Superconducting Lines for the Transmission of Large Amounts of Electrical Power over Great Distances: Garwin – Matisoo Revisited Forty Years Later

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***Abstract*— In 1966, following a decade of discovery and development on A15 compounds, Richard Garwin and Juri Matisoo [1], two research staff members then in the IBM Research Division, submitted for publication a paper examining the prospect to employ one of the most promising of these materials, Nb_3Sn, in a cable system for transmission of electricity. The scale of their proposal was truly enormous – 100 GW (+/- 100 kV at 500 kA direct current) over a distance of 1000 km, the entire length refrigerated by liquid helium. At the time, such a cable would have been capable of carrying half the entire electric power generated in the United States, and about one-tenth today. This paper will revisit their vision in the context of the subsequent discovery of high temperature superconductivity twenty years later, and the now emerging availability of long lengths of high performance wire and tape for operation in the 20 – 80 K range. Whereas the scenario set by Garwin and Matisoo addressed the one-way transmission of electricity from remote coal and nuclear generation multi-plant "farms" to large population centers, we will extend their picture to include two-way transmission on a diurnal or longer period to take advantage of regional electricity pricing and production which has resulted from the deregulation of generation. We conclude that the advent of high temperature superconductivity substantially extends and brings closer both the technical and economic feasibility of Garwin and Matisoo's dream. However, we note, as did they, the caveat that "whether it is desirable or necessary is another matter entirely." We believe this question will be decided in the affirmative as societal demands continue to increase for the clean, reliable and ecologically gentle delivery of large amounts of electric power, a need that was foreseen but not as overriding forty years ago as it is now.**

***Index Terms*— DC power transmission, High-temperature superconductors, Superconducting cables**

I. Introduction

IMMEDIATELY following on the astounding discovery of absolutely perfect conductivity in mercury metal at 4.2 K in 1911 by a team in the Leiden Laboratory of Kamerlingh-Onnes [2], hopes arose that extremely powerful electromagnets and lossless transmission of electric power would soon be enabled. These hopes were quickly dashed which it was found that superconductivity completely disappeared under a transport current of only a few amperes or in a field of just several gauss (yet, in or about 1915, Onnes proposed a persistent current loop be built between Paris and London!).

Such was the situation regarding both potential applications and theoretical development up until the decade of the 1930s, which saw the observation of the Meissner-Ochsenfeld effect, its explanation by the London electromagnetic model and the first glimpses of type II superconductivity [3]. However, the development and discovery of new materials was severely interrupted by World War II and the Cold War thereafter. It took until the 1950s and early 60s to witness the arrival of intermetallic compounds and alloys, especially the A15 compounds, that would lead to practical type II superconductors capable of sustaining large currents and fields encountered in electromagnet applications [4]. This same period was accompanied by advances in empirical metallurgical treatments necessary to optimize their performance, and the formulation of the "engineering" macro-microscopic theory of Ginzburg, Landau, Abrikosov and Gorkov as a tool to guide and understand experimental efforts. By the mid-1960s, the time had at last arrived where one could revisit the dreams of Onnes and begin to seriously consider the application of superconductivity to electric power transmission.

Manuscript received August 28, 2006. This work was supported in part by the Electric Power Research Institute (EPRI) under Contract 060573. P. M. Grant is an independent energy consultant and science writer, Principal of W2AGZ Technologies, and a Visiting Scholar in Applied Physics at Stanford University He can be contacted by e-mail at w2agz@pacbell.net, and more information found at http://www.w2agz.com.

II. The Garwin-Matisoo Cable

A. Background

The potential use of cryoresistive power transmission cables, employing elemental metals such as beryllium at 77 K and aluminum at 20 K, had been studied by workers in France and England throughout the early 1960s, but the savings accrued from lowering I^2R losses did not offset the high capital expense of refrigeration plant and conductor (the intention of these studies was to increase energy efficiency, not circuit capacity). In 1966, K. J. R. Wilkinson, an engineer with the British Electrical Industries Central Research Council, submitted a paper exploring the employment of niobium foil at 4.2 K in its superconducting state and concluded that only "perfect conductivity" presented an economic opportunity offering recovery of cryogenic plant and material costs [5]. His target implementation was a plug-in retrofit of the 275 kV, 1600 A, 5-cm diameter inner copper conductor alternating current cable commonly installed for underground transmission in Great Britain at the time. However, he noted that in order to withstand the standard design fault current of 40 kA, the diameter of the Nb foil cylinder could not be less than 10.4 cm in diameter to maintain a surface magnetic field that would not exceed the its critical field of around 0.16 T at 4.2 K. He thus concluded that that neither cryoresistive nor superconducting cables were not viable economic and engineering alternatives to conventional underground transmission cables.

