

10kHz INDUCTIVELY COUPLED POWER TRANSFER - CONCEPT AND CONTROL

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ABSTRACT

Electric vehicles are used throughout the materials handling industry because they are low cost, reliable, inoffensive, and simple to control compared to alternative forms of motive power. But conventional methods of power transfer to the vehicle such as electrified tracks and batteries have remained less than ideal; that is until the recent development of a novel inductively coupled power transmission (IPT) system that is clean and spark-free, is robust to dust and water, and has very low maintenance. Load power in an IPT system is sourced at 10kHz from tuned pick-up coils mounted adjacent to, but not touching, a sealed track conductor driven by a resonant power electronic converter. Power transfer of several kilowatts is possible from a single pick-up coil, and multiple pick-ups can be powered from the same track. The paper describes the IPT concept and presents practical control solutions to some important problems.

1. INTRODUCTION

The transfer of "electrical" signals from one frame of reference to another is the basis of many Electrical Engineering systems. In perhaps the majority of such instances the electrical signal itself is not important but the information it contains by way of modulation or the like is, and may be recovered in an appropriate way using independently powered amplifiers. In terms of power transfer efficiency such systems are very poor indeed, but such an efficiency measure is in fact inappropriate for them.

In a very important class of applications however independent power amplification is not possible and the system efficiency in terms of power out/power in is of critical importance. To this class belongs electrical machines such as transformers, motors, generators, and electrified tracks. In some of these, energy is transferred directly by physical contact - for example electrified tracks and commutators/slip-rings in machines; in others it is transferred by magnetic coupling - transformers and induction motors. Such magnetic coupling is very advantageous - it is immune to dirt, dust and the environment, it is spark free, robust and reliable, and machines that use such principles inherit all these highly desirable features.

In these machines - particularly induction motors - power is transferred from the stator of the machine to the rotor (and thence to mechanical output power) by a magnetic interaction between the rotor and the stator. This interaction arises only under specific conditions -

the rotor and the stator must be tightly magnetically coupled with but a small air-gap between them, and the rotor and stator magnetic circuits must be carefully designed for the particular application.

In another class of applications involving robots, moving vehicles, electrified monorail systems, and extending up to electric buses and trains, the advantages of a magnetically coupled system would be considerable but to date such technology has not been available. Some progress has been made with linear induction motors but the track (stator) costs are extremely high while in other applications magnetic levitation with or without superconducting magnets offers great potential for high speed trains.

There are a number of features that make the inductive coupling of power from a stationary track/rail to a moving vehicle difficult. In practical situations any longitudinal motion - especially at higher speeds - is always accompanied by small - largely unpredictable - lateral movements. Also a vehicle may be quite small while the track it operates on may be very extensive so that the cost per metre of track is critical to the economic viability of the project. The combination of these features means that the coupling factor between the track and vehicle must necessarily be quite small and to allow for lateral movement there must be a considerable air-gap between the track conductors and the pick-up system on the vehicle. Also, while the vehicle may justifiably use magnetically permeable material to enhance its coupling to the track such a luxury is usually not viable for the track itself.

In a practical situation a track for an electrified monorail system may be 100 metres long while the active pick-up length per vehicle may be ~30cm so that the maximum possible coupling coefficient (equivalent to mutual inductance) between the two is ~0.3%. This figure compares with transformer coupling factors of ~95-98% and induction motors of ~92%. The figure of 0.3% also assumes perfect coupling of the magnetic systems in the immediate vicinity of the vehicle and, as outlined above, with a low cost track a much lower coupling coefficient ~0.1% is to be expected.

From an electrical engineering point of view the voltage V coupled from a current-carrying wire on a track to a moving vehicle is given by

$$V \propto \omega M I_1 \quad (1)$$

where M is the mutual inductance between the track and vehicle magnetic circuits, I_1 is the current in the track,

and ω is its angular frequency. Since M is necessarily small, techniques for increasing the coupled voltage are to increase ω and/or to increase I_1 .

This paper describes a practical inductively coupled power transmission system which has been implemented in both electrified monorail systems and in "battery-less" automatic guided vehicles (AGV's). The paper covers the elements of this technology and aspects of its control.

