewed following the discovery in 1986 at the Massachusetts Institute of Technology (MIT) of ceramic material with high temperature superconducting capabilities, which enabled the use of liquid nitrogen as cooling medium about 200^0C. This marked the discovery of high temperature superconductivity. Liquid nitrogen is widely used in a variety of industrial applications, and is recognized as a cheap, abundant and environment friendly (Nexans, 2010). More than 22 years, Greg Yurek's dream of utilizing high temperature superconductivity (HTS) technology in a power transmission cable in commercial grid finally came through in 1986. A year later, Yurek, in April, 1987, with three MIT Professors, founded American Superconductor Corporation (AMSC, 2009). In spite of the initial challenge that faced him and AMSC to commercialize these problematic materials in flexible power cables, they remained undaunted. Their victory was announced in June 2008, when Yureh celebrated the commissioning of the world first transmission voltage HTS system at long island, New York, USA. Today many countries, powered by AMSC, produce ATS cables.

High temperature superconductor cables are ideal solutions for breaking the grid bottlenecks. They enable effective transmission and distribution of more energy, with minimal community in pact (AMSC, 2009). High temperature superconductor wire enables power transmission and distribution cable with three to five times the capacity of conventional underground AC cables and up to ten times the capacity of DC cables. They support general load growth, add controllability of power over meshed grid and are implemented with low environmental impact, and below are other advantages of the cable:

(a) The design of superconducting cables generally includes flexibility (Hull and Myers, 1992). Superconductor cables can carry more power than the conventional cables; advantage gained with the use of flexibility.

(b) Superconductor cables provide more reliability and security of power grid than the conventional cables. Smart controllable superconductor cables can make the power network in which they are installed self-protecting: able to adjust and automatically to disruptions in power network equipment caused by weather, willful the vandalizations of transmission cables which are common in our system.

(c) The high capacity of super conductor cables allows 3 to 5 times the power for transmission systems and to 10 times the power distribution systems to be delivered at voltage or equivalent power delivered at reduced voltage. For instance, a superconductor cable operating at 11kV can have the same MVA rating than a 132kV cable (Hull and Myers, 1992). The combination of high power capacity and compact size makes superconducting cables a solution where conventional cables and/or overhead lines would be difficult or impossible.

(d) Minimal Environment Impact

Superconductor cables contain no oil, thus, eliminating containment issues associated with conventional cables. The shield combination of cold dielectric cables also eliminates external electromagnetic field common to overhead transmission technologies.

In fact, the reduction in green house gas (GHG) emissions which has been a topical issue due to the Kyoto Protocol that requires the European Union (EU) to reduce emissions by 8% from 1990 levels by 2012 could be achieved using superconductors. Physicists in Finland have calculated that the EU could reduce the CO_2 emissions by up to 53 million tons if high temperature superconductivity were used in power plants.

(e) In superconducting cable, there is a significant reduction in the disruption caused by cable construction and installation activities.

(f) The superconductivity power cables have significantly lower impedance than conventional cables. This characteristics means that they can be strategically placed in the grid to draw flow away from the overtaxed conventional cables or overhead lines thus relieving network congestions; moreover because the permitting cycle can be completed faster, superconductivity cable system can ease grid congestion more quickly.

(g) The installation of superconductor cable is easier, and less expensive than installation of conventional cable. In addition, because they can operate at lower voltages, more expensive high voltage, equipment and transmission losses can be avoided.

(h) With super conductor cables, utilities may solve power flow problems with shorter circuit lengths, example, connecting to more pervasive 11/132/330 kV (i.e.) local feeder/short/far distance transmission system rather than tying back to more EHV transmission system.

1.2. Superconducting cable design

W. A. Little and V.L. Ginzburg began working on the problem of HTS around 1964. And since that time the prospects of room-temperature superconductivity have varied from gloom (around 1980) to glee (in 1986, when HTSC was discovered) (Pickett, 2006). The most important application of superconductivity is in the transmission of electrical energy through superconducting cables.

