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INDUCTIVE POWER COUPLING FOR AN ELECTRIC HIGHWAY SYSTEM

J. G. Bolger, F. A. Kirsten, and
L. S. Ng

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INDUCTIVE POWER COUPLING FOR AN ELECTRIC HIGHWAY SYSTEM*

J.G. Bolger, F.A. Kirsten and L.S. Ng
Lawrence Berkeley Laboratory
Berkeley, California

Summary

A Dual Mode Electric Transportation (DMET) system is under development in which energy is electromagnetically transferred from a powered roadway to moving vehicles. Energy from the roadway can be used for high-speed, long-range travel and for replenishing energy stored in the vehicle in batteries or flywheels. The stored energy is then available for short-range travel off the powered highway network.

The power coupling between roadway and vehicle is functionally similar to a transformer. A source is embedded in the roadway flush with the surface. When the vehicle's pickup is suspended over the source, energy is magnetically coupled through the clearance air gap between pickup and roadway source.

The electromagnetic coupling mechanism has been extensively studied through computer models, circuit analyses and by tests of a full-size physical prototype. The results of these tests are described.

Introduction

The relative importance of the factors which influence the design of automobiles has changed markedly in the last decade. Major concerns of the sixties were emissions and safety; major concerns now are the consumption of critical energy and material resources. A particularly urgent need is to reduce the use of imported and domestic petroleum in the transportation sector. This is part of the incentive which has spurred research and development of electric vehicles. Electricity is an especially attractive form of energy since it is a common factor to all principal power generation technologies, present and future.

Most electric automobile development is centered on battery-powered propulsion systems. The widespread acceptance of such systems is impeded by certain of their characteristics, namely limited range capability, poor performance and high operating costs.

In this paper, we describe an alternative concept that bypasses many of the disadvantages of electric vehicle systems that rely solely on battery power. The system is called the Dual Mode Electric Transportation (DMET) system. In this alternative, electric power is continuously available to the moving vehicle from a source embedded in the highway. It is proposed that the power source be installed on high-speed arterials within a network of streets and highways. Power is then available to propel the vehicle while moving on the powered highway and can also be utilized to recharge an energy storage device on the vehicle.

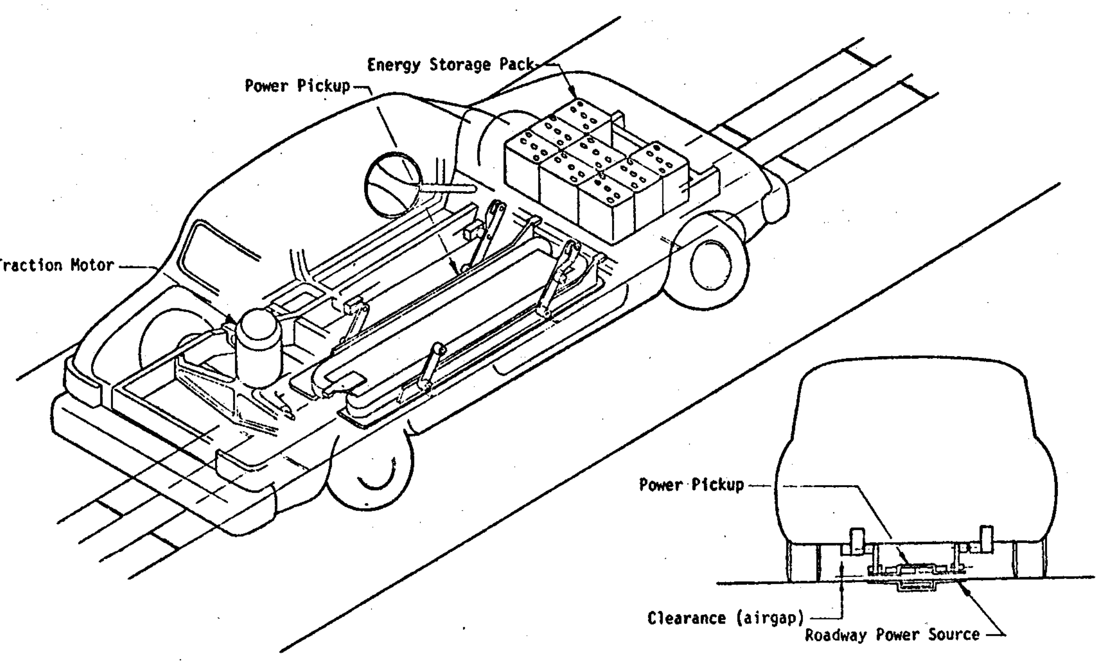


Fig. 1. These sketches illustrate the relationship between vehicles and power coupling mechanism in the Dual Mode Electric Transportation system.