On the other hand, later that same year, Richard Garwin and Juri Matisoo (hereafter "G-M") of the IBM Research Division submitted a manuscript to the journal of the IEEE in the US, describing their concept for a cable not only highly efficient, but one suitable for the green-sited transmission of unheard of massive amounts of power over very long distances, a recipe only superconducting ingredients could fill [1].

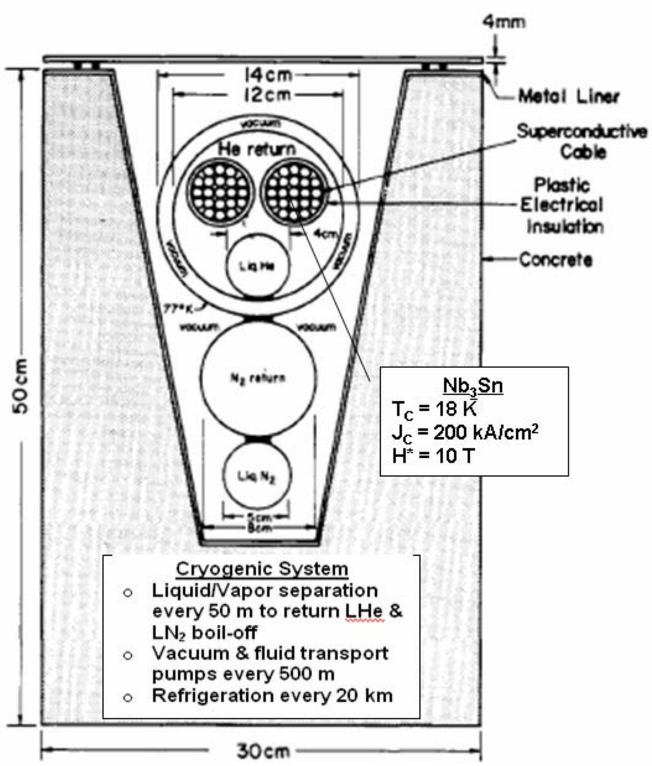

Fig. 1. Cross-sectional view of the Garwin-Matisoo 1000 km, 100 GW LHe-cooled Nb_3Sn based superconducting dc cable, taken form Fig. 1 taken from their 1967 paper [1], with annotations added by the present author.

B. G-M Transmission Cable Design and Specifications

Fig. 1 illustrates the key elements of a 1000 km, 100 GW dc line based on cryogenic and superconducting technologies. To give these parameters some perspective, the maximum electric power delivered on single-circuit overhead HVDC transmission lines deployed at Itaipu-Brazil and Three Gorges-China is roughly 3 GW over distances on the order of 800 km from hydroelectric generation ranging from 6.3 – 14 GW.

The practical upper power capacity limit for underground transmission of electricity, either ac or dc, is constrained by the materials physics of dielectrics and is around 750 kV and is actually reached in some submarine applications. For overhead transmission, again both ac and dc, corona discharge loss becomes very serious above 1200 kV for conductors of any reasonable diameter. Length limits of 50 km and 500 km are placed on ac transmission underground or overhead, respectively, due to capacitive charging and reactance in the former and radiation and inductive reactance in the latter. In all cases, excessive ohmic losses and heating set in around 3000 A [6].

The only path upward to greater capacity electric power corridors, if that indeed is the desired goal, is to deploy superconductors transporting 10-100 times greater current .

In the mid-1960s, the total dispatchable power in the United States was roughly 200 GW – today it is around 1200 GW and about 450 GW in China. Garwin-Matioo foresaw tremendous growth in US electricity demand and consumption in the remaining decades of the 20th century requiring the construction of large generation "farms" based on coal, nuclear and hydro located far from urban populations, and a restructuring of the US industry into four or five major transmission companies requiring very high capacity power corridors exceeding levels possible to accommodate with conventional technology. Although not fully in place today, this transition is clearly underway and the inclusion of a hydrogen economy and a certain amount of renewables in such a vision has recently been addressed by Chauncey Starr, Tom Overbye and myself [7].

