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AI-Enhanced Superconducting Technology for Power Transmission and Distribution Loss Reduction

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Abstract. *Superconducting technology has wide applications in superconducting generator, superconducting transmission lines and superconducting energy storage systems. Most of the studies undertaken conclude that although the application of superconducting material in power system did indeed lead to improved efficiencies, the capital cost and cooling energy requirement were too large and that it was not economically feasible to implement. But the major result in the following studies is that in the future, a full superconducting urban area distribution level power system could be cost-effective with existing solutions. It also offers lower voltage drop and improved stability. The studies employ the use of High-Temperature Superconductors (HTS) cables and HTS current limiters. HTS power equipment has reached such a maturity level that its large-scale integrated use will be feasible in up coming years. Energy savings from efficient power transmission and distribution can align with the decarbonized electric vehicles market.*

Keywords: *superconductors, energy savings.*

1. Introduction

The discovery of High Temperature Superconducting (HTS) materials has provided scope towards utilization of superconductivity technology in power system. Superconductivity being characterized by zero resistance (or resistivity), makes the superconductor an ideal conductor of electricity [1]-[3]. The critical parameters of a superconductor are critical temperature, critical magnetic field and critical current density. In power system the important one is the critical current density other two also have importance.

The demand is increasing this had led to congestion in the power system making it more complex and less reliable. This growing demand at consumer end needs some advancement in technology or adoption of new technology in the power system. The need of the present time is to have a more reliable, higher efficiency cables. HTS cables technology is a major breakthrough because it utilizes less wire and transmitting five times more electricity than currently used conventional cables. The superconductivity technology will also have wide applications in superconducting generator and superconducting energy storage system also. The use of superconducting cables can reduce the size of machine by improving the overall efficiency of the system.

The private companies have started investing into the HTS technology discovered long back by Karl Müller and Johannes Bednorz in 1986. To accomplish this effort, the Department of Energy (DOE), Oak Ridge National Laboratory (ORNL) and Los Alamos National Laboratory (LANL) established partnerships with various cable companies, utilities, state agencies and many stakeholders to enact cable projects. They had been carrying out studies over practical models of HTS since year 2000 which are set up in various parts in USA. The goal is to transform the way power is generated, transmitted and used [4]. The newly developing technology and devices for power generators, underground transmission cables, transformers, fault-current limiters, motors, and many other applications are the major concern. HTS wires show reduced electrical losses compared to conventional copper and aluminum wires. HTs also have improved performance. HTS wires developed in the recent offer power densities 30 times that of copper. However taking advantage of this increased performance is a significant challenge. Superconducting cable technology offers benefits to power transmission and distribution including reduced voltage levels, simplification of networks, reduction or elimination of substations, increased power densities, and electricity savings.

A large scale integrated use of HTS cables in countries having congestion problem can be used. Scheme discussed later will help you understand the how the present system can be up graded to a Superconducting system.

1.1. Superconductivity

Superconductivity is a phenomenon observed when materials such as in several metals and ceramic are cooled to temperatures ranging from near absolute zero i.e.-459 degrees Fahrenheit, 0 degrees Kelvin, -273 degrees Celsius to liquid nitrogen temperatures i.e. -321 F, 77 K, -196 C, they show zero electrical resistance. The temperature at which superconductivity occurs is called the critical temperature (T_c) and varies with the individual material [5]. The critical temperatures are achieved by cooling materials with either liquid helium or liquid nitrogen. The following table 1.1. shows the critical temperatures of various superconductors:

Material	Type	T_c(K)
Zinc	metal	0.88
Aluminum	metal	1.19
Tin	metal	3.72
Mercury	metal	4.15
$YBa_2Cu_3O_7$	ceramic	90
TlBaCaCuO	ceramic	125

Table. 1.1. Critical Temperature of various materials

These materials have no electrical resistance, which means electrons can travel through them freely without collisions (root cause of resistance), they can carry large amounts of electrical current with low energy loss for longer durations. Superconducting loops of wire have been shown no measurable loss when they carry electrical currents for long periods. This makes superconductivity technology fruitful for electrical power transmission. We have to use superconducting ceramics in such case. Superconductor is characterized by Meissner effect i.e. once the transition from the normal state to the superconducting state occurs, external magnetic fields can't pass through it. This makes it suitable for making high speed, magnetically-levitated trains. It is applicable in making powerful, small, superconducting magnets for magnetic resonance imaging (MRI).