*Work performed under the auspices of the Department of Energy.

The stored energy is then available for use while traveling on non-powered highways and streets. Power is transferred from highway to moving vehicles via an inductive (transformer) coupling mechanism which requires no physical contact between vehicle and roadway.

This system has some important advantages which, we feel, make it a practical solution to the problem of supplying energy to transportation systems. These include:

- The DMET power source can be installed on existing highways. Highways with installed DMET power source are compatible with conventional vehicles. The transition to DMET therefore causes a minimum perturbation in the existing transportation system.

- Because of the dual-mode characteristic of the vehicles, only a minor fraction of roads need to be powered. The stored-energy pack is utilized for off-network driving. However, the amount of stored energy required is reduced to only that necessary to gain access to the nearest powered highway, or to supply the typically modest energy demands of city driving patterns.

- The efficiency of energy utilization is greater than for electric vehicles having only battery power.

- The DMET system may be a useful tool in achieving better, safer vehicle control. Although the power coupling is tolerant of steering misalignment (unlike third rails, for example), automatic guidance and vehicle detection features can readily be added.

The initial design of the system was done analytically, resulting in a configuration that appears to be reasonably well optimized and is technically feasible and practical. Some of the results of this study are presented here; more details are given in a reference.[1] At present, preliminary tests are being conducted on a prototype of the power coupling. Some of these have been completed and are described in this paper. Others will be completed in the near future. Within the next year, it is planned to build a 50 meter test track, to be used in conjunction with a vehicle adapted to the system.

Basic Concept

The DMET system is based on a continuous electric power "source" installed in arterial roadway lanes. As shown in Fig. 1, the source is installed with its upper surface flush with the roadway. Electric vehicles will carry a power "pickup" which is supported by the vehicle approximately three centimeters above the roadway surface. Both the source and pickup are constructed of laminated transformer iron, together with suitable windings. The single-turn source conductor carries approximately 1000 A at a frequency of 180 Hz. When the pickup is in the position shown in Fig. 1, the magnetic circuit is completed through the air gap. The resulting magnetic flux links the pickup winding. Sufficient power can thereby be transferred to propel the vehicle at freeway speeds and to recharge the stored energy device. The power capacity of the pickup is proportional to its length. Small automobiles require approximately 20 kW to travel at 90 kph. This can be supplied by a pickup of the order of 2 meters in length. Trucks and buses may require more than one pickup. Roadside power conditioners will accept power from the electric utilities and convert it to a frequency and power level suitable for the powered highway. As shown in Fig. 2, each power conditioner would provide electric power to several source loops. It is planned that each loop would be 2 km or more in length. The required maximum power level would be approximately 0.6 megawatt per lane-kilometer for a fully loaded roadway (30 vehicles per km @ 20 kW per vehicle).

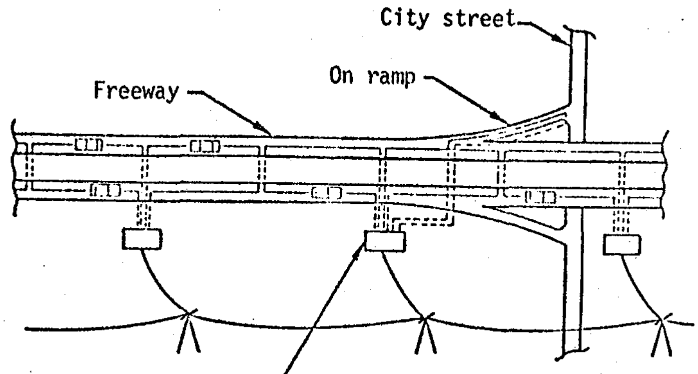


Fig. 2. In a typical installation, each power supply (power conditioner) energizes several loops of DMET source. Each loop would be one or two kilometers in length.

Pickups are suspended by mechanisms that can maintain relatively close control of the elevation of the pickup while it is lowered over a source, and will raise the pickup to provide normal clearances under vehicles while they operate on city streets.

Each vehicle will contain an electronic control system capable of continuously regulating the coupled power. Variations in coupled voltage will otherwise result from small changes in the air gap and from guidance errors. The energy storage on board the vehicle serves as a "load leveler" capable of averaging effects of momentary variations or interruptions in coupled power.