On viewing Fig. 1, one is immediately struck by the very small cross-sectional footprint, about the area of a conventional trench, and the resultant areal power density accorded by superconductivity. Further specifications worth noting are the following:

1) Why dc?: With the advent of very high critical current and field type II superconductors in the early 1960s, e.g., the A_3B A15 phases, it was soon observed that irreversible motion of the Abrikosov vortex lattice under even moderately low frequency magnetic fields in the mixed state led to significant thermal heating, a hysteretic effect very similar to irreversible domain wall motion in "hard" ferromagnets. These effects were quantitatively explained by the development of "critical state models" by C. Bean and others [8]. The "Bean Model" losses in watts per meter at a frequency ν Hz for a round superconducting wire is given by

$$W/m = 2\times10^{-7}\nu I_C^2\begin{bmatrix}2\left(1-I_0/I_C\right)\\ \times\ln\left(1-I_0/I_C\right)\\ +\left(I_0/I_C\right)\left(2-I_0/I_C\right)\end{bmatrix};$$

$$\text{for } 0\le I_0\le I_C=\pi R^2 J_C, \tag{1}$$

where R is the wire radius in meters and J_C is the superconducting critical current density in amperes per square meter. For Nb_3Sn at 4.2 K carrying 500 kA at 60 Hz, one obtains a hysteretic power loss of an astounding 6 megawatts per meter! Clearly dc is the only choice at such power and current magnitudes. We will employ (1) in its various limiting forms extensively in Section III. In passing, we point out that ac losses due to vortex lattice hysteresis determine the maximum practical limit to use of ac HTSC cables to 3000 A_{rms} at 60 Hz for an acceptable power dissipation of 1 W/m [9].

2) Cryogenic System: As indicated by Fig. 1, G-M based the refrigeration system on liquid He at 4.2 K surrounded by a liquid N_2 heat shield, a common configuration of the time. However, due to frictional losses arising from the flow of both cryogens, liquid-vapor separation stations are deployed every 50 m to reduce more friction arising from “two phase flow” and return “boil off” gases to refrigeration stations for re-liquefaction. This is a complication that may be unnecessary even over long distances if the cryogen is liquid nitrogen alone.

3) Magneto-Mechanical Aspects: The “side-by-side” arrangement of the two Nb_3Sn conductors has important implications for the design of an HTSC equivalent to G-M. First of all, because of the very high value of the irreversibility field, H^*, of Nb_3Sn, roughly 10 T and isotropic, interpenetration of pole co-fields and subsequent quenching is not a serious problem…but it would be for any planar copper oxide perovskite material. Repulsive magnetic forces between conductors in this geometry can in an external pressure on each of 400 atm, a challenge for all HTSC tape at present. These two issues can, in principle, be circumvented by the coaxial geometry to be discussed in Section III.

C. Engineering Economy Analysis of the G-M Design – Yesterday and Today

Table I below abstracts the major results of the engineering economy analysis G-M performed on their design in 1966. We have updated their results to 2006 using dollar appreciation (inflation) values obtained from the Bureau of Labor Statistics (see Table I footnote for direct link to the BLS website). It is interesting to note that the “present day” cost for a G-M cable is essentially \$5 B, very close to that of the proposed 1200 km Mackenzie Valley natural gas pipeline to run from the Mackenzie River Delta on the North Slope shelf in the Northwest Territories of Canada to the Province of Alberta [10]. However, the power delivery capacity of the Mackenzie pipeline will be 18 GW-thermal, whereas the G-M cable would be 5 times greater if Delta wellhead generation of electricity were to be implemented [11].

