# AN ULTRA-COMPACT TRANSFORMER FOR A 100 W TO 120 kW INDUCTIVE COUPLER FOR ELECTRIC VEHICLE BATTERY CHARGING

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**Abstract - A new generation of electric vehicles is being developed. A key problem to be solved is that of charging the batteries. One means of charging uses inductive coupling. The inductive coupling approach is essentially a transformer with a removable primary winding connected to a charging unit via a cable. The secondary and the core of the transformer are on the vehicle.**

**This paper presents an inductive coupler which has been demonstrated delivering from 100 W to 120 kW continuously at a frequency of 75 to 120 kHz. The transformer is very compact (<100 in$^3$). The primary purpose of this paper is a discussion of the power transformer. In addition the paper briefly addresses how the design of a magnetic device, which is usually a strictly technical exercise between engineers, is impacted when it is directly accessible to consumers in a mass market.**

## I. INTRODUCTION

A new generation of electric vehicles is being developed by many different organizations in the world. One of the key problems which has to be solved for all of these vehicles is that of charging the batteries which form the energy reservoir. Charge powers vary from 100 W to over 100 kW. Three general means are available to connect to the vehicle: Direct conductive coupling (a plug), capacitive coupling and galvanically isolated, inductive coupling (a transformer). Of these three only conductive and inductive coupling are currently in an advanced development stage.

The inductive coupling approach is essentially a transformer with a removable primary winding. The primary winding is connected to the charging unit via a cable. The secondary and the core of the transformer are on the vehicle. The transformer primary takes the form of an insulated disk with a handle which is referred to as the "paddle".

Besides operating efficiently over a wide range of powers, the coupler is subject to a number of severe constraints associated with a consumer automotive application. The following are a few examples:

1. Like the ubiquitous gasoline nozzle, the charge port of an electric vehicle must have a universal, world-wide standard which is used by all vehicle and charger manufacturers. To be widely accepted there cannot be any built-in limitations to the charge power. For that reason, even though there are at present few, if any, applications which require charging powers above 25 kW, much higher power capability had to be demonstrated now to assure that the adopted standard does not create a bottleneck at some future time. In addition the basic design must be as simple, foolproof and economical as possible. It must also be suitable for reproduction in tens of millions of units.

2. The automotive environment is notoriously harsh. High and low temperature extremes, high shock and vibration and exposure to dirt and liquids ranging from sea water, to solvents, to mud. All of these must be accommodated over a long service life and at very low cost.

3. The charge port and the charge paddle are directly accessible to the consumer. There must be no shock hazard, even if the customer is standing knee deep in water. In addition to the shock hazard there are limits on temperature for any surface that the consumer might come in contact with. For handles and other surfaces which the user might grasp the limit is 60° C for plastic and 50° for metal - per UL-Subject 2202. Casual contact surfaces can be somewhat warmer. This limitation is of particular importance when attempting to run at high power and high flux levels.

4. Besides the obvious shock and temperature hazards there are a number of other safety concerns. In use, it is very likely that objects other than the charge paddle will be inserted into the port. For example, a child could insert its hand and arm into the port. The child must not be injured! Besides an arm, the child may very well insert other objects such

as toys, pets, rocks, etc, into the port. All of these objects must not damage the port and be readily removable to restore normal operation.

5. The charging will be performed by people with a wide range of physical capabilities, from young children to the elderly. This imposes severe limits on the size and weight of the cable and charge paddle. The cable from the charger to the vehicle must be flexible even when filled with pressurized coolant.

These constraints go well beyond the norm for transformer design and made the design very challenging.

## II. CHARGE CIRCUIT DESCRIPTION

Figure 1 is a simplified schematic of an inductive charge system. The charger is connected to the utility and is generally fixed in place (small portable units are possible). The transformer primary, with an attached cable, is inserted into the charge port which contains the rest of the transformer (core and secondary) and the rectifier filter assembly which converts the AC input to a DC charge current. The battery charge state and control functions are on board the vehicle. A communications link is provided back through the paddle-cable assembly to control the charger. Additionally, interlocking is provided to prevent charger activation unless the paddle is properly engaged.

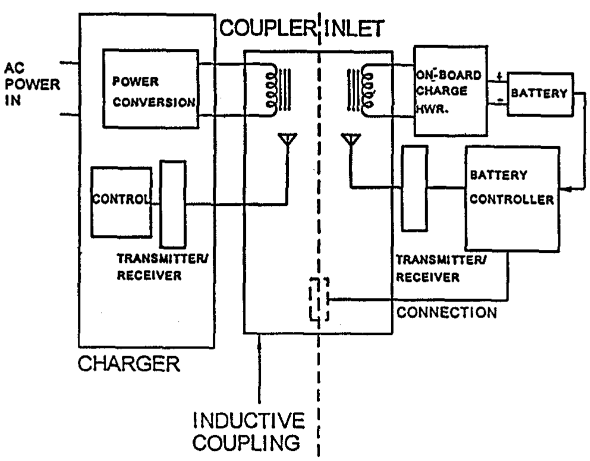


Figure 1. Inductive charge system

The heart of the system is the transformer and its design is the primary subject of this paper. The description given is intended to illustrate the problems and possibilities associated with high power, high frequency operation of a ferrite core transformer. Electric vehicle battery charging is only one of many possible applications for compact high power transformers.