The size of the storage pack will be sufficient to allow vehicles to leave or enter powered lanes at freeway speeds, or to pass stalled vehicles. A stored energy pack of this minimum power capability would also support approximately 40 km of travel at 56 kph off the powered roadway.

Inductive Power Coupling Design

The transfer of power from roadway to vehicle is accomplished by inductive coupling. The coupling mechanism is somewaht similar to that in conventional power transformers. However, several features require special comments. First, there is an air gap of nominally 3 cm between the two parts of the magnetic core structure. Second, the secondary and its associated core moves with respect to the primary. Third, to the secondary, the primary appears to be supplied from a constant current source.

Figure 3 is a cross-section of the source and pickup structures. As shown, the linear source structure, which consists of the source conductor (primary winding) and one-half of the core of the equivalent transformer, is embedded in the roadway. The core associated with the source includes two pole faces that are flush with the roadway surface. The pickup, which behaves as the secondary of the equivalent transformer, is attached to the vehicle. The cross-section of the pickup is similar to that of the source; when its two pole faces are opposite the pole faces of the source, magnetic coupling results and power can be efficiently transferred from source to pickup.

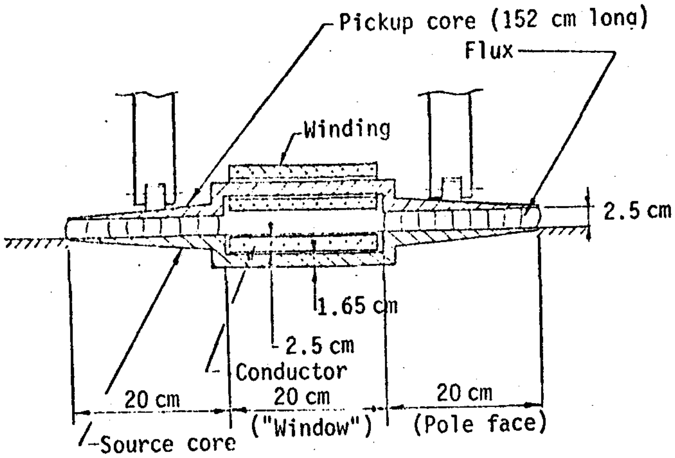


Fig. 3. Power coupling cross-section used in computer studies.

The source winding consists of a single stranded aluminum conductor along the center of the traffic lane; the return leg to complete the electrical circuit is a similar conductor in an adjacent lane (see Fig. 2). The lane spacing is assumed to be 3.7 m. The conductor carries a current that is regulated to be approximately 1000 A at a fequency of 180 Hz. This frequency offers a good compromise between weight of magnetic materials and hysteresis losses.

The cross section of the continuous iron core that surrounds the lower half of the conductor is chosen to minimize its mass and yet keep the magnetic field low to reduce hysteresis losses. For the preliminary study, a cross section approximately 61 cm wide and 1.65 cm thick has been chosen. The center portion of the core is depressed 2.5 cm in order to accommodate the conductor. The edges of the core are tapered so as to retain approximately constant field intensity throughout the iron.

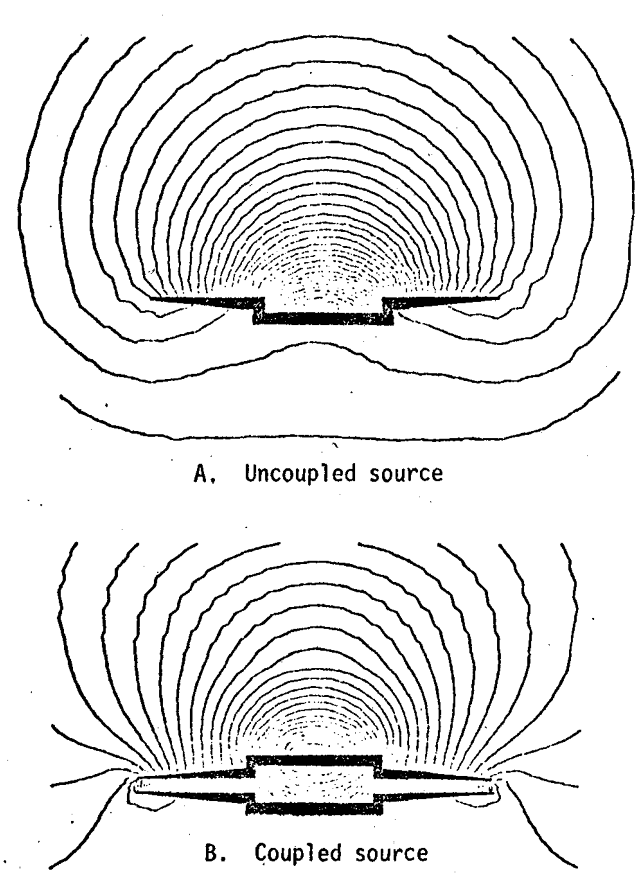
The vehicle's pickup is assumed to have a core of similar cross section, 1.5 m long, separated from the roadway core by a 2.5 cm air gap. The windings for the pickup return along the top of the pickup core. This configuration was chosen to give a reasonable performance in both coupled and uncoupled conditions. In order to study the performance, a computer program which is designed to analyze magnetic structures was used to make flux plots of both coupled and uncoupled conditions.