Figures 3 and 4 show the symmetric cable design by Nexan, a French company, founded in 2000. It is the world’s largest manufacturer of cables. It has an industrial presence in forty countries. Nexan uses its expensive experience in high voltage cable and accessories to manufacture super conducting cables, using existing industrial process.

HTS cables are capable of serving very large power requirement or the medium and high voltage ratings. The cables use tapes made of super conducting materials as current carrying element (Nexans, 2010).

In superconducting materials, the superconducting state exists as long as temperature, current and magnetic field are below their critical values superconductor materials used in HTS cables are $Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO) and Y$Ba_2Cu_3O_7$ (YBCO).

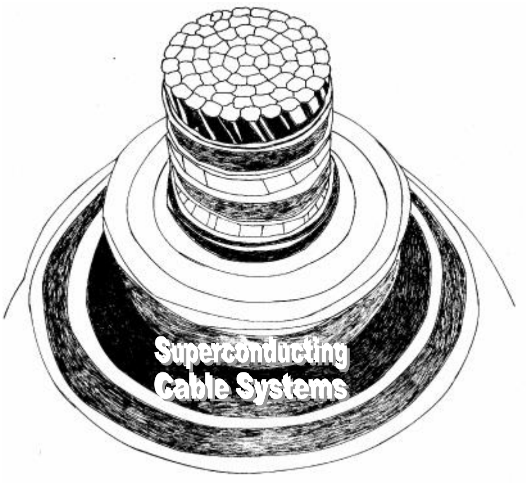

Fig. 3: Symmetric view of superconductor cable design (Nexans, 2010)

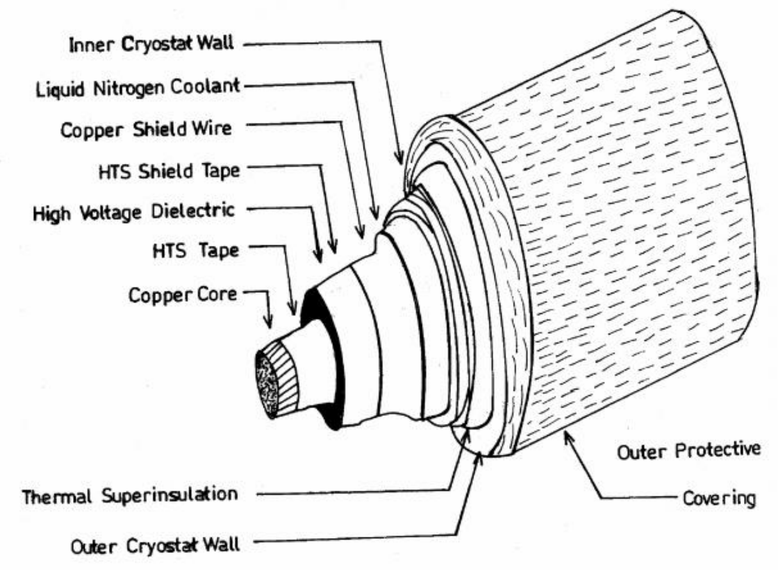

Fig. 4: Lateral view of superconductor cable design (Nexans, 2010)

2. Theoretical Consideration

According to Hull *et al.* (1989), the major losses in a super conducting power transmission line include: current-dependent losses in superconductivity, voltage-dependent losses in insulation, heat leakage of the cryogenic enclosure containing the cables and losses associated with pumping the cryogenic refrigerant. The first three losses, he observed, form the refrigeration systems, and the heat leakage into the enclosure and voltage dependent losses must be aborted regardless of the power carried by the cables.

However, for the four losses mentioned above, the current-dependent losses in the superconductor are the most difficult to calculate.

If there is a good control of the load power factor, the cable current is proportional to the power carried by the transmission system thus, the conductor loses very by roughly square of the power completely negligible, and this design criterion may be completely different. The dielectric losses per unit length are directly dependent on the capacitance and dissipation factor.

In AC superconducting cables, the dissipation factor must be especially low or low losses of the conductor will be swapped by the dielectric loss. These stringent requirements eliminate many candidate electrical insulation materials for flexible ac cables.

