SUPERCONDUCTING TRANSMISSION LINES — COMMUNICATION AND POWER*

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INTRODUCTION

During the past few years interest has grown in the application of superconductors to electrical power transmission lines and other power apparatus.[1-11] The probability of doing so seems very remote to the majority of the industrial and scientific community. However, there are those of us who believe that such large scale superconductive systems are practical and, when realized, will provide technical and economic advantages.[12-17] Make no mistake about the motive for utilizing superconductors; simply put, the economic payoff would be very great.

The purpose of this paper is to strongly declare that a superconductive power transmission system would (and should) be much more than a power transmission line. Considering the capital investment required to build such a system it is then imperative that the maximum economic benefit be derived from the system. Accordingly it is my contention that the subject under discussion is not a superconductive power line, but a much more encompassing system, a "Superconductive Transmission System" (SCTS).

As seen through my mind's eye, the SCTS would consist of four subsystems:

1. Data Processing Subsystem.
2. Cryogenic Liquid Transport Subsystem.
3. Electrical Power Transmission Subsystem.
4. Electrical Communication Subsystem.

Consequently, it is apparent that my vision is actually concerned with four systems and not just one system. The four subsystems have a common characteristic within the perspective of our technologically based society: each subsystem may span great distances. Furthermore, operation of such a multifaceted utility complex would require very effective interaction between the constituent utilities. There may be some raised eyebrows as a result of my calling a data processing system "a utility," but if everybody in the cities of tomorrow is going to have access to a computer, then an extensive time share system of the magnitude of a utility will be necessary.

With the preceding comments serving as an introduction, my remarks will now center upon some aspects of the four subsystems. It is my intention to discuss in greater detail that which I know something about. Accordingly, I will not say much about the data processing subsystem or the cryogenic fluid transport subsystem. Also I will deal in somewhat of a broader sense with the power transmission subsystem in order to clearly establish in your minds that dc power transmission is presently a reality and that superconductive dc power transmission is only an extension to superconductivity and not to dc. Finally, I will discuss in greater detail the superconductive communication transmission subsystem as I know more about such systems by virtue of experience and training.

*The mention in this paper of trade names or proprietary products is not to be construed as an endorsement of these items by the National Bureau of Standards.

DATA PROCESSING SUBSYSTEM

The data processing subsystem would have two functions: an internal one and an external one. Internally, the data processing subsystem would provide data processing services to the other three subsystems in order to execute the required instrumentation and control for each subsystem. Externally, the data processing subsystem could provide time share computer facilities for subscribers along the length of the SCTS.

The data processing subsystem could be implemented by using cryogenic digital and analog electronic components which possess inherently large packing densities.[18] These brief remarks comprise my discussion of the data processing subsystem. I will now briefly discuss the cryogenic liquid transfer subsystem.

CRYOGENIC LIQUID TRANSPORT SUBSYSTEM

Many industrial and research centers require cryogenic fluids for their operations. Accordingly, a SCTS connecting such centers could provide a means of transporting cryogenic fluids to the individual centers. For example, if a SCTS passed through the helium producing fields in Kansas, liquid helium could be introduced into the SCTS at the helium production source and then be distributed by transmission through the SCTS network. The cryogenic and gas transport industries could no doubt think of many ingenious ways to utilize the SCTS. In any event my brief remarks may serve as stimuli to their thoughts. Next, I will discuss the status of superconductive power transmission.

POWER TRANSMISSION SUBSYSTEM

A superconducting wire can transmit a dc current without losses or an ac current with an extremely small loss. At first glance, the complete absence of losses in the dc case engenders some attractive possibilities for dc power transmission, while the existence of ac losses (due to electrical and mechanical forces) apparently decreases the practicality of ac power transmission. That such is the case, stems from consideration of refrigeration costs. Personally, I do not believe that ac power transmission systems are to be ruled out. However, in terms of our present-day lack of experience with really large-scale superconductive systems, it is probably prudent to concentrate our present speculation on dc power systems. Present-day developments and future experience will no doubt engender ac systems.[5]

Dc transmission of large amounts of electrical power is a reality.[19] Today, there exist roughly six systems in operation ranging over distances of 72 to 750 miles, operating in the voltage range of 100 kV to 800 kV, and transmitting powers in the range of 30 MW to 750 MW. Also, there is a similar number of systems under design and construction which will cover distances of 25 to 875 miles, operate in the voltage range of 130 kV to 800 kV, and transmit powers ranging from 78 MW to 1440 MW. The input and output terminals of these dc systems are mercury-arc grid controlled rectifiers which convert and invert ac to dc and dc to ac, respectively. Consequently, the idea of using superconductive dc power transmission is clearly an extension of technology only to superconductive systems, not to dc systems.