The atomic structure of most metals like a window screen called lattice structure, in which the intersection of each set of perpendicular wires is an atom. The electrons are held quite loosely in the metal lattice hence they can move freely. This results in good conductivity of heat and electricity in metals. When potential difference is applied across the conductor the electrons start flowing in one direction. They collide with each other. While in superconductor, the electrons are paired up and move quickly between the atoms with less energy loss.

As a negatively-charged electron moves through the space between two rows of positively charged atoms (like the wires in a window screen), it pulls inward on the atoms. This distortion attracts a second electron to move in behind it. This second electron encounters less resistance, much like a passenger car following a truck on the freeway encounters less air resistance. The two electrons form a weak attraction, travel together in a pair and encounter less resistance overall. In a superconductor, electron pairs are constantly forming, breaking and reforming, but the overall effect is that electrons flow with little or no resistance. The low temperature makes it easier for the electrons to pair up.

One final property of superconductors is that when two of them are joined by a thin, insulating layer, it is easier for the electron pairs to pass from one superconductor to another without resistance [6]. This effect has implications for superfast electrical switches that can be used to make small, high-speed computers.

The future of superconductivity research is to find materials that can become superconductors at room temperature. Once this happens, the whole world of electronics, power and transportation will be revolutionized.

1.1.1. Classification of Superconductors

The superconductors can be classified according to following parameters:

- Physical properties:

Type I (if their phase transition is of first order) or

Type II (if their phase transition is of second order).

- Theory to explain them:

Conventional: They are explained by the BCS theory or its derivatives.

Unconventional: They are not explained by the BCS theory or its derivatives.

- Critical temperature:

High temperature (generally considered if they reach the superconducting state just cooling them with liquid nitrogen, that is, if $T_c > 77$ K),

Low temperature (generally if they need other techniques to be cooled under their critical temperature).

- Material:

Chemical elements (as mercury or lead), alloys (as niobium-titanium or germanium-niobium), ceramics (as YBCO or the magnesium diboride), or organic superconductors (as fullerenes or carbon nanotubes, which technically might be included among the chemical elements as they are made of carbon).

2. Superconducting Devices

2.1. Superconducting Generator

The difference between the basic design of a conventional and superconducting generator will be better understood if we study the fundamentals of generation. The mechanical energy is converted into electrical energy by rotating a conductor relative to magnetic field produced usually by an electromagnet. The emf is induced and direction of current are given by Fleming's Right Hand Rule. The resulting flow of current in conductor generates its own magnetic field. The final useful electrical output depends upon the interaction of these two magnetic fields. The electrical and magnetic loadings (current density and flux density) determine the output from a generator. Neither of these can be increased indefinitely due to certain limits. The electrical loading limited by the rate at which the heat produced can be removed, so the temperature rise is within the value that the insulation can withstand.

The magnetic loading is limited by magnetic saturation. Thus flux density cannot be increased beyond this level, with using special steels. These limits can be significantly relaxed by the using superconductors. Field winding will provide at least four to five times higher magnetic field with negligible DC voltage [7]. This is possible because superconductors have zero DC electrical resistance and extremely high (100,000 times more than copper conduction of the same size) current carrying capacity. Thus machines with very high rated capacity are possible with superconductors.

Another very attractive feature of the Superconducting field windings is that due to very high magneto motive force set up, it is not necessary to use magnetic iron in the machine. Due to reduced rotor dimensions, the air gap in the machine can be expanded and greater machine stability could result.

2.2. Superconducting Magnetic Storage Systems (SMES)

A wire carrying electric current generates a magnetic field. The higher the current, the stronger is the generated field. The current carrying wire, wrapped as a coil is called the solenoid is proportional to the current and the number of turns Superconducting solenoids made by wrapping a Superconducting wire in the coil from are functionally superior to conventional solenoids because of zero dc electrical resistance, no resistive losses.

2.3. Advantages of Superconducting devices

1. Compactness and High Capacity**:** Superconducting cable can transmit electric power at an effective current density of over 100 A/mm2, which is more than 100 times that of copper cable. This allows high-capacity power transmission over the cables with more compact size than conventional cables, which makes it possible to greatly reduce construction costs.
2. Low Transmission Loss and Environmental Friendliness: In superconducting cables, the electrical resistance is zero at temperatures below the critical temperature, so its transmission loss is very small.
3. Low Impedance: A superconducting cable that uses a superconducting shield has no electromagnetic field leakage and low reactance. Depending on the shape of the cable, the reactance can be lowered to approximately one-third that of conventional cables.
4. They also improve the stability of the system.
5. The HTS cable technology can solve congestion issues and other weak spots in power grids. HTS cables have enormous technical and environmental advantages.
6. No leakage of electro-magnetic field to the outside of the cable,

