CONTACTLESS POWER TRANSFER - AN EXERCISE IN TOPOLOGY

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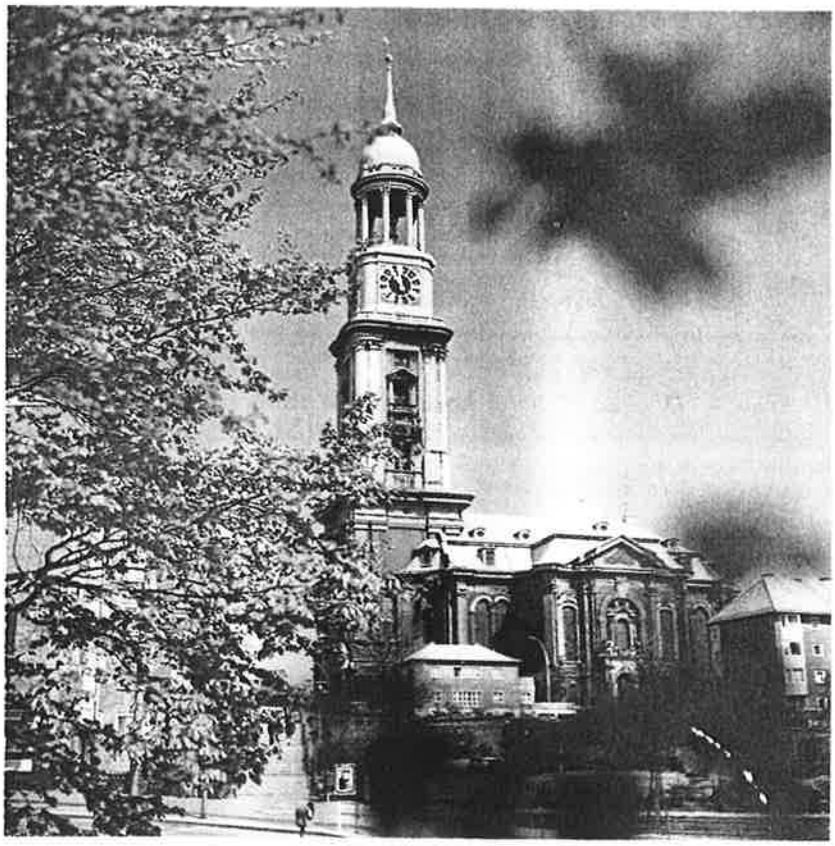

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ABSTRACT

Previous attempts at different forms of contactless power transfer systems associated mainly with high speed ground transportation and magnetic levitation are reviewed. Two different types of contactless power transfer systems are proposed as replacements for the brush-and-conductor, trailing cable, or reeling drum, where these options were inappropriate or would suffer excessive wear or other degradation in the stringent applications encountered in the nuclear or mining industries. The first system uses busbars as longitudinal members along which an output transformer can move. The second system uses magnetic material as the longitudinal members, can be formed into a robust composite structure, and can be arranged to provide a surface wiping geometry for the moving output core: this system is essentially the magnetic dual of a conductor rail and contacting brushgear. Examination of the systems' topologies allows longitudinal, curved or circular systems to be developed, and non-nuclear applications which include, for example, contactless power transfer for robotic joints are envisaged.

INTRODUCTION

The transfer of electrical power between moving components usually presents few problems. Where routes are well defined and limited in length, trailing cables and cable reeling drums may well be adequate, and for installations where any distance has to be covered, the choice would be between brushgear running on rigid or suspended conductors. Particular difficulties in specialized areas such as ground transportation and the mining and nuclear industries have, however, provoked the need to seek alternatives to a permanent connection or a brush-and-conductor combination.