As I mentioned earlier, considerable analytical work has been done on the possibilities for superconducting power transmission. In many of the papers cited, economic data were presented which indicated when superconducting power transmission would be economically favorable. I will not go into any specific cases; but I should point out that some of the papers developed economic data on transmission systems having capacities which could be fully utilized today or in the next few years. For example, Norris and Swift[15] discussed transmitting 750 MW at 100 kV dc and 750 MVA at 33 kV ac. On the other hand, Garwin and Matisoo[14] envisioned economically transmitting very large amounts of power, 100 GW at 200 kV dc over distances of 1000 km.

Superconductive power transmission studies have entered the experimental phase. In England, an experimental line has been constructed and operated.[20] Also, a 3000 hp superconductive motor is being built.[21] In the U.S.A., Meyerhoff, Beall and Long[22] have designed and are to construct a 20 ft section of niobium coaxial power line. A 60 ft section of a superconductive power line is being built in West Germany.[23] In France, and in the U.S.A., liquid hydrogen cooled (20°K) cryogenic power apparatus is being designed and constructed.[8,24] Also, power apparatus manufacturers are recruiting engineers and scientists to work on the development of superconductive power apparatus.[25] Consequently, it is evident that superconductive power systems are already with us in a limited sense. The remainder of my comments will be concerned with superconductive electrical communication transmission.

ELECTRICAL COMMUNICATION SUBSYSTEM

First of all, I would like to briefly describe a fairly general model of a communication system.[26] By my doing so, you will have some idea of how communication electrical engineers view a communication system. The model is general enough to characterize all forms of wired or radio communications. The system consists of a serial chain of elements beginning with a data source and ending with a data processing and storage element. Information flows unidirectionally through the system in serial order starting from element No. 1 and ending at element No. 7; the elements are as follows:

1. Data Source. A system which produces the information to be transmitted.
2. Encoder. A system which transforms the data into a favorable form which insures successful transmission through the noisy transmission channel.
3. Modulator and Transmitter. A system which converts the encoded information into a signal form capable of passing through the transmission channel.
4. Transmission Channel. A noisy system or physical medium through which the signal flows. Noise is inherent in any transmission channel and arises from natural physical causes or unnatural (man-made) causes.
5. Receiver and Demodulator. A system which extracts the signal information from the noisy output of the transmission channel and converts the extracted information into a form suitable for the decoding operation.
6. Decoder. A system which converts the encoded information into some form for data storage and processing.
7. Data Storage and Processing. The recipient system requiring the information generated by the Data Source (element No. 1).

Upon considering the various elements comprising a communication system, it is evident that a superconductive one could employ a large amount of integrated circuit cryoelectronics. Of particular interest to me is the utilization of the superconductive coaxial line as the physical transmission channel. Other electrical waveguides such as hollow metal pipes for microwaves or light pipes for laser wavelengths could also be employed with improved characteristics compared to their room temperature counterparts. However, the coaxial line can be miniaturized and transmit a baseband signal whose frequency components extend upward from dc.

The baseband signal propagates in the TEM electromagnetic mode which is the ordinary two-conductor transmission line mode (as contrasted to single conductor modes).

The TEM mode can exist in any two-conductor transmission line and extremely great baseband bandwidths may be realized with the coaxial geometry. In a lossless coaxial line waves of any frequency are propagated without loss. Above a certain frequency undesirable higher order modes (single conductor modes) can propagate.[27] Consequently, for a given coaxial line the upper operating frequency is usually chosen to be less than that of the lowest frequency higher order mode. As the diameter of the coaxial line is decreased, the higher order mode cutoff frequency is increased; for example in a 50 Ω coaxial line having a relative dielectric constant of approximately 2.0 and a 0.03 in. o.d., the higher order mode cutoff frequency is approximately 100 GHz.