Uncoupled Condition

The uncoupled condition can occur either when no vehicles are on the roadway or when the only vehicles present are not equipped with pickups. In this, the "idling" condition, the prime objectives are to keep the power losses to a minimum and to keep the stray magnetic flux as low as possible. It is clear that the long-term energy efficiency of the DMET system depends on maintaining the idling power losses as low as possible. This is accomplished by using a low-resistance conductor and by keeping the flux density in the iron to a reasonably low level.

The magnetic field strength above the roadway source must also be kept reasonably low to reduce undesirable coupling to other nearby structures. One of the most common nearby structures will be the frames of automobiles not equipped with the pickups.

While optimization of the coupling design has not been completed, the structure shown in Fig. 3 has evolved from computer studies of the magnetic fields associated with the coupling. These studies have been carried out using a computer code designed at this laboratory for such purposes. Figure 4A shows the results of a computer analysis of the uncoupled condition. The results are tabulated in Table I. A full-scale prototype of the structure has since been built and is being tested. The results of these tests are in a later section.



A. Uncoupled source

B. Coupled source

Fig. 4. Computer generated magnetic flux plots for the source configuration shown in Fig. 3.

Coupled Condition

When a pickup is magnetically coupled to the source, it is necessary to have a reasonably high coupling coefficient between the primary and secondary, good power transfer efficiency, and the capability to transfer power at a sufficiently high level.

TABLE I

Computed Properties of the Inductive Coupling

General

Geometry: See Fig. 3
Frequency: 180 Hz
Design power per passenger car: 20 kW
Source conductor current: 1000 A

Core

Material: Transformer iron, 29 gauge (0.055 mm)
Core thickness at point of maximum flux: 1.65 cm
Unit weight for source and pickup separately: 56 kg/m
Pickup length per passenger car: 1.52 m

Conductor

Material: Aluminum, stranded
Winding slot dimensions: 2.5 x 20 cm
Conductor area: 25 cm^2
Source conductor resistance: 10.9 μΩ/m
Source conductor weight: 7.2 kg/m
Source conductor loss: 10.9 W/m
Resistivity: 2.8 μΩcm
Space factor: 0.5

Magnetic Properties	Uncoupled	Coupled (2.5 cm air gap)
Maximum flux density in core (gauss peak)	544	10,000
Maximum flux density in air gap (gauss peak)	12*	676
Source core loss (W/m)	1.0	191
Pickup core loss (W/m)	---	191
Inductance		
Source self-inductance (μH/m)	1.2	5.7
Pickup self-inductance (μH/m)		6.1
Mutual inductance (μH/m)		5.2

*At a point 20 cm above pole face

The results of a computer study of the coupled condition are shown graphically in Fig. 4 and in numerical form in Table I.

Circuit Model

As shown in Table I, the computer analysis gives values for the equivalent inductances of the coupling. This allows the formulations of circuit models valid for coupled and uncoupled conditions. Fig. 5a, for example, shows the equivalent circuit of an uncoupled length of source. The values of R_{Loss} and Lu are 0.0118 ohms and 1.27 milli henries respectively for a one-kilometer length of source. R_{Loss} represents the sum of conductor and magnetic circuit loss. For a current of 1000A, the idling power losses can be seen to be 11.8 kW.