It has been shown that the viability of high speed ground transportation (HSGT) systems depends strongly on the overall choice of electromagnetic energy conversion[1]. Inefficient power transfer and distribution severely degrade the high lift to drag ratios of lift and guidance systems so that the energy benefits of magnetically levitated (Maglev) vehicles can be lost. The early HSGT research assessed different forms of contactless power transfer, including controlled electric arcs, inductive, capacitive and waveguide systems[2], but none reached full sized application. White and Thornton at MIT proposed an inductive system[3] which used a moving E shaped ferrite core running at a 10mm clearance above a ferrite strip laid along the track. The primary winding consisted of rigid conductors carrying up to 400A at 18kHz, and it was claimed that 2.5MW could be transferred to vehicles travelling at 135m/s. At General Electric, iron and air cored moving transformers were also investigated[4], but were not considered feasible because of the weight of on-board equipment and the expected low efficiencies. Because of the uncertainties associated with contactless power transfer systems, and the absence of full sized demonstrations, the large scale tests carried out at the US Pueblo Test Centre relied upon either on-board power, or rigid trackside power conductors.

More recently, techniques have been developed to supply on-board power at high speeds to prototype Maglev vehicles. The German electromagnetic system (EMS) uses pole face windings in the lift magnets to collect flux harmonics from the iron cored linear synchronous machine airgap[5]. The Japanese National Railways' electrodynamic system (EDS) uses separate secondary coil arrays on the vehicles to absorb power by interaction with the harmonic components of flux produced by the track coils, which in turn have been excited by the passage of the vehicle superconducting levitation and guidance magnets[6]. The full sized realization of the Japanese system would consist of a 12 car train travelling at 140m/s, with propulsive power obtained from a linear synchronous motor with superconducting field magnets. The motor would transfer some 66MW, without contact, and the addition of the harmonic flux induction power source producing 100kW per car would require an increase in propulsive power of only 2MW. As both of these systems for EMS and EDS contactless power transfer require motion before significant power levels are achieved, an auxiliary on-board power supply for low speed operation is obligatory.

As new equipment and installations are contemplated in the nuclear industry, the designer is charged with the duty to ensure that human exposure to radiation from installation, operation and maintenance activities is as low as reasonably achievable (the ALARA principle). Maintenance of equipment from contaminated controlled areas is non trivial and any unwarranted or extended downtime for parts of a facility is expensive. Because of degradation of cable insulations and other materials characteristics it is not usually practicable to use unmodified industrial standard equipment in radioactive environments. For these reasons research was undertaken at AERE Harwell into contactless forms of power transfer to avoid either brushgear which needed frequent replacement or trailing cables and reeling drums where insulation may become suspect under constant irradiation, and whose delivery systems might require expensive maintenance (in exposure terms).

Two generically different types of contactless power transfer systems (CPTS) which also have possible non-nuclear applications will be described. The first configuration employs longitudinal conductors along which moves an iron cored transformer carrying an output winding. In the second configuration, magnetic material replaces the conductor in the longitudinal members, and a moving output winding may be placed on additional magnetic material. Both systems have many topological variants which enhance performance or better suit particular applications.

LONG BUSBAR CPTS

A typical arrangement for a long busbar CPTS is shown in Figure 1. In this case, industrial frequency three phase power is fed at one end into the busbars, whose remote ends are connected in star. The busbars are simply supported at each end and the moving transformer travels on an auxiliary suspension. Guide