Before summarizing the results achieved to date with miniature superconductive coaxial lines, I am going to make a few remarks about cryogenic normally conducting coaxial lines. Depending upon the metal purity and structural order (electronic mean free path length) the classical or anomalous skin effect may occur. The anomalous skin effect strongly occurs when the electronic mean free path is greater than the electromagnetic field penetration (skin) depth. For short (impure metal) or long (pure metal) electronic mean free paths the high frequency complex attenuation of the coaxial line will follow an $s^{1/2}$ or an $s^{2/3}$ variation, respectively, where s is the complex frequency variable.[28] Furthermore, the anomalous skin effect produces a greater attenuation than would be expected (classical theory) from the increased dc metal conductivity produced by the low temperature environment. Typically, for copper having a 4.2°K to 293°K conductivity ratio of 400, one would expect a 10 GHz classical attenuation reduction of 20 while in practice the anomalous skin effect may yield an attenuation reduction of 5.

Because the high frequency losses in a superconductor are dependent upon the normal state of electronic mean free path and decrease with increasing mean free path, the superconductor purity and structural regularity strongly affect the surface impedance frequency dependence. Experimental data from superconductive coaxial transmission lines have been compared with the two-fluid superconductivity theory.[29] The results suggest that the particular superconductor samples employed possessed relatively short normal state electronic mean free paths. Typical transmission line parameters were as follows: 50 Ω characteristic impedance, polytetrafluoroethylene dielectric, Nb 0.015 in. diam center conductor, Pb 0.045 in. i.d. outer conductor, and 1360 ft length. In terms of the two-fluid model, at 8 GHz, the metal losses would produce a transmission attenuation of 35 dB or 0.7 dB for a purely classical normal component or a purely anomalous normal component, respectively. The observed attenuation was 10 dB. Consequently, improvements in the superconductor metallurgy should provide an attenuation approaching that of the anomalous limit. The effect of the normal state electronic mean free path was strikingly seen in the time domain response curves. For a long mean free path the step response rose abruptly with a 10-90% rise time of about 5 psec. For a short mean free path, the step response rose relatively slowly reaching the 80% level in about 30 psec.

Using the two-fluid model curves,[29] the transmission characteristics of a miniature superconductive line can be compared against that of a room temperature 2 in. i.d. corrugated circular waveguide. Using a circular waveguide operating frequency of 56 GHz in the TE_{01} mode, one obtains an attenuation of 1.5 dB/mile,[30] with perhaps a bandwidth of 20% of the operating frequency, 11.2 GHz. A 50 Ω superconductive coaxial line made of the same materials mentioned above and having an 0.061 in. i.d. outer conductor would have a higher order mode cutoff frequency of 56 GHz. The lowest temperature listed in the two-fluid model curves is 2.3°K. Upon using the anomalous limit at 2.3°K, the superconductive line attenuation would be 3.5 dB/mile at 56 GHz. Consequently, it is seen that the superconductive line provides a baseband bandwidth of greater than 50 GHz while the circular waveguide yields a bandpass bandwidth of greater than 10 GHz centered at 56 GHz; the attenuation values are comparable. Also, because of its baseband characteristic, the miniature superconductive coaxial line is capable of transmitting baseband digital information at very rapid rates. Therefore, it is evident that such miniature lines could provide large bandwidth transmission channels for use in a SCTS.

SUMMARY

It has been declared that a superconductive power transmission line system could be much more than just a power transmission line, but rather a composite of four subsystems: (1) data processing, (2) cryogenic liquid transport, (3) electrical power transmission, and (4) electrical communication.

At present, dc power transmission in superconducting cables appears to be economically feasible. However, ac transmission with its associated joule heating losses is not to be discounted. Improvements in cryogenic refrigeration, operating experience, and technical convenience will no doubt engender ac systems.

Cryoelectronics has a great potential for implementing the various subsystem electronic systems. The cryoelectronics components developed to date have demonstrated that the electronic functions necessary for the various subsystems can be implemented with such components. The spectrum of components includes active analog elements, digital elements, transmission lines, waveguides and large-scale digital systems.

Finally, the idea of transporting cryogenic liquids through a SCTS network offers some intriguing possibilities for the transportation of gases. Not only does this suggest transporting the usual cryogenic liquids, but also other liquefied gases.

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