2. ELEMENTS OF AN IPT SYSTEM

Following the argument in the Introduction, an IPT system may be constructed as shown in Fig. 1 [1, 2, 3]. It comprises essentially of two independent electrical systems with mutual coupling between them. The track system takes power from a conventional three-phase mains supply to generate a high frequency current in the track magnetic circuit. This magnetic circuit is coupled to the vehicle system and the voltage (power) transferred to the vehicle is then conditioned to produce a stable supply on the vehicle capable of driving travelling motors and/or other vehicle electronic systems as required in particular applications.

thus the short circuit current I_{sc} (maximum possible real current) is

$$I_{sc} = \frac{j\omega M I_1}{j\omega L_2} = I_1 \left(\frac{M}{L_2} \right) \quad - (3)$$

while the output or load voltage is

$$V_2 = j\omega M I_1 Q_2 \quad - (4)$$

where Q_2 is the quality factor of the tuned circuit with effective load represented by resistor R_2 . The potential volt x ampere capacity for the system is therefore

$$VA = V \times I_{sc} = j \left(\frac{I_1^2 M^2 Q_2 \omega}{L_2} \right) \quad - (5)$$

so that the highest possible power transfer will be achieved for the highest value of

$$\left(\frac{I_1^2 M^2 Q_2 \omega}{L_2} \right).$$

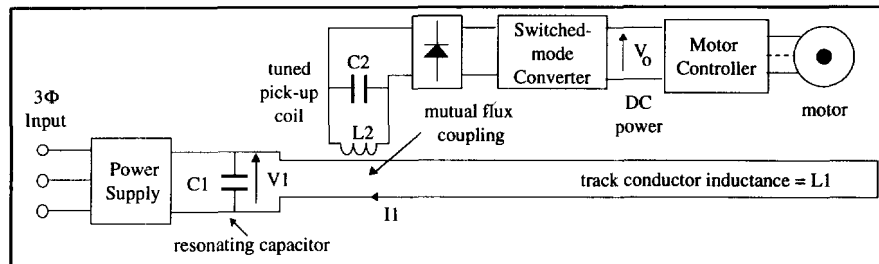


Fig. 1 - A tuned IPT system.

A number of factors are apparent in the conceptualisation of such systems. Firstly since a high frequency is advantageous the track current is best generated by power electronic circuitry to minimise noise and weight, and to improve the reliability. Secondly to minimise RF emissions the track current should be as sinusoidal as possible. In a practical system these two characteristics are implemented using a resonant power electronic converter producing a sinusoidal current in the track. Furthermore, since the reactive part of the track current (the largest part) simply circulates in a resonating capacitor only the real power must be supplied by the power electronics so that the system losses are small.

The resonant system operates at essentially constant frequency - here a frequency of 10kHz has been chosen - and advantageously the vehicle system can also be tuned to the same frequency. A simple relationship for the potential power transfer may now be developed using the conceptual circuit of Fig. 2. The induced internal emf in the vehicle coil is given by

$$V = j\omega M I_1 \quad - (2)$$

In a practical system the values of M and L_2 are largely fixed at the best that the system designer can achieve - note though that higher M values due to more magnetic material in the track are highly advantageous - so that the product to be maximised is $(\omega I_1^2 Q_2)$.

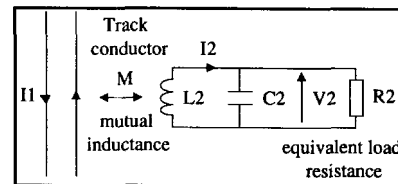


Fig. 2 - Tuned pick-up circuit.

In practice, values of $Q_2 > 10$ are not sensible in Engineering power systems as they are too sensitive to minor variations in components, so that the best designs have the highest possible ωI_1^2 . In the systems used here ω corresponds to 10kHz. At this frequency a Q of 5-10 is easily achieved and capacitors, transistors and the like operate with negligible derating. At higher

frequency the component cost increases for a given power level as the power electronics costs increase. At lower frequencies the current I_1 must be larger hence the cost of the copper in the track increases and thus the capacitance needed to tune the track (and the vehicles) increases. These considerations seem to produce an optimum at ~10kHz, but at this frequency the track conductors must be Litz wire - in the system discussed in section 4 10,250 strands of individually insulated 40AWG wire are used for each 50mm squared conductor.