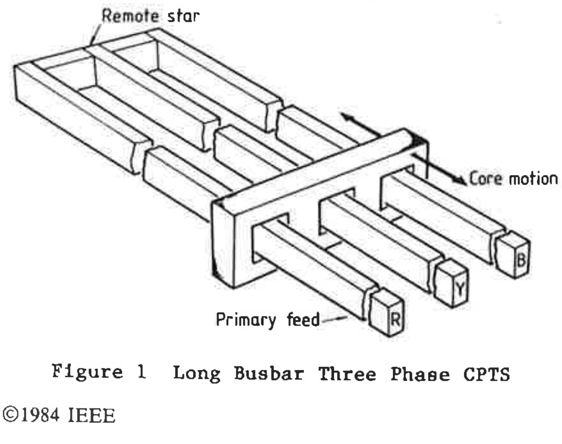

Figure 1 Long Busbar Three Phase CPTS

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rollers feed the busbars into the window areas of the transformer. The load may, for example, consist of a hoist and a traversing motor which propels the hoist (and transformer) to the required position within a radioactive environment. The motors would naturally be brushless, and their direction and speed would be determined by contactors controlled by demultiplexing a signal picked up by a capacitive probe running near one of the busbars. The control signal is superimposed onto the busbar voltage at the primary feed. Other loads, such as remotely controlled power manipulators with several degrees of freedom have been considered.

There are, however, several aspects of a long busbar CPTS which inhibit its efficiency. Because the core essentially links only a small part of the busbar external field, the overall efficiency of electromagnetic energy conversion for long length CPTS is low. As the core encircles the busbars, supporting arrangements are limited to simple fixing at either end - additional supports would have to latch and unlatch as the core progressed, and would introduce complexity greater than existed in the original systems. Finally, because the conductors are not symmetric, there is considerable difference in interphase mutual inductance and hence voltage and current in both primary and secondary sides may have high unbalance factors.

The sag of the busbars is proportional to the fourth power of the span, and only inversely proportional to the modulus of elasticity. Some reduction in sag to manageable limits is possible by constructing a composite bar and artificially increasing the modulus. A 7 metre long two phase CPTS was constructed with pultruded carbon fibre bonded to upper and lower edges to reduce sag. The system was coupled to the industrial supply and conventional loads through Scott connected input and output transformers. The sag was reduced by 40% from 59mm to 35mm, and this avoided the need for additional guidance of the transformer core to track the busbar catenary. The original bar modulus was raised from 67 GPa to 91 GPa for the composite by the addition of the carbon fibre.

The working width of the system should be minimized to give a compact transformer core and to reduce the unbalance caused by the interphase mutual inductances. The busbars' pitch is limited by the space needed for the core limbs, winding volumes and running clearances. For practical designs the ratio of maximum to minimum mutual inductance for three line abreast conductors can be substantial. Figure 2 shows this ratio for filaments [at these spacings the bar cross-sections do not dominate the calculation and so filamentary approximation is sufficient]. A three phase system, 9.8 metres long with busbar pitch of 0.15 metres has a mutuals ratio of 1.22, and similar voltage and current unbalance. To reduce the unbalance auxiliary windings are required on the input transformer. An alternative solution is to support the busbars at equal distances, but this requires a more complex suspension and non standard laminations and lay up procedures applied to the core stack.

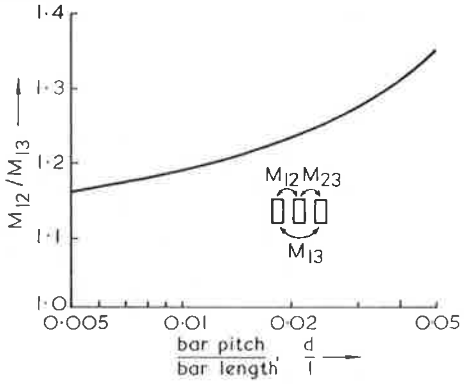
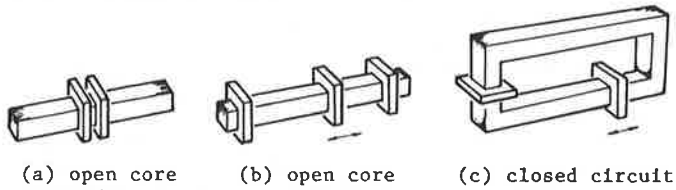