2.1. AC Losses

The current-dependent losses of a superconducting material in alternating fields can be predicted from theory only for well-prepared samples in fields parallel to the surface. In practical conductors, the losses can be substantially increased by surface roughness, large grain size, and the addition of materials to the superconductor. In addition, eddy current losses may occur in normal metal laminated to the superconductor.

2.2. Intrinsic Conductor Losses

Type-II super conductors transporting ac currents are subject to hysteresis loss, due to irreversible magnetization during a cycle. For power frequencies (<20 kHz), this loss is independent of frequency, *f*.

Hull *et al.* (2008) states that the power loss per unit area Q for a slab of superconductor is,

$$Q = \frac{kfH_0^3}{J_c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where H_0 is the maximum magnetic field at the surface of the conductor and J_c is the critical current density which increases with H_o and *k* is a constant that depends on geometry. If the superconductor is a slab, then

$$k = \frac{2\mu_0}{3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

In eqn. (2) μ_0 = 4π $\times$ 10^7 Hm^{-1} is the magnetic permeability of free space at any temperature *T*.

In some designs, the superconductor shells shield the conductor until superconductivity is lost. For any normal conductor in the system, which we assume to be flat slab, loss is dependent on the skin depth defined by,

$$\delta = \left(\frac{2\rho}{H_0\omega}\right)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where ρ is the electrical resistivity, and ω is the angular frequency (=$2\pi f$).

The power loss per unit area depends on the surface resistance, R_s, and the peak surface magnetic field (Hull *et al.,* 1989) is given by,

$$Q = R_s H_0^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where R_s depend on the thickness, t_n of the conductor slab. In the limits of thick and thin conductors,

$$R_s = \begin{cases} \dfrac{\rho}{\delta}, t_n > \delta & (5a) \\ \left(\dfrac{2}{3}\right)\left(\dfrac{t_n}{\delta}\right)\left(\dfrac{3\rho}{\delta}\right), t_n \ll \delta \quad \ldots\ldots & (5b) \end{cases}$$

2.3. Scaling Law

For a power transmission system it is important to design for low losses in order to minimize the weight penalty of the losses the refrigeration system required to remove this heat. If the loss minimization is the primary design constraint, then the scaling laws for the transmission system are very different from terrestrial system.

For a superconducting slab, the surface magnetic field is

$$H_0 = J_c t_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where t_s is the thickness of the superconductor.

Substituting eqns. (1) and (2) into (6) yields

$$Q = \left(\frac{2}{3}\right)\mu_0 f t_s^3 J_c^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

But, the power transmitted is given by

$$P = VI = VJ_c w t_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

where w is the width of the slab. If *L* is the length of the transmission line, then the fractional loss *F* in a two-superconductor single-phase system is

$$F = 2Q\frac{Lw}{P} = \left(\frac{4}{3}\right)\mu_0 f t_s^2 J_c \frac{L}{V} \quad \ldots\ldots\ldots\ldots \quad (9)$$

Obviously, losses are diminished for thin conductors. The weight of the bare transmission line, that is without dielectric or mechanical support, is proportional to $t_s J_c w$. This can be expressed mathematically as $W \propto t_s J_c w$,

The loss per unit length of the superconductor is also proportional to $\frac{t_s}{w}$

i.e. $$\frac{F}{A} \propto \frac{t_s}{W} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

Equation (10) is independent of J_c .