3. CONTROL OF AN IPT SYSTEM

3.1 10kHz power control

The inductive transmission track is ideally driven from a constant sinusoidal current source having low RFI and high efficiency. To achieve this, two parallel resonant dc-ac converter topologies have been developed - one for operating directly off 200V three-phase utility supplies, and one for 400V supplies. In the case of the former the push-pull topology shown schematically in Fig. 3 is used. Here the ac utility supply is first rectified then filtered to produce a smooth dc voltage bus. Transistors S1+ and S2- provide transient control of the resulting output voltage by limiting the current I_d in the dc link to the resonant part. They also provide current limiting in the event of an overload, transient, or track fault to ground. Transistors S3- and S4- are switched with complementary 180° conduction at the ringing frequency of the circuit formed by the track inductance L_1 and primary tuning capacitance C_1 . The natural resonant frequency of this parallel pair is chosen to correspond to 10kHz and is calculated from

$$\omega_o = \frac{1}{\sqrt{L_1 C_1}} \quad - (6)$$

The switching action produces a very pure sine wave voltage across the track with very low harmonic distortion. Moreover, because the transistors switch on and off at voltage zero crossings RF interference is virtually non-existent and the converter operation is very efficient. The zero voltage switching and resulting high spectral purity are clearly visible in Fig. 4, which shows a typical voltage waveform across one of the switching transistors. For the converter in Fig. 3 the 10kHz rms voltage produced across the track is given by

$$V_1 = 3V_{ll} \quad - (7)$$

where V_{ll} is the rms line to line voltage of the utility supply. The peak voltage across the switching transistors is then

$$\hat{V}_{ce} = \sqrt{2} V_1 \quad - (8)$$

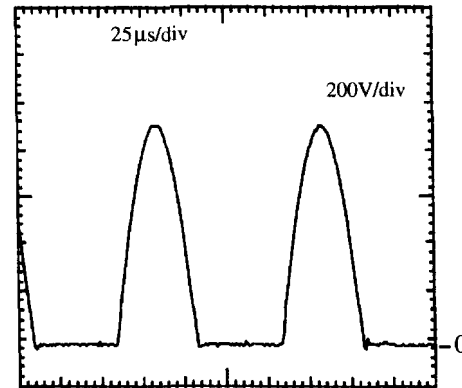


Fig. 4 - Transistor switching voltage V_{ce} .

This is well within the capability of commercially available 1200V IGBT devices, but under transient excursions is more safely coped with using the latest generation of 1600V devices. Assuming large dc link inductance L_d , the required peak current rating of the IGBT's is determined from the dc link current I_d under maximum load conditions, and is given by

$$I_d = \frac{\pi P_1}{3\zeta_1 \sqrt{2} V_{ll}} \quad - (9)$$

where P_1 is the total real power supplied by the converter, and ζ_1 is the 10kHz power supply efficiency which is typically about 0.95.

To maintain a fairly constant current the track is operated with a quality factor $Q_1 \geq 3$ under maximum load conditions; that is the ratio of reactive power to real power in the track is greater than about 3:1. Fig. 5

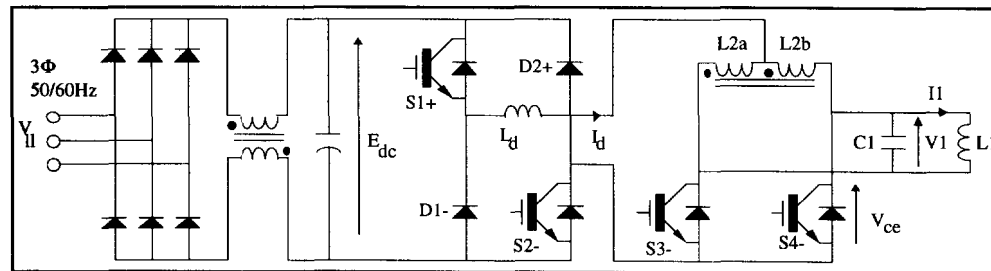


Fig. 3 - Push-pull parallel resonant IPT power supply .

depicts using phasors how this restricts the steady-state track current to vary by less than 5% from no load to maximum load.