TABLE I
ABSTRACTED TABLE I FROM GARWIN-MATISOO [1], COMPARING VARIOUS COMPONENT COSTS OF A 1000 KM, NB-SN CABLE IN 1966 AND NOW

Item	Description/Quantity	1966 Cost (M\$)	2006 Cost (M\$)*
Superconductor	10^4 Tons Nb_3Sn	550	3405
Line Refrigeration	0.5 M\$ for 1 kW LHe station every 20 km	25	155
End-Station Refrigeration	10 kW each	5	31
Vacuum Pumps	\$500 per station (2000)	1	6
Fabricated Metal	\$1/lb, linear line weight = 100 gm/cm	20	124
Concrete	\$10/yd^3 for a total volume of 0.5 yd^2 times 1000 km	5	31
ac/dc Converters	Thyristors at \$1/kW	200	1238
Total:		806	4990

*2006 costs relative to 1966 are estimated from the Bureau of Labor Statistics table of annual Consumer Price Indices that can be found at ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt. The 2006/1966 ratio used above is 6.19.

Note that wire costs comprise approximately 70% of the total, a ratio we expect to be even higher for an HTSC cable.

III. HTSC DIRECT CURRENT CABLES

A. Past Superconducting dc Cable Efforts

We begin this section with a brief review of past superconducting dc cable studies both pre- and post-1987 that followed on Garwin-Matisoo bearing on the remainder of this paper.

1) Multiple Use of Cryogenic Fluid Transmission Lines. In the early 1970s, there was speculation that a NASA space shuttle launch center might be constructed near White Sands, New Mexico. This prospect prompted Bartlit, Eduskuty and Hammel at the Los Alamos Science Laboratory to propose a 600 mile “pipeline” running from the gas fields near the Four Corners region that would carry LNG and electricity over cryoresistive conductors to Los Angeles returning liquid hydrogen to New Mexico as rocket fuel. There was some consideration given superconductivity as accompanying liquid helium flow used to sustain the liquid states of hydrogen and methane, but it is unclear whether this was to be dc or ac, although it was likely to be dc given the long distance, probably employing an A15 compound as conductor [12].

2) dc Superconducting Power Transmission Line Project at LASL. A massive and inclusive study of a large capacity, 5 GW SCDC cable employing Nb_3Sn, sponsored by DOE and the Philadelphia Electric Company (PECO) representing the interests of several eastern utilities carried out in the mid-1970s. The project was discontinued after building and testing a few meters of conductor due to lack of funding and lack of utility interest [13].

3) Hydrogen-Refrigerated $NbGe_3$ dc Superconducting Cables. This was a study carried out at Stanford in 1975 using slush hydrogen at 14 K for a cable made of Nb_3Ge (T_C = 23 K) [14].

4) BICC HTSC dc Transmission Line. This was actually the first (1995) prototype HTSC cable to be constructed and tested, albeit only 1 meter long. The design is an interesting one, targeting a 400 km European "ring buss" with a 400 MW, 40 kV, 10 kA capacity with cold He gas at 4.2 K blown in one end and warming to 40 K at the other, well within the critical parameter limits of Bi-2223 throughout that range [15].

5) EPRI: "The e-Pipe" This study compared the relative economic alternatives between HVDC lines, gas pipelines and an HTSC "electricity pipe" to transport 5 GW of chemical or electrical power from the Qatar gas fields near the Persian Gulf 1000 miles to Palestine-Israel. It was, in effect, mini-G-M project [16].

B. Generic SCDC Coaxial Cable Configuration

Fig. 2 shows a very oversimplified, but nonetheless representational, cross-section of a basic coaxial cable, the principal difference here is that instead of a solid center conductor, we have an annular cylinder of superconductor through which flows a suitable cryogen (We neglect complications of cryogen return and details of thermal and electrical insulation. A "fully engineered" coaxial SCDC cable design can be found in [18]). The choice of power and operating parameters, 10 GW, +/- 50 kV and 100 kA, will be explained in Section IV to follow. We do indicate explicitly in Fig. 2, a diameter of 17.5 for the inner conductor set by the desire that its surface field and that seen by the outer conductor, remain below 0.3 T for a current of 100 kA, safely below the nominal irreversibility field for copper oxide perovskite superconductors at 77 K.