Figure 2 Ratio of Maximum to Minimum Mutual Inductance

LONG CORE CPTS

The difficulty in trying to design a CPTS using longitudinal busbars for distances above 20 metres prompted a reassessment of the system topology, which began with interchanging the roles of conductor and core. The longitudinal element now became magnetic material with a fixed primary winding and moving secondary windings. Laithwaite[7] has shown that the open core transformer so formed (Figure 3a) does not necessarily suffer severe degradation in performance. The return path is large, but the air cored return section is very large, so the effective airgap does not unduly dominate the magnetic circuit design. The calculation performed assumes that an open core transformer can be modelled by an ellipsoid with a demagnetization factor along the major axis; this is then equated to that of a gapped anchor ring, to give an equivalent airgap value, g.



(a) open core transformer (b) open core CPTS (c) closed circuit CPTS

Figure 3 Elementary Long Core CPTS

Extending the analysis to include a rectangular section bar, the axial demagnetization factor, N, is

$$N = \frac{hw}{\mu_0 l^2}\left[\ln\left(\frac{4l}{h+w}\right) - 1\right] \qquad (1)$$

where h, w, l are the bar height, width and length. The equivalent anchor ring demagnetization factor is

$$N = \frac{g}{\mu_0 l} \qquad (2)$$

so the equivalent airgap for an open core transformer is

$$g = \frac{hw}{l}\left[\ln\left(\frac{4l}{h+w}\right) - 1\right] \qquad (3)$$

This airgap value is given for a range of core-bar cross sections in Figure 4, and it can be seen that for a metre long bar of 25 x 25mm section, the equivalent airgap is only 2mm. Figure 3b shows an initial attempt at a long core CPTS, where the input windings are located at the bar ends and the output winding too encircles the bar and moves between primaries. This arrangement does not rigorously satisfy the ellipsoid-anchor ring analogy, but power transfer between coils is naturally enhanced by the presence of the core. Completing the magnetic circuit (Figure 3c) brings the flux linkage at extremes of travel between two coils on a 1 metre long system up from 20% to 90%, which confirms that elongated magnetic structures have practical application for CPTS.

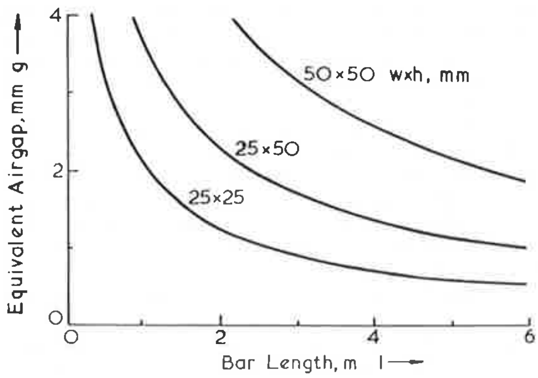
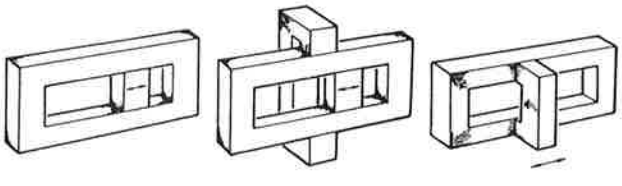


Figure 4 Equivalent Airgap for Open Core Transformer

The examples shown in Figure 3 can only be supported at their ends as the output winding surrounds the longitudinal member. The change in material to iron does not alter the sag, as the density to modulus ratio is similar to that of aluminium. If an additional iron cored slug is used to carry the output windings of Figure 3c, flux can be shunted between the upper and lower longitudinal members, Figure 5a. When the distance travelled is excessive, auxiliary primary coils on modified close fitting C cores provide intermediate compensation for the long iron magnetic paths and the two airgaps introduced at the slug, Figure 5b. The role of slug and auxiliary core can be reversed and then the majority of the core structure becomes a composite block. These arrangements allow wall mounting of the main core structure without interference to the motion of the output winding, and three phase versions, although complex in construction, are possible.