3. High Temperature Superconductivity

High-temperature superconductors are materials which have a superconducting transition temperature (T_c) above 30 K (−243.2 °C). During 1980s 30 K was thought to be the highest theoretically possible T_c. The first HTS superconductor was discovered in 1986 by IBM Researchers Karl Müller and Johannes Bednorz, for which they were awarded the Nobel Prize in Physics in 1987. Fe-based superconductors were discovered in 2008. The term high-temperature superconductor also implies cuprate superconductor for compounds such as bismuth strontium calcium copper oxide and yttrium barium copper oxide.

High-temperature has three common definitions in the context of superconductivity:

1. The temperature above of 30 K that had historically been taken as the upper limit allowed by BCS theory.
2. The transition temperature that is a equivalent to Fermi temperature for conventional superconductors such as mercury or lead. This definition puts use in a wider variety of unconventional superconductors in the context of theoretical models.
3. The temperature greater than the boiling point of liquid nitrogen (77 K or −196 °C). This can be much acceptable because liquid nitrogen is relatively inexpensive.

Technological applications are benefited from higher critical temperature which is above the boiling point of liquid nitrogen. In magnet applications the high critical magnetic field may be more valuable than the high T_c itself. Some cuprates have an upper critical field around 100 teslas. However, cuprate materials are brittle ceramics which are expensive to manufacture and not easily turned into wires or other useful shapes.

Two decades of intense experimental and theoretical research, with over 100,000 published papers on the subject, have discovered many common features in the properties of high-temperature superconductors, but as of 2009, there is no widely accepted theory to explain their properties. Cuprate superconductors (and other unconventional superconductors) differ in many important ways from conventional superconductors, such as elemental mercury or lead, which are adequately explained by the BCS theory. There also has been much debate as to high-temperature superconductivity coexisting with magnetic ordering in YBCO, iron-based superconductors, several ruthenocuprates and other exotic superconductors, and the search continues for other families of materials. HTS are Type-II superconductors, which allow magnetic fields to penetrate their interior in quantized units of flux, meaning that much higher magnetic fields are required to suppress superconductivity.

4. Superconducting Cable used in Projects

The HTS cables have widely used for carrying out practical studies over their feasibility. Presently super conducting cables are used only for demonstration purpose they have not yet been used at mass level. It will take 10-20 years for HTS technology to come in larger scale use. The utilization of this technology has been done successfully in certain areas in USA. Important projects are mentioned below:

4.1. Carrollton, GA

On January 6, 2000, Southwire energized the first superconducting cable system in a commercial /industrial setting. The pioneering cable project, a partnership between DOE and Southwire, was constructed and installed above ground with three, 100-foot, single-phase, HTS cables rated 12.4kV, 1,250 Amps. The cables delivered power to Southwire manufacturing plants. The system operated continuously for 7 years at 100 percent load for over 40,000 hours. When taken offline to perform an inspection of the system, it was concluded that there was little to no significant degradation in the conductivity of the wire. This cable project enabled the development of newer cable designs that carry twice the current of this original project.

4.2. Albany, NY

Albany’s cable project began development in 2001 with a partnership between the DOE, New York State Energy Research and Development Authority (NYSERDA) and Superpower, Inc. The team also included BOC (Germany), Sumitomo Electric Industries (Osaka Japan), and National Grid (Westborough, MA). The first phase on the Albany project consisted of two sections; a 320 meter long section connected to another 30 meter section of HTS cable made with first generation HTS wires. The cable connected two substations from Riverside to Menands and was energized July 19, 2006. It operated flawlessly as an integral part of the grid’s 35kV network in Albany and served an equivalent of 25,000 homes. On May 1, 2007, the system was taken offline to execute phase II of the project which involved installing a 30m section of cable made with second generation HTS wires (2G Wires). On January 8, 2008 the system was reenergized. This milestone demonstrates the first use of 2G wires in HTS device of any kind in a live grid application. All aspects of this program have been successfully demonstrated and completed.