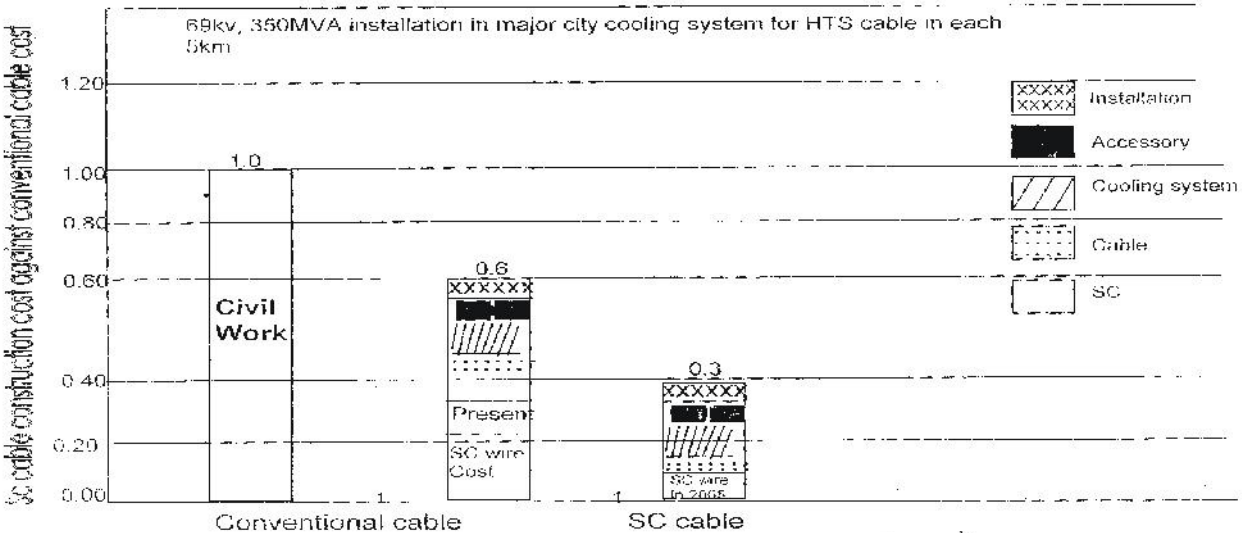

Fig. 5: Total installation cost of SC cable (Takato, 2005)

Comparing 66kV, 3kA, 350MVA class cables it is shown that the loss of electric power using a superconductor cable is appropriately half of that when the conventional one is used.