In Fig. 5b, two vehicles have been added to the circuit. It is readily apparent that the characteristics of the coupling are measurably improved by the addition of the capacitors, C, which compensate for certain inductive parameters of the coupling. The value of C is chosen to approximately resonate at the driving frequency, 180 Hz. Resistors, R_{V1} and R_{V2} represent the variable loads imposed by the two vehicles. If the capacitors are adjusted for resonance, the equivalent impedance presented to the section of source directly under the pickup is simply the transformed resistance in series with the leakage inductance. This is shown in Fig. 5c.

The total loaded source circuit, then is represented by Fig. 5d, where the values of R_T and L_T vary according to the vehicle loading on the highway. It can be seen that the power factor of the source equivalent circuit changes with loading. Under typical conditions, the total impedance of the source,

$$Z_T = \sqrt{R_T2 + 2\pi fL_T2}$$

changes relatively little with loading. Thus the voltage that the power conditioner must supply to maintain the 1000A remains relatively constant.

It is interesting to note that, because a constant current flows in the primary of the equivalent transformer, the value of R_V must be <u>reduced</u> to reduce the power. This is in contrast to situations in which a transformer is driven from a constant voltage.

Prototype Tests

As a second phase in the development of the DMET system, a prototype of the power coupling has been constructed. This is being used to verify some of the basic design concepts and to build a base of data on which to design a test track facility. The prototype is now under test; some preliminary results are presented here.

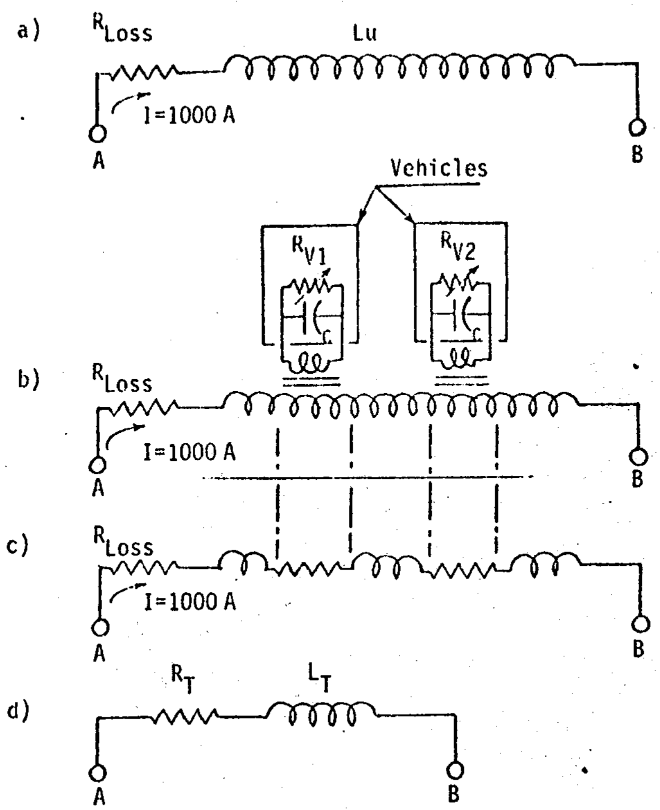


Fig. 5. Development of a simplified equivalent circuit for a source loop. Terminals A and B are driven by the power conditioning equipment.

The prototype test facility includes a 2.3 meter section of source, a 0.8 meter pickup, a source of 180 Hz power and an array of instrumentation for measuring currents, voltages, power, phases and magnetic fields. The facility is shown in Fig. 6.

A schematic of the test connections is shown in Fig. 7. The source loop is excited by a motor generator set capable of generating power over the 150-210 Hz frequency range. The pickup is equipped with a variable capacitor bank to resonate the pickup circuit. It can be loaded either with a resistance load or a circuit to simulate an on-board battery charger circuit.

A cross-section of the prototype power coupling is also shown in Fig. 7. The prototype coupling has been made with a slightly different configuration from that used in the computer analysis. This was done to enhance the tolerance to misalignment of source and pickup over that determined for the model used in the computer analysis.

The tests for which the prototype is intended include the measurement of mechanical forces, electrical characteristics and magnetic fields. A preliminary phase of the testing program has been completed. The results presented here are from part of the data obtained in that work.

Force Measurements

Magnetic structures tend to move in the direction to minimize the energy stored in the magnetic field. Therefore, a vertical force is generated between the pickup and source that tries to reduce the air gap. In addition, horizontal forces are generated whenever the pickup and source are misaligned. It is necessary to insure that these forces are within reason--i.e., of such a magnitude that the handling characteristics of the vehicle are not impaired.