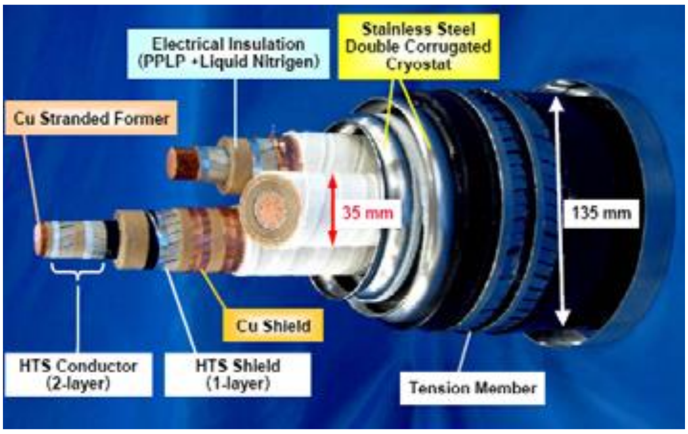

Figure 4.2. First generation HTS wire
(Source: Superconductivity News Update November 2008)

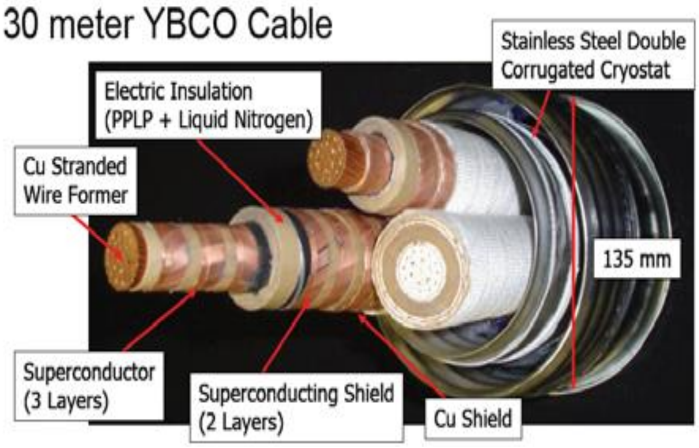

Figure 4.3. Second generation HTS wire
(Source: Superconductivity News Update November 2008)

4.3. Columbus, OH

This 200 meter cable project was awarded in late 2002. The cable was installed in the Bixby substation and was energized August 8, 2006. The cable project serves residential and industrial customers in parts of Columbus, Ohio. The cable is designed to operate at 13.2 kV and carries up to 3,000 amps. A majority of the cable was pulled into its conduit underground, and a cable splice was built in a man-hole to demonstrate joining multiple cable sections. Since being energized, the cable system has worked flawlessly and has served power to 36,000 homes. Its peak load has been charted at 2,700 A.

4.4. Long Island

On April 22, 2008 American Superconductor Corporation (AMSC) and its partners energized the world’s first high temperature superconducting transmission-voltage power cable system in a commercial power grid. AMSC’s partners included Long Island Power Authority (LIPA), Nexans, Air liquide and the Department of Energy (DOE). The 138,000 volt (138kV) system consists of three individual HTS power cable phases running in parallel. Since being energized, the system has operated successfully. When operating at full capacity, the HTS cable system is capable of transmitting up to 574 megawatts (MW) of electricity, enough to power 300,000 homes. Phase II of the project consists of an extension of the cable system by replacing one of the existing cables with a 600-meter long cable made with AMSC’s proprietary 344 superconductors, also known generically as 2G HTS wire.

5. Application of Superconducting Technology

5. Long Island Transmission Level HTS Cable

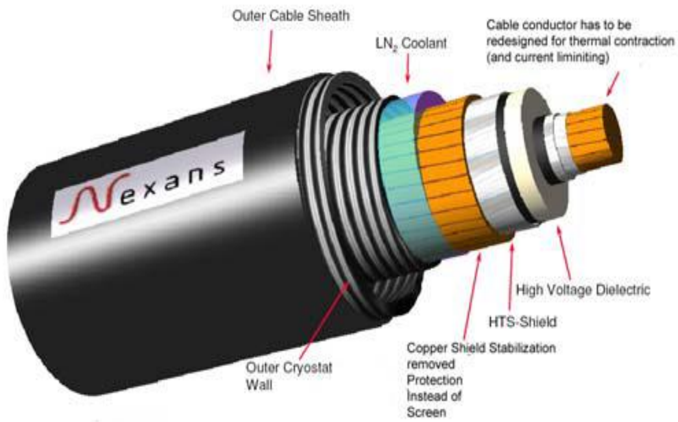

Fig. 5.1. LIPA HTS Cable (Source: energy.gov) [8]-[9]

5.1. Construction Details:

The Fig 5.1 shows the cross-sectional view. This cable was manufactured by Nexans. The cable consists of five layers. Outer most is cryostat (thermostat which operates at very low temperature) wall. LN2 (liquid nitrogen) is circulated between shield stabilization layer and second layer of cryostat [10]. There is one cable for single phase hence three cables in total are used. The cable consists of a copper former, two HTS conductor layers, an insulation layer, an HTS screen layer, a copper screen stabilizer and a cryogenic envelope. Liquid nitrogen is circulated for cooling the conductors below critical temperature.