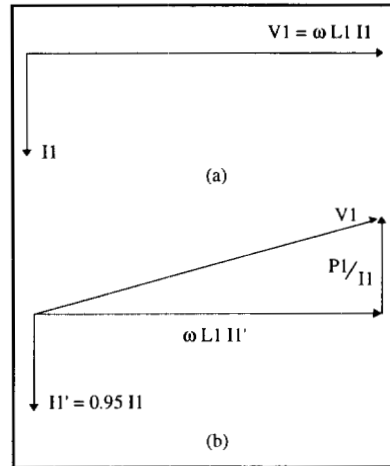


Fig. 5 - Phasor representation of track operation. a) No load, b) Maximum load.

Owing to the current source nature of the dc into the resonant converter, sudden load changes can cause transients in the track voltage and track current. Current transients can be a source of interference to communication systems, while voltage transients caused by load removal can compromise the reliability of the system. These transients may be reduced by incorporating a simple damping controller like that shown in Fig. 6. This circuit uses the quadrature relationship between the track voltage and current to generate a dc measure of the track current magnitude. If the current (plus some derivative) exceeds some maximum then the two current limiting IGBT's are switched off to limit additional energy being fed into the resonant stage. Fig. 7 shows a typical voltage transient (combined IGBT collector emitter voltages) caused by the sudden removal of load, (a) without the damping control, and (b) with the damping control. Clearly it is very effective.

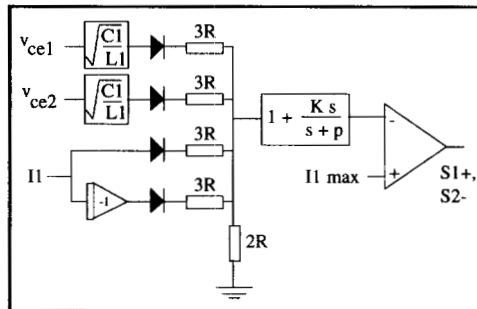


Fig. 6 - Transient damping controller.

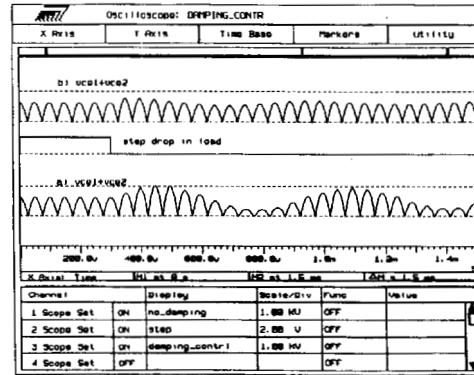


Fig. 7 - Simulated effect of damping controller, a) without control, b) with control.

3.2 Pick-up power control

The pick-ups in an IPT system consist of several turns of Litz wire wound around a ferrite core that concentrates the 10kHz flux into a smaller volume. Fig. 8 shows a cross-sectional view of the type of pick-up used in overhead monorail applications. Comparatively good coupling between the pick-up and the track is possible in this application while still providing up to ± 5 mm lateral displacement.

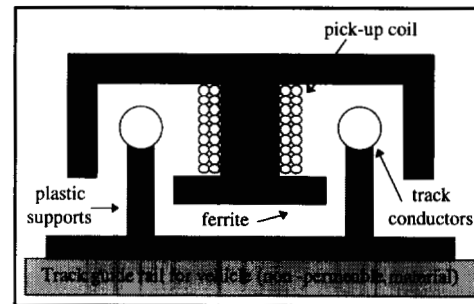


Fig. 8 - Monorail style pick-up.

However, while good coupling increases the output power, in a double tuned system it also poses some serious implications. Consider the referred circuit model shown in Fig. 9, where the series equivalent impedance $Z2$ of the pick-up secondary side is given by (10). From the referred model it is clear that high values of $Q2$ caused by "lightly" loaded pick-ups will reflect a large impedance back into the track. This will dramatically reduce the track current thereby effectively blocking power to other pick-ups on the system. In addition, high values of $Q2$ can result in dangerously high output voltages that may damage components.

$$Z2 = \frac{1}{\omega C2 Q2} + j \left(\omega L2 - \frac{1}{\omega C2} \right) \quad - (10)$$

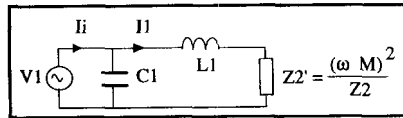


Fig. 9 - Referred coupled model.