(a) (b) (c)

Figure 5 Face Mounted Long Core CPTS

The topology of Figure 5a may be altered to enhance the mechanical structure. If the laminations are realigned so that the stack height is in the same direction as the structure height, then the end cores and output core may be constructed from C cores directly (Figure 5c). The input and output portions of the CPTS now represent a truly co-planar interface, and the structure can be supported along the entire back face by fixing to vertical or horizontal surfaces.

A three phase CPTS based on Figure 5c is simple to construct, consisting of long laminated bars made from bonded strip, and conventional E cores to carry input windings at each end and also to carry the output winding (Figure 6). Because of the action of the output E core in shunting flux at different positions, it is known as the trombone transformer[8], and is effectively the magnetic dual of a three phase conductor rail and contacting brushgear system. The structure can be made extremely rigid by casting into a composite block, which ensures face alignment and reduces core vibration. For long lengths, where flux leakage predominates the linkage with the output coils, additional primary coils can be placed on E cores along the back face of the block at suitable intervals, and because they form part of the stationary structure, they can be energized and de-energized in sequence as the moving output E core progresses.

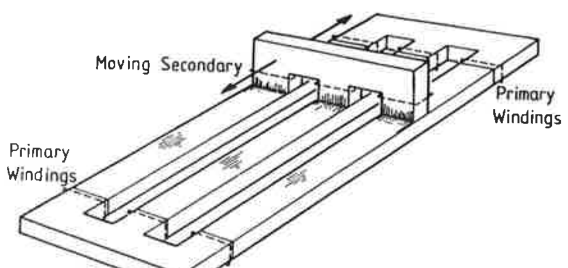


Figure 6 Three Phase Trombone Transformer

The manipulation of CPTSs in other directions allow curved and circular motions to be accommodated. For example, bending the CPTS in Figure 6 in the same plane gives an arrangement of three concentric toroids linked by an E core. Figure 7 shows the system, with an extra E core on the back face of the toroids. Either part can be allowed to rotate and variations will depend on the application. This type of CPTS is expected to find application in robotic or manipulative devices where arm joint maintenance requires a complete disassembly of component parts to replace brushgear or sliprings.

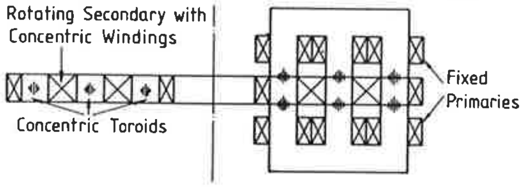


Figure 7 Low Profile Rotary Secondary CPTS

For more complex shapes, and indeed for increases in power to weight ratios, high frequency systems are anticipated. The use of ferrite material also avoids the need to make three dimensional flux paths by butt jointing lamination stacks. Finally, Figure 8 shows a three phase high frequency rotary CPTS which presents a plane face between input and output structures.

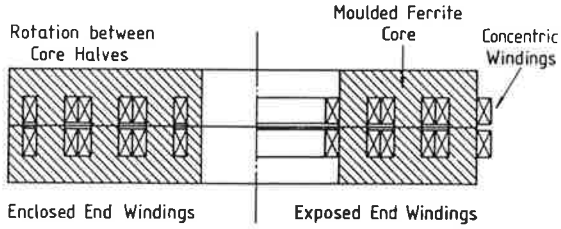


Figure 8 Low Profile High Frequency CPTS

CONCLUSIONS

Different forms of contactless power transfer systems have been described which may provide solutions to those applications of power transfer where the use of conventional brush-and-conductor combinations, trailing cables or cable drums incur penalties. By examining the topology of various systems, a simple robust construction has been proposed which can also be reconfigured to make available extended longitudinal, curved or circular motions. Because the system is novel, further evaluation of the device characteristics is required, but the performance will not necessarily be degraded by the inclusion of airgaps and multi-dimensional flux paths in the magnetic circuit.

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