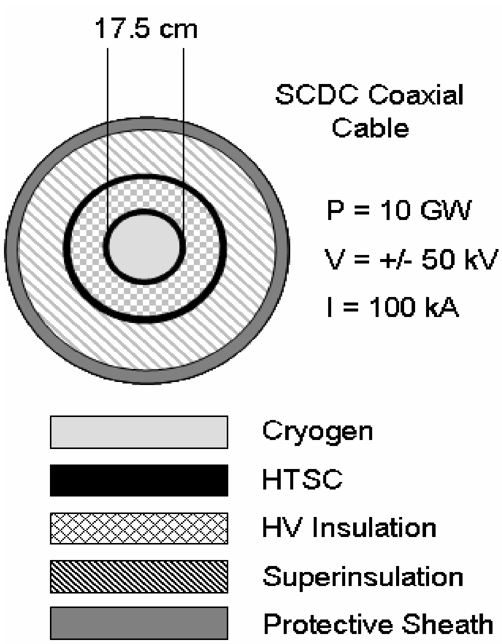

Fig. 2. Sketch of a generic SCDC coaxial cable with geometric symmetry and performance characteristics to be employed throughout this rest of the present paper. The two superconducting "conductors" or poles are shown as two concentric annular black rings for current "go-and-return." The diameter of the inner conductor was chosen to reduce self-field to a level below 0.3 T for a current flow of 100 kA.

Although throughout the rest of this paper, we will assume use of the latest "Gen X" cuprate high temperature superconductor, the general scope of Fig. 2 could accommodate a wide range of materials and cryogens, from an A15 compound at 4.2 K, to MgB_2 at liquid hydrogen (21 K), through the cuprates at 77 K, all the way to up to Hg-1223 (T_C = 135 K) refrigerated by liquefied natural gas at 110 K. The top portion of Table 2 contains the "Gen X" parameters we will apply to Fig. 2 and use throughout theto the subsequent discussion. Detail on some of the other superconductor-cryogen combinations can be found in [19] and [20].

IV. SUPERTIE

Ever since the growth of the grid reached continental scale proportions, proposals have been put forward take advantage of fluctuation in diurnal demand for electric power – as evening falls in the eastern states and demand for lighting ramps up, excess power available in California could be tapped. Correspondingly, reserve electricity resources from the Atlantic seaboard in its early morning hours can be sent westward as the business day begins in California and the Pacific Northwest.

A. The "Two Californias" Scenario

In order to explore this concept in a basic and simple way, we will assume the East – West seacoast electric power supply-demand picture is qualitatively represented by a mirror image of an "Atlantic California," as schematically shown in Fig. 3 linked westward to the "real California" by a 10 GW SCDC "SuperTie" as shown. A somewhat more realistic view, which takes into actual power conditions in New York State, is considered in [7].

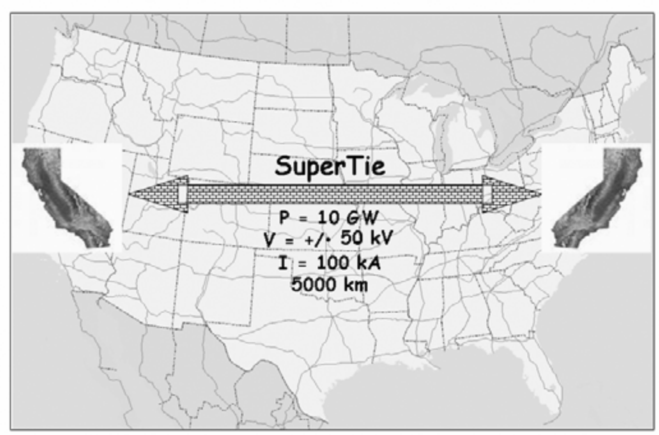

Fig. 3. Cartoon of an hypothetical continental US East-West Intertie to implement diurnal intercoastal electricity trading. For simplicity, we assume eastern electricity demand to be identical to California on any given day, shifted three hours forward relative to PST.

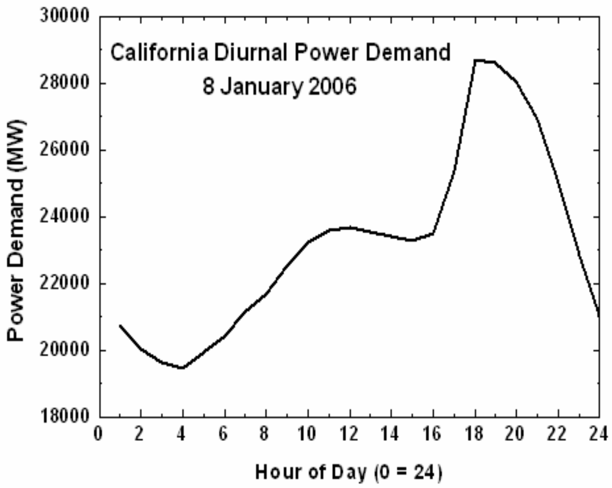

Fig. 4. Actual diurnal load on a typical midwinter Sunday throughout the state of California from 01:00 hours to 24:00 hours [21]. Note the late afternoon "lights on" surge typical of that time of year.