5.2. Testing Performed

5.2.1. Before Energization:

Several tests were performed before energizing the cable for power flow. Firstly the cable was colled and the refrigeration system was operated for a period of time so that the dielectric gets completely impregnated with the liquid nitrogen used for refrigeration. This was to check whether cable is ready for operation. The capacitance measurements were done for dielectric to check its properties. The parameters for the refrigeration system were also examined and tested so that its safety controls can be determined based on actual operational conditions. When the completion of the saturation of the dielectric the cable was tested the system was ready to connect [11]-[12]. A voltage withstand test as well as an onsite partial discharge measurement test were both performed successfully, no partial discharge was observed. Once the control and protection system were adjusted, LIPA performed its operation on April 22, 2008 with the breakers at both end of the cable.

5.3. Operational Experience

1. After testing results the cable was finally energized to take load. There were several unexpected trips due to supply voltage issue. The control system was monitored to find out the cause. There was no failure in mechanical parts of the cable. This was a remarkable achievement.
2. There were some unexpected trips in the refrigeration building. It was resolved by addition of and additional air conditioning system which would operate during hot onditions automatically.
3. The operational parameters were found consistent with the expectations during the design of the cable. The system is operating well.

6. Implementation of HTS technology in Power System

The superconductivity technology can be employed in the power system at distribution level. This will help in reduction of copper losses, hence improving the efficiency and reduction in cost of generation of power.

6.1. Conventional Scheme

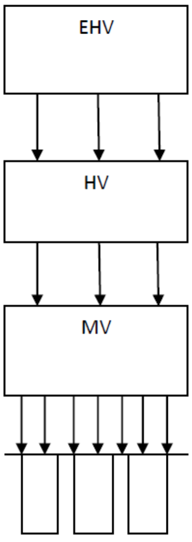

Fig. 6.1. Diagram of Conventional Scheme

6.1.1. Features:

This scheme represents the conventional power system. Since the studies were carried out in Europe we will use voltage levels accordingly at various levels of transmission and distribution. Taking them as follows:

Extra High Voltage (EHV): 380kV

High Voltage (HV): 220kV or 110kV

Medium Voltage (MV): 10kV-30kV

Low Voltage (LV): less than 1kV

No HTS equipment is used in this scheme.

6.2. Scheme 1

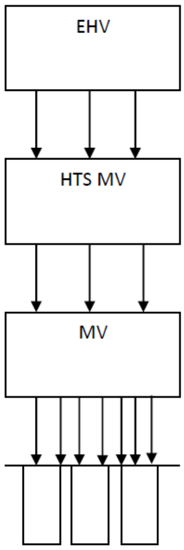

Fig. 6.2. Diagram of Scheme 1

6.2.1. Features:

1. Scheme 1 includes HTS at MV level.
2. The MV part is directly connected to HV part.
3. Except HTS part rest all remains same.
4. This scheme can be easily be fitted in conventional scheme.

6.3. Scheme 2

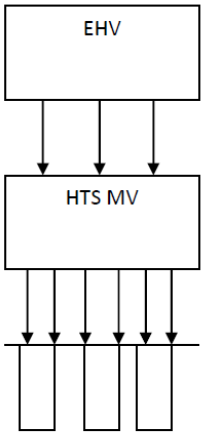

Fig. 6.3. Diagram of Scheme 2

6.3.1. Features:

1. In this scheme HV and MV parts of conventional scheme are replaced by HTS MV part.

2. The conventional scheme cannot be upgraded to scheme 3. Hence for new loads we can adopt this particular scheme.

3. It has advantage over scheme 1 that it has greater current carrying capacity and lower voltage drop.

6.4. Scheme 3

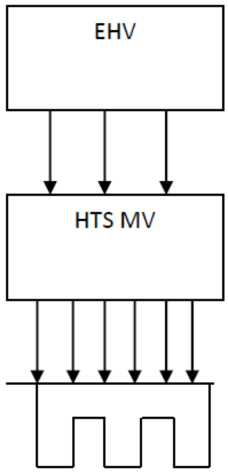

Fig. 6.4. Diagram of Scheme 3

6.4.1. Features:

1. In this scheme we increase cell size i.e. area to which distributer feeds is increased.

2. Since there are lower voltage drops in HTS technology this hence enhances the use of larger cell size at distribution level (<1kV).