A novel method for regulating the output voltage and preventing the power blocking effect is shown schematically in Fig. 10. The rectified output of the tuned pick-up coil is connected to a Boost dc-dc converter topology which is switched to maintain a regulated dc output voltage with high ripple content. A hysteresis control strategy is adopted in which the transistor is turned on if the output dc voltage V_o exceeds an upper limit, and is turned off if the voltage falls below a lower limit. The switching rate of the transistor is generally kept below about 10Hz since appreciable energy in the tuned pick-up is dissipated every time the transistor is switched on. To keep below this rate a $\pm 5\%$ hysteresis level is typically employed, and additional capacitance is placed across the dc output. At light loads the pick-up coil is shorted by the transistor a higher percentage of the time thus effectively decoupling it from the track and preventing it from interfering with other pick-ups in the system.

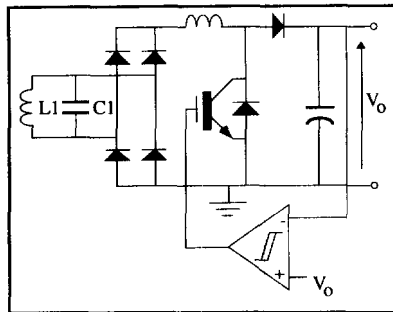


Fig. 10 - Pick-up coil power controller.

3.3 Frequency control

The resonant converter driving the track is allowed to operate at the ringing frequency of the system, given by (11), in order to maximise its efficiency.

$$\omega = \omega_o \sqrt{1 - \left(\frac{1}{2Q1}\right)^2} \quad - (11)$$

At this frequency the applied track voltage $V1$ and the equivalent input current Ii (Fig. 9) are always in phase and maximum power is transferred via the pick-up. An analytical analysis of the circuit in Fig. 9 however, reveals that multiple zero phase conditions occur if the system is over-coupled. Mathematically it can be shown that this condition corresponds to equation (12), where N = the number of coupled tuned pick-up coils in the IPT system.

$$Q2^2 \geq \frac{L1 L2}{NM^2} \quad - (12)$$

For the system data contained in section 4, equation (12) predicts that multiple zero phase angle conditions should start to occur when $N > 6$. A SPICE simulation of the model, shown in Fig. 11, confirms this result. Under these conditions the nominal 10.2kHz operating point becomes unstable and only the frequencies corresponding to the two side zero crossings are valid. Since the output voltage at these two frequencies is clearly less than at the centre frequency, the maximum power that can be coupled is significantly reduced. This phenomenon imposes a serious limitation to the number of pick-ups that can be coupled.

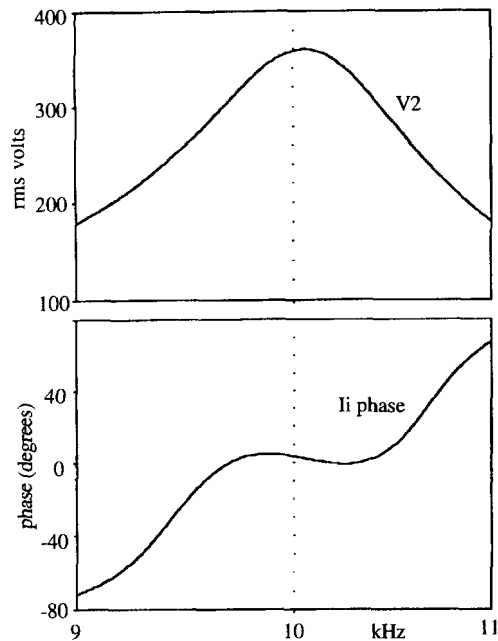


Fig. 11 - Pick-up frequency response with $N = 7$.

Fortunately, a second novel method has been developed which extends the number of pick-ups that can be coupled. By switching in and out extra capacitance across the track it is possible to force the track frequency to be astable about the centre frequency ω_o while still giving fixed frequency performance. A simple circuit for achieving this bang-bang form of control is shown in Fig. 12. Two additional IGBT's are gated to switch in or out about 10-15% of the total track tuning capacitance. Switching out this capacitance if the frequency detunes to a low frequency causes the frequency to move to a stable point above ω_o . Switching in the capacitance when the frequency is higher than ω_o shifts the frequency to a stable low point. In this way the frequency can be forced about the nominal centre frequency ω_o . An added advantage of this method is that it breaks up the standing wave patterns produced by the

10kHz sound, and makes the emitted noise sound subjectively better.