Fig. 4 shows the power demand throughout the "real" California on a typical midwinter weekend day [21]. During the summer, the peak demand can swing between 22,000 MW and 45,000 MW and higher, mostly due to air conditioning load, and more "sinusoidal" in shape. We chose to use a wintertime sample because the rapid late afternoon "lights on" surge would more severely stress a high current SCDC cable. Fig. 5 below contains the midwinter "differential" East-West "Two Californias" potential trading flow. This plot is suggestive of what might transpire, and is not intended to reflect an actual market transaction, instead when such transactions might indeed occur (zero crossings) and how rapidly (10 A/s).

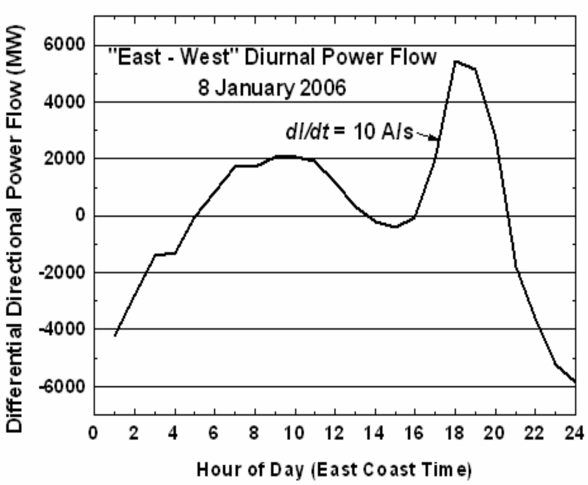

Fig. 5. East-West differential power flows as a function of EST. This plot is not intended to reflect actual magnitudes of power transfer on the SuperTie, but rather when they might occur (zero crossings) and how rapidly.

We observe from Figs. 3 and 5 that a 10 GW cable should prove sufficient to handle most expected levels of power transfer on the intercontinental SuperTie. The cable parameters and resultant performance and cost are summarized in the bottom portion of Table II. Note that the wire cost stated is per conductor or pole. The total wire cost is $52.6 B.

TABLE II
SCDC SUPERTIE CABLE DESIGN AND PERFORMANCE PARAMETERS

Item	Value/Quantity	Units
HTSC Tape Parameters (77 K, 0.3 T)		
- Critical Current Density, J_C	15,000	A/cm^2
- Tape Critical Current, I_C	150	A/tape
- Cost/Performance	50	$/(kA×m)
- Width	0.4	cm
- Thickness	0.025	cm
- Single Tape Length	800	m
- Integration "wasteage"	5	%
- Joint Resistance	0.92	mW
- I^2R Dissipation per Joint	0.8	mW/m
SuperTie SCDC Cable Parameters and Performance		
- Overall Length	5000	km
- Number of Conductors*	2	1 per pole
- Conductor Annular Radius	8.75	cm
- Maximum Power	10	GW
- dc Voltage	50	kV per pole
- dc Amperage	100	kA
- Field at Conductor Surface	0.23	T
- Conductor X-Section Area	6.62	cm^2
- # HTSC Tapes/X-Section	667	
- Total Tape Length/Pole	3,475,600	km per Conductor-Pole
- Total # Joints per Pole	4,345,000	
- Power Lost in Joints/Pole	4.0	kW
- HTSC Tape Cost per Pole	26.3	B$

*The term "conductor" herein is taken as in the lexicon of utility engineers, in that a conductor is that which is wound from a given number wires or tapes and a cable is what goes around conductors. Thus, in the coaxial dc cable of Fig. 2, there are two concentric annular conductors, or, equivalently, "poles."

B. Analysis of Vortex Flow Losses due to Current Fluctuations

In this Section we will identify and analyze several sources of vortex flow loss arising from vortex lattice motion in the operation of the SuperTie.