The computer analysis indicated that the forces were reasonable. To verify this, a series of tests was made on the prototype facility. To measure vertical forces the pickup was placed in a tray and hung from a supporting structure. Three force gauges were used to measure these forces at the points of support. Another force gauge is used to measure the horizontal force required to maintain the pickup structure at selected offset positions. Fig. 8 shows some representative results.

Electrical Parameters

For electrical parameters, in addition to the meters shown in the schematic (Fig. 7), current shunts are used at certain key points of the circuit to observe wave forms and phase angles. After first determining the characteristics of the loop without the pickup (not presented here) and some open and short circuited pickup measurements, the equivalent circuit in Fig. 9 can be constructed. The parameter values differ from those presented earlier in Table I because of the different source and pickup geometry. Also, no figures for leakage inductance of the source are given. Because of the end effects of the short section of source used in these tests, it is difficult to make meaningful measurements of this parameter.

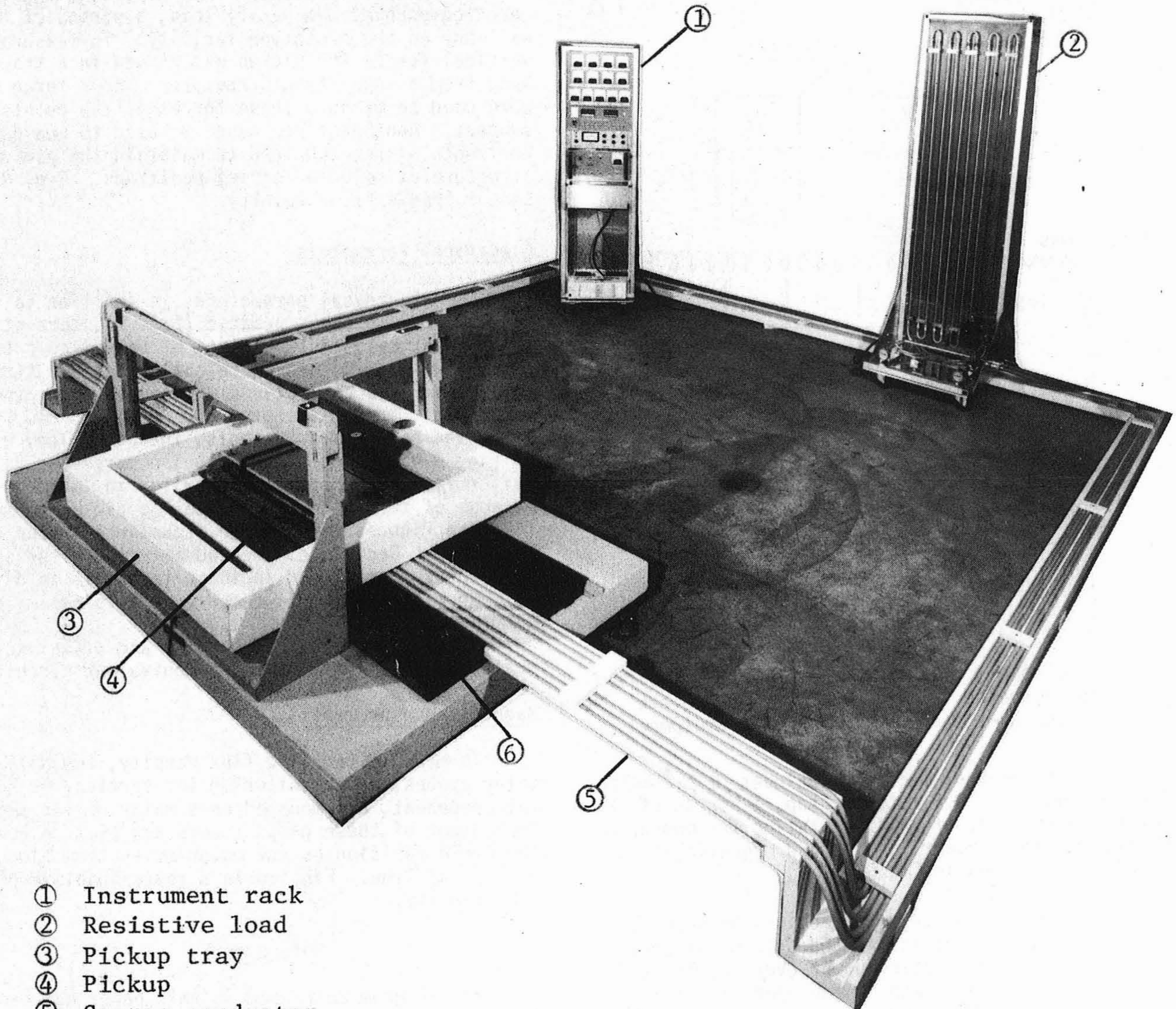
The power coupling character and efficiency is sufficiently described by the equivalent circuit.