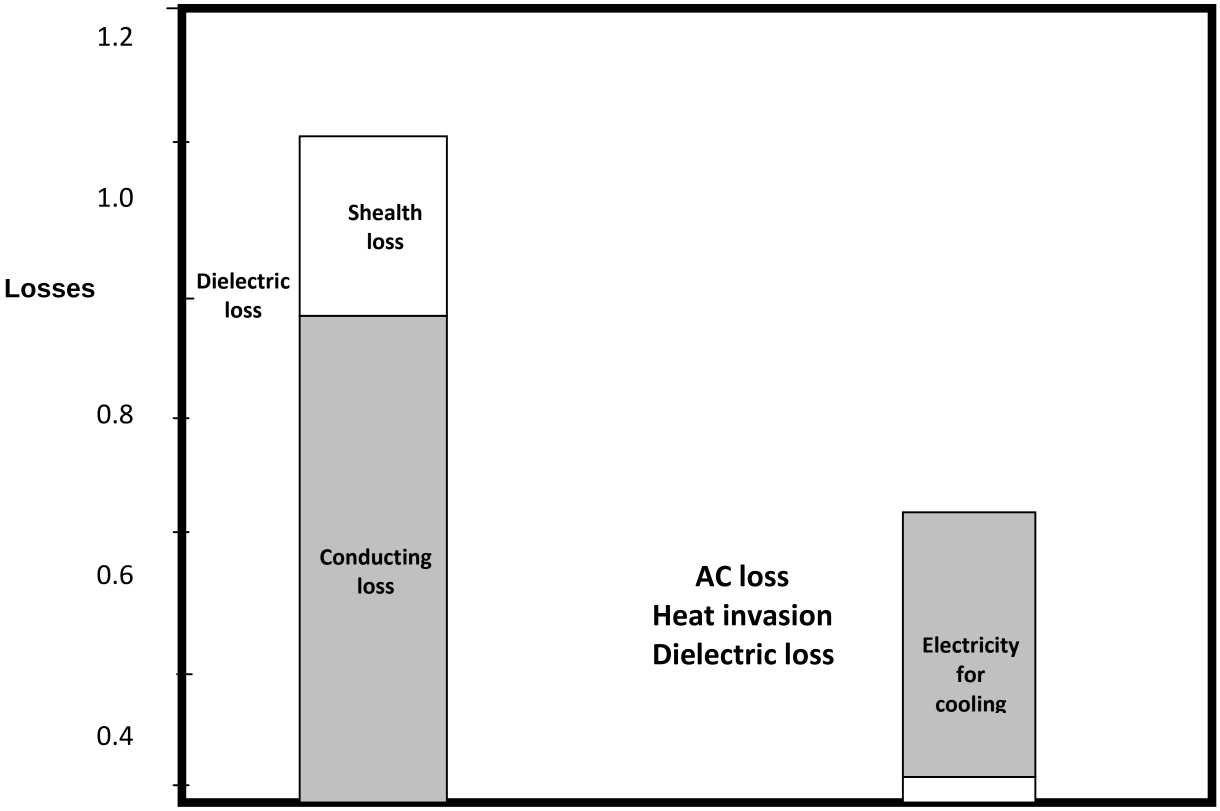

Fig. 6: Transmission loss for 350 MW cables (Takato, 2005)

3. DISCUSSION

The results of the study are shown in Figs. 5 and 6. Figure 5 delineates a case study of the comparative cost of the conventional cable and that of high temperature, superconducting cables, in a large city like Tokyo, using current construction technique and cooling systems, every 5km, as parameters. It was found that the superconducting was cost competitive. It was also observed that the cost of installing a superconductor cable line decreases with time, and, the present cost, with time, reduced to half.

Re-examination of existing data shows that Nigeria experiences the highest transmission losses of 6.81×10^{15} *kWh* among African countries and the world. These losses are five to six times what obtain in well-run power systems (Akin, 2008).

Figure 6 shows comparison of transmission loss in a superconducting cable and a conventional cable. Comparing various cable ratings shows that the loss of electric power using a superconductor cable is appropriately half of that when the conventional one is used.

Analysis shows that the use of HTS cables is a panacea to solving the problem of transmission and distribution of electric power in Nigeria with a number of advantages over conventional AC and DC cables (AMSC, 2009). This has passed the experimental stage as some countries of the world are already encouraging installation and use of HTS cables in electric power transmission (Takato, 2005).

4. CONCLUSION

The study has focused principally on the comparison of superconducting cables and conventional ones. The result has revealed that superconducting cables have myriad advantages over the conventional cables. It is, therefore, concluded that to solve the endemic and seemingly intractable problems of transmission and distribution, which have been the bane of our power supply for many decades, Nigeria needs superconductor cables.

REFERENCES

Adeleye, E. A., 1997. Physics and Energy Utilization in the 21st Century. A paper at the 20th Annual Conference, Nigerian Institute of Physics, Minna, Nigeria, 21-22.

Akin, I., 2008. Nigeria's Dual Energy Problems. Journal of International Association for Energy Economics. Fourth Quarter, 17-18.

Emeka, E. O., 2008. Development Crisis of Power Supply and Implication for Industrial Sector in Nigeria stud. Tribes, 6, (2): 83-92.

Hull, J. R and Myers, T., 1989. High Temperature Superconductor for Space Power transmission Lines. Argonne national Lab., Illinois 891208-32.

LTS., (Losses in Transmission Lines): *http://www.tpub.com/meets/book/41b.hm,* June (2010).

Nexans., *http://www.nexans.com/coperate/2010/nexans.* Retrieved 4th June 2010.

Onohaebi, O., 2009. Power Outages in Nigeria Transmission Grid. Research Journal Applied Sciences. 4, (1): 1-9.

Onuu., 1998. The challenges of the Global Energy Demand. Global Journal of Pure and Applied Sciences, 4, (3): 311-318.

PHCN., 2008. In Akin Iwa Yemi: Nigeria Dual Energy problems (IAEE). Fourth Quarter.

Pickett, W. E., 2005. Design for a Room Temperature Superconductor. Journal of Superconductivity and Novel Magnetism, 19, (3-5):

Takato, M., Hirpo, Y. Y and Michihiko, W., 2010. High Temperature Superconducting Cable and Development Trend., Supercond. Sc. Technol., 014022.

Uchenna, K., 2009. Is FG's 6000Mw Power Target Still Feasible? Energy world: http:/businessworldng.com/web/articles/689/1/Is-Keis6000Mw-Po.