1) ac Losses Due to Ripple. Rectification or conversion of ac to dc at each end of the SuperTie cable will result in a certain amount of ac ripple superposed on the overall dc current. Equation (1) in the limit where the of ac modulation is small compared to the background current becomes

$$W = \frac{4\times10^{-8}(\Delta I)^3 \nu}{J_C R^2}, \tag{2}$$

where R is the effective radius of a solid round wire of cross-sectional annular area given in Table II (6.62 cm^2) or 1.45 cm, J_C the critical current, 15 kA/cm^2, ΔI the rms ripple current, which we take to be 1% or 1000 A (actual ripple can be substantially reduced by proper filtering in the inverter/converter stations) and ν is the ripple frequency, 360

Hz for 6-phase ac input. Under these conditions, we obtain $W \approx 1$ W/m, a quite tolerable value readily accommodated by the refrigeration system.

2) Diurnal Harmonics Arising on the "Two Californias" SuperTie. Fig. 6 displays a Fourier analysis of the diurnal power flow transfer time dependence resulting from Fig. 5.

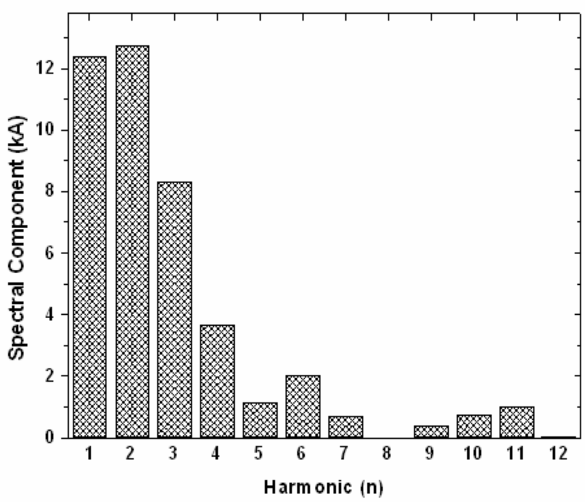

Fig. 6. Spectral distribution of the time dependence intercoastal power demand plotting in Fig. 5. The period is 24 hours, thus the first harmonic frequency is 11.6 μHz.

The power loss per harmonic in the limit where their respective amplitudes are of the order of the total dc current as derived from (1) are,

$$W_H(n) = 2\times10^{-7} I_n^2 \nu_n, \tag{3}$$

where n is the harmonic number, and I_n and ν_n its amplitude and frequency, respectively. The consequent power losses for the first four harmonics are summarized in Table III.

TABLE III
SUPERTIE DIURNAL HARMONIC CONTENT FOR A PERIOD OF 24 HOURS

n	I_n (kA)	ν (μHz)	W (kW/5000 km)
1	12.4	11.6	1.8
2	12.8	23.2	3.8
3	8.31	34.7	2.4
4	3.67	46.3	6.2
Total			8.7

We see immediately that there is absolutely no barrier arising from flux flow loss to operating the SuperTie to accommodate trading transactions on the time scale of Fig. 5. In fact, this result could have been anticipated by observing in Fig. 5 the "lights on" ramp is around 10 A/s, whereas the slope of a sawtooth ripple of 1% at 360 Hz to produce heating of 1 W/m would be 720,000 A/s! Moreover, assuming 1 W/m loss as an upper benchmark, (1) predicts the entire SuperTie could be reversed in about two hours or even faster if this limit were to be raised three- or fourfold.

C. Recovery of Capital Cost of HTSC Wire in the SuperTie from Electricity Savings

We now inquire what length of time it would take to recover the extra capital cost of the HTSC wire deployed in constructing a SuperTie, based on the numbers contained in Table III. For reasonable choices of present cost of electricity, capacity factor and interest rates, the results are summarized in Table IV.