Magnetic Measurements

To measure magnetic flux density, two Hall gauss meter probes, each monitoring the vertical or horizontal component, are mounted on a motor driven support. The output of these gauss-meters are plotted against the probe position as the motor moves them along a horizontal line. Fig. 10 is a representative plot of flux density.

Future Work

The program described in this paper has been supported by the Division of Transportation Energy Conservation of the Department of Energy. Development phases subsequent to the completion of the static prototype tests are planned to consist of a dynamic prototype system with a 50 meter source and skeletal electric vehicle. Successful completion of this work would be followed by the construction and testing of a test track system and advanced vehicles, and finally a pilot installation would be made. Work included in these phases includes the development of roadside power conditioners and vehicle power systems, control electronics for vehicles and conditioners, and the investigation of strategies for automatic vehicle guidance and control.



① Instrument rack
② Resistive load
③ Pickup tray
④ Pickup
⑤ Source conductor
⑥ Source core

Fig. 6. Static Power Coupling Prototype (under construction).

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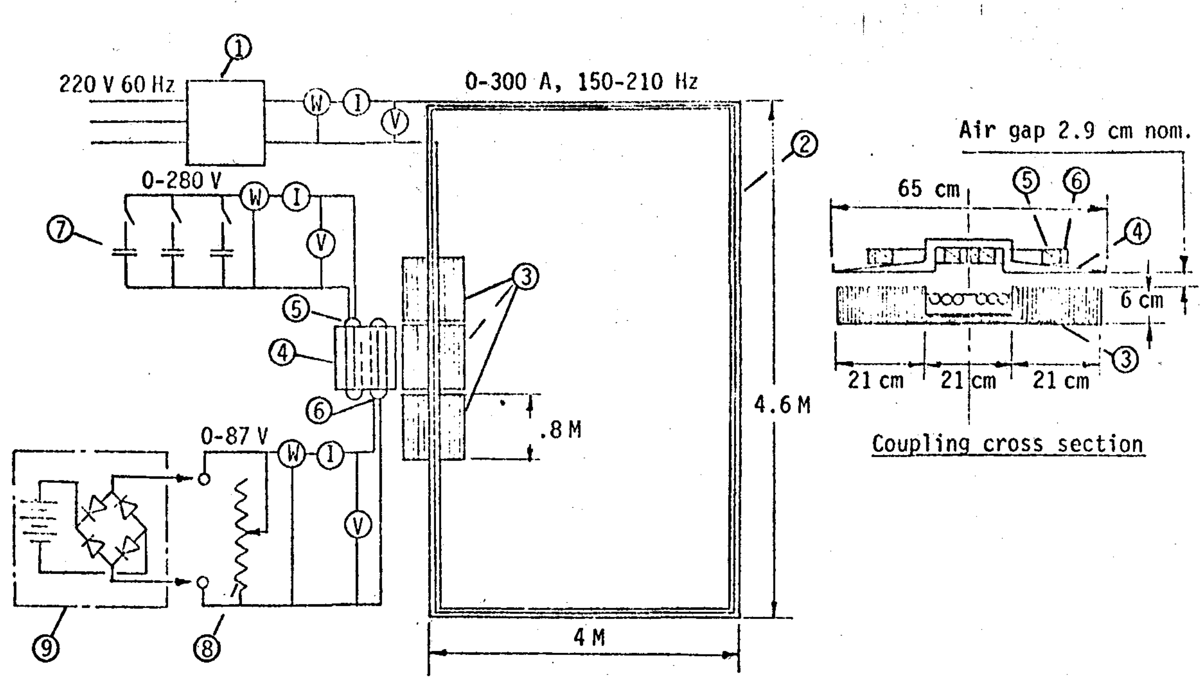

① Motor-generator set with capacitive phase correction and control:
② Three turn loop (2 parallel conductors/turn)
③ Source core
④ Pickup core
⑤ Reactance winding
⑥ Power winding
⑦ Power control capacitors
⑧ Resistive load (water cooled)
⑨ Vehicle energy storage simulator

Fig. 7. Static Prototype Test Facility Schematic.