3. Greater line length reduces the number of LV transformer.

6.5. Comparison of Scheme 1,2,3 and Conventional

6.5.1. Assumptions made for this comparison are:

1.Load density: 30 MW/square km

2.Medium voltage level: 30 kV

3. HTS cable ampacity: 2.5 kA

4. Cost of energy loss: 100 €/MWh.

And the charges for carbon dioxide emission or reduction have not been considered. However this will provide with a positive effect if considered because there is least carbon dioxide emission in HTS system.

Schemes	Investment (Mio. Euro/Annum)	Operation (Mio. Euro/Annum)	Losses (Mio. Euro/Annum)
Scheme 1	50	2.5	2.5
Scheme 2	75	3	2
Scheme 3	57	2	2
Conventional	45	2.5	7

Table 6.1. Schemes [1] (Source: Mathias Noe, Robert Bach, Werner Prusseit, Dag Willén, Wilfried Goldacker, Juri Poelchau , Christian Linke, “Conceptual Study of Superconducting Urban Area Power Systems” 2009)

6.5.2. Components of investments

In this comparison break up of investment are shown.

Schemes	LV Line (Mio. Euro/A)	LV Transformer Station (Mio. Euro/A)	MV Line (Mio. Euro/A)	HTS MV Line (Mio. Euro/A)	HV Line (Mio. Euro/A)	HV Switchgear (Mio. Euro/A)	Substation (Mio. Euro/A)
Scheme 1	22	7.5	12.5	7.5	0.5	0	0.5
Scheme 2	22	7	0	45.5	0	0	0.0125
Scheme 3	39	1	0	16.5	0	0	0.0125
Conventional	22	7	11	0	4	0.5	0.5

Table 6.2. Schemes [1] (Source: Mathias Noe, Robert Bach, Werner Prusseit, Dag Willén, Wilfried Goldacker, Juri Poelchau , Christian Linke, "Conceptual Study of Superconducting Urban Area Power Systems" 2009)

6.5.3. Inferences from Table 6.1.:

1. Scheme 1 and scheme 3 are acceptable because investment for both is close and losses and operational cost are also comparable. Hence total annual cost is comparable.

6.5.4. Inferences from Table 6.2.:

1. In scheme 1 the investment for HV component is least. Scheme 3 do not requires MV line.
2. In scheme 1 HTS required is least and total investment is also least.
3. Scheme 2 is not acceptable because HTS MV required is maximum hence increasing the investment cost.
4. Scheme 3 is also acceptable because of low over all investment. Although its HTS MV investment is twice that of Scheme 1.
5. Smaller cell size hence longer length will reduce the number of transformer at LV distribution level hence there is reduction in cost.

6.6. Limitations of this study:

This review study was conducted to show how we can integrate superconducting equipment at large scale and use them at distribution level power system. The length for HTS is not greater than 100km since it focused over urban areas only. It is also limited to power transmission to 1 GW. In urban areas power is transmitted in such a way that length is not more than 100km.

7. Conclusion and Discussion

The superconductivity technology has an emerging tool which can be implemented easily into present grids in power system. The studies of Long Island show that how the HTS cables can be installed at high voltage level (138kV) of the grid. The studies conclude that the use of HTS cable is reliable. Its analytical studies indicated that it will remain stable on long run. The system can be put on long run, providing power to commercial loads without interruption and maintaining proper efficiency when compared to conventional system. The High Voltage section in present power system can be replaced with a new HTS MV section. Such a scheme reduces overall costs and conventional system can be easily be upgraded to the Scheme 1. Besides a single HTS MV section in Scheme 3 will be applicable to newly developing systems for loads from upcoming townships and industries. A large scale integrated use of High Temperature Superconductors (HTS) Cables in power system will be more efficient. Besides super conducting generators have more benefits such as reduction in size, increased stability due to reduced machine reactance. The studies had certain limitations such as line length was less than 100km a total load less than 1GW. Also the costs for various equipment are assumed constant. Such a system is considered only for urban areas having shorter line lengths. Keeping these constraints in mind we can develop a new power system in developing country like India. Finally, the energy savings from transmission and distribution from superconducting materials opens the doors for increased power available to meet the rising demand of power from electrified transportation system with electric vehicles and their charging infrastructure.

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