TABLE IV
SUPERTIE RETURN ON HTSC INVESTMENT
ACCRUED FROM REDUCTION IN ELECTRICITY LOSSES

Item	Value/Quantity	Units
Cost of Electricity	0.05	\$/kWh
Conventional Transmission Line Loss	5	%
Annual Value of Loss on 10 GW Transmission Line @ 50& Capacity	110	M\$
HTSC and Refrigeration Capital Costs	52.6	B\$
Present FRB Discount Rate	5.5	%
Recovery Period for HTSC ROI from Energy Savings	62	Years

We see the payback under the assumptions made in Table IV would take 62 years. Even if the capacity factor were to be 100%, this time decreases only to 49. Clearly, it would be difficult to economically justify construction of a SuperTie on energy savings alone

V. DISCUSSION

It will be useful to re-scale the SuperTie and G-M to the equivalent distances. Thus, at 1000 km, the HTSC wire cost for the SuperTie becomes \$10.5 B, but this does not include infrastructure costs as does Table I for G-M. We note from Table I that the Nb_3Sn wire constitutes approximately 70% of the total project outlay and the remainder (refrigeration, conversion, and construction addenda) amounts to approximately \$1.6 B in present dollars. If we assume a similar cost (it will actually be considerably less) for the latter quantities will also apply to the SuperTie, that will bring its cost per 1000 km to \$12.1 B. Thus we would conclude that a Nb_3Sn SuperTie at 10 GW capacity would cost much less than an HTSC version.

In any event, a large capacity superconducting dc cable, using either low or high temperature superconductors, would be difficult to justify on electricity savings alone. However, other issues, such as reduction in carbon emissions, lower ecological impact and deferment of power plant construction may in the future override economic considerations alone. Time will tell.

ACKNOWLEDGMENT

The author wishes to acknowledge the support, encouragement and inspiration provided over the years by many colleagues at EPRI, especially that of its Founder, Chauncey Starr, as his mentor in matters of energy science and technology and its vital role in determining public policy. He is indebted to Steve Eckroad of EPRI's Power Delivery Division for his steadfast support and suggestion to apply the Garwin-Matisoo model to a power trading embodiment.

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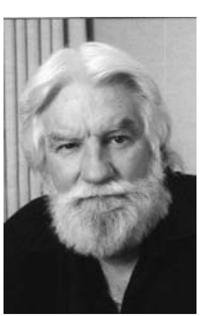
[21] Data taken from the California Independent System Operator "Today's Outlook" webpage at http://www.caiso.com/outlook/SystemStatus.html.

Biography



Paul Michael Grant was born in Poughkeepsie, NY, on May 9, 1935. He holds a BSEE degree from Clarkson University and the AM and PhD degrees in Physics from Harvard University. His career with IBM began at age 17 in 1953 as a pinsetter in the employee bowling allies followed shortly thereafter by service in the mailroom of the company's technology development laboratory in Poughkeepsie. Within his first year of employment, he was promoted to technician and system programmer on Project SAGE, the world's first supercomputer and prototype for NORAD and assigned to the IBM support team at MIT's Lincoln Laboratory. In 1956, he entered Clarkson University supported under the company's employee educational assistance program, followed in 1960 by graduate studies at Harvard under an IBM Resident Graduate Study Fellowship. During college, he returned to work summers at IBM on thin magnetic film memory development, silicon epitaxial film growth and laser spectroscopy. His Harvard PhD thesis addressed the optical properties of semiconductor thin films.

Upon completing graduate school, Dr. Grant was posted to the IBM San Jose Research Laboratory where he pursued a variety of basic research studies on the physical properties of magnetic semiconductors, organic and polymer metals, and high temperature superconductors and participated in the initial development of laboratory automation software and systems. His IBM career also included management and divisional executive staff responsibilities to evaluate IBM's printer, storage and display technologies. From 1990-92, he served a two-year sabbatical as IBM Visiting Professor of Materials Science at the National University of Mexico.

In 1993, Dr. Grant retired from IBM to accept a position as Science Fellow at the Electric Power Research Institute (EPRI) where he oversaw a variety of exploratory studies on wide bandgap semiconductors, new superconducting materials and power applications of superconductivity, and served as a consultant to EPRI's executive management and utility membership on a broad range of energy science issues. He retired from EPRI in early 2004 to undertake a variety of personal and professional interests.

Dr. Grant has published over 100 papers in scientific peer-reviewed journals, as well as numerous articles on science and energy issues in the popular press and interviews on television that have earned him several awards as a science writer and commentator. He is a co-inventor on the international base patent for high temperature superconductivity and consults regularly with the US Department of Energy on the science and power applications of superconductivity. He currently holds an appointment as Visiting Scholar in Applied Physics at Stanford. Dr. Grant is a Fellow of the American Physical Society and has served on the Executive Committees of the Society for Industrial Physics and Education. He is also a Fellow of the Institute of Physics in the United Kingdom.