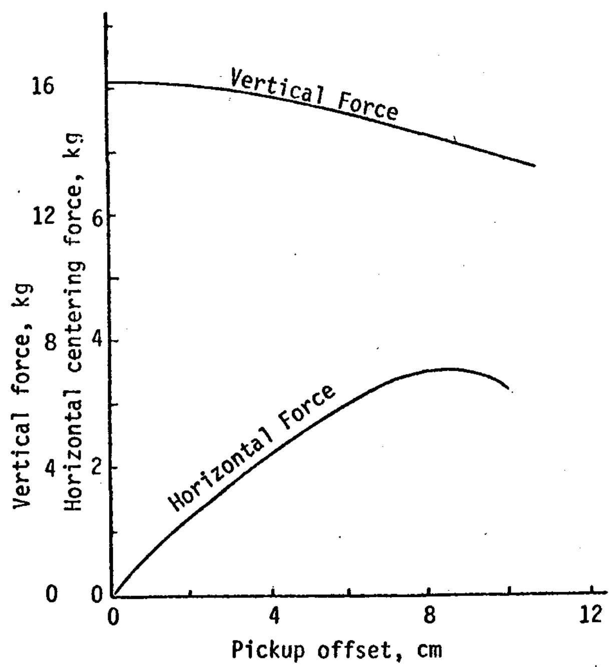

Fig. 8. Magnetic Forces vs. Offset at Rated Voltage.

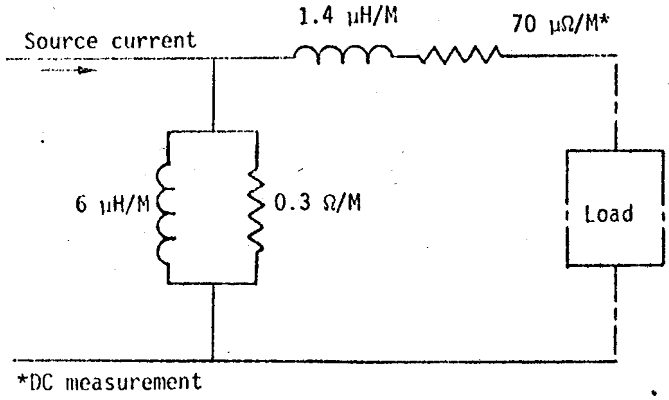

Fig. 9. Equivalent circuit of a prototype coupling normalized to a single turn.

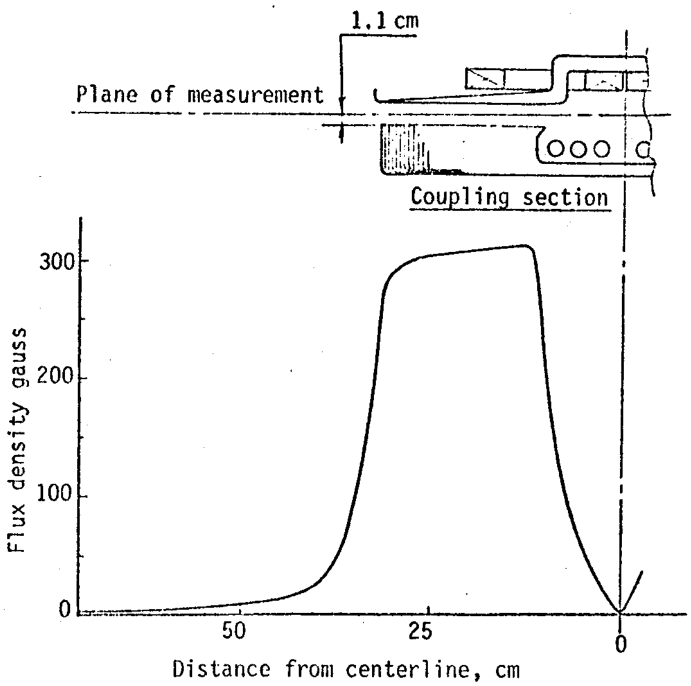

Fig. 10. Magnetic flux plot at 96% voltage output.

Reference

[1] Bolger, J.G., and Kirsten, F.A., Investigation of the Feasibility of a Dual Mode Electric Transportation System, U.S. ERDA Report TID-4500-R65, National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

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