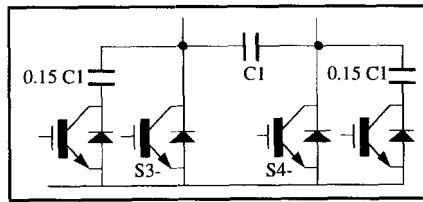


Fig. 12 - Frequency controller.

4. EXPERIMENTAL RESULTS

To practically demonstrate the control techniques described in this paper, an IPT system having ten 600W pick-up coils and operated off a reduced voltage mains supply was constructed. The system parameters are listed in Table 1.

Ac mains supply voltage	V_{ll}	140V
Dc bus voltage	E_{dc}	190V
Track conductor spacing	w	70mm
Track inductance	$L1$	123 μ H
Track length	$l1$	120m
Track current	$I1$	54A
Track voltage	$V1$	422V
Track capacitance	$C1$	2.0 μ F
Nominal track frequency	ω_0	10.2kHz
Number of pick-ups	N	10
Pick-up self inductance	$L2$	634 μ H
Pick-up tuning capacitance	$C2$	0.38 μ F
Equivalent load resistance	$R2$	185 Ω
Mutual inductance	M	24 μ H
Pick-up regulating voltage	V_0	300V

Table 1 - Prototype IPT system data.

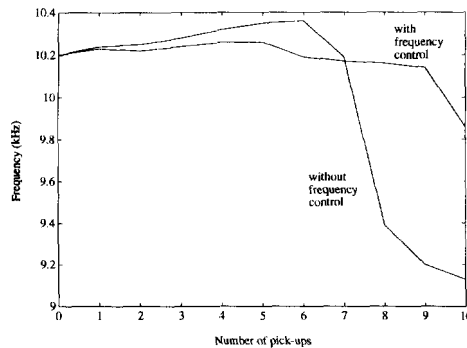


Fig. 13 - Effect of frequency control.

As predicted by equation (12) and illustrated in Fig. 13, significant detuning occurred at about $N=7$ without frequency control. A consequence of this is the output power drops by 30%. However, with active frequency control no such drop occurs since the system frequency

remains fairly constant across the whole load range. Measurements of the system efficiency were also taken. Fig. 14 indicates that at full load the IPT system efficiency is about 75%. Since losses in the track caused by $I1$ remain relatively fixed the efficiency falls off as the number of loads reduce.

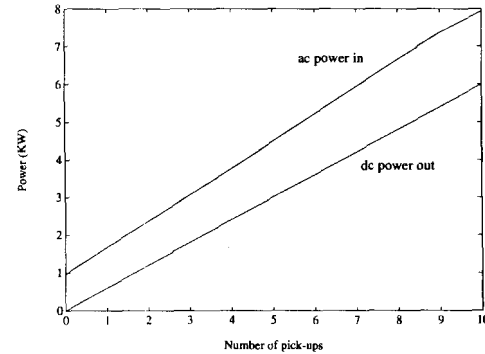


Fig. 14 - Input and output power of an IPT system.

5. CONCLUSIONS

Inductively coupled Power Transmission (IPT) is set to revolutionise the materials handling and transportation industries. Clean, spark free, environmentally benign, low maintenance power transfer to moving electric vehicles has long been sought after by engineers and is here now in the form of IPT. In the embodiment described here IPT is a tuned coupled system that inherits some interesting control problems. Most notably the power blocking and frequency detuning caused by "lightly" loaded pick-ups. Novel power electronic control solutions that overcome these have been described and practically demonstrated. The technology described in this paper is patented and the licensee's include Daifuku Co., Ltd., Osaka, Japan, and Auckland Uniservices, University of Auckland, New Zealand.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

- [1] Boys, J.T., and Green, A.W.: "Inductively coupled power transmission - concept, design, and application", IPENZ Conf., Nelson, 1994, Vol. II, pp. 254-259.
- [2] Klontz, K.W., Divan, D.M., Novotny, D.W., and Lorenz, R.D.: "Contactless power delivery system for mining applications", IEEE Industry App. Soc. Ann. Meeting, 1991, Vol II, pp. 1263-1269.
- [3] Green, A.W., and Boys, J.T.: "An inductively coupled high-frequency power system for materials handling application", IPEC Conf., Singapore, 1993, Vol. II, pp. 821 - 826.