## III. THE CHARGE PORT

Figure 2 is cutaway drawing of the charge port assembly and the paddle. The paddle shown in this figure is for low power charging (<25 kW). The more robust paddle for 120 kW operation is shown in figure 3. The port design must accommodate a wide range of paddle designs for different power levels and frequencies.

The port is designed to have no moving parts other than the paddle. This increases the ruggedness and longevity.

The paddle contains the primary winding and a disk of ferrite core material (the puck). One of the problems associated with a removable primary is maintaining reasonable magnetizing inductance since there must be an air gap on each side of the paddle which is made larger by the need to fully encapsulate the primary for safety reasons. The puck is placed in the center of the primary to minimize the air gap reluctance. This is very effective but has the undesirable effect of adding power dissipation to the paddle. Because the puck is completely insulated removing the heat from it is a problem. Minimizing the air gap also reduces the stray field from the gap which could create eddy current losses in the windings. The location of the gaps, in relation to the windings, is an important consideration[1] because there will be a magnetic field near the air gaps. This field can induce eddy currents in nearby windings which can lead to greatly increased winding loss. A more detailed discussion of air gap fields and winding losses is given in [1].

Approximately half of the charge port is taken up by the transformer, with its windings and cooling arrangements. The rest of the port is occupied by the rectifier-filter assembly. The cooling arrangement in figure 2 uses forced air from two fans on the rear of the unit. For high power charging, liquid cooling was used.

Normally a transformer will be designed for minimum total loss at full power. This usually (but not always!) occurs for core loss-copper loss ratios in the range of .3 to 1.5. Because of the large charge power variation and the very limited volume available for the transformer the usual copper loss-core loss optimization did not apply. At low power levels the loss is almost entirely core loss.

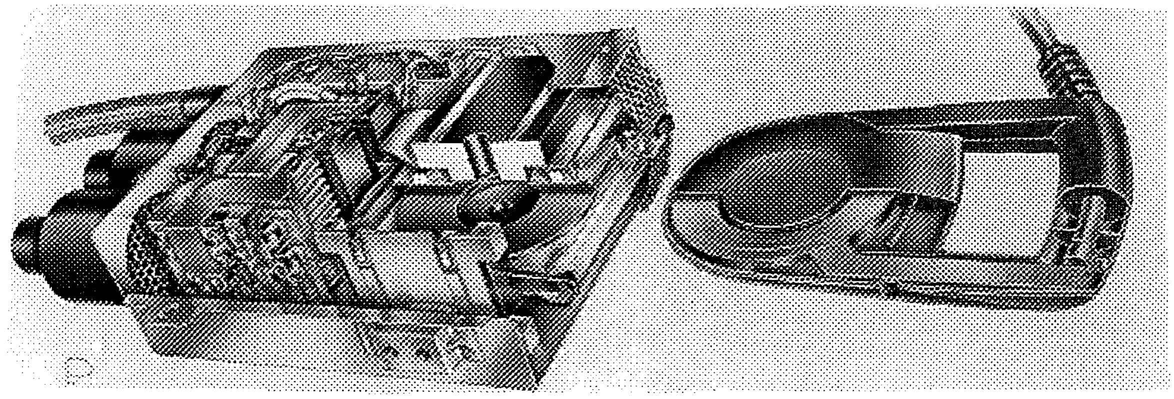

Figure 2. Charge port example

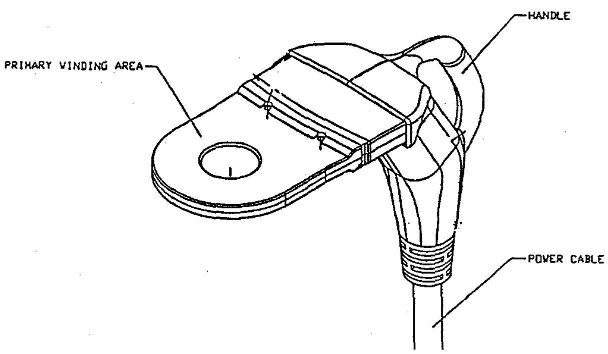


Figure 3. High power paddle.

The copper contributes little to the loss. In a low power charging mode as much power as possible must be used for actually charging the battery and the core loss must be kept low. The core loss is essentially independent of power level for a given number of windings turns and output voltage. To keep the core loss down and to increase the magnetizing inductance the turns were increased. This of course conflicts with the effort to minimize copper loss at high power levels. Although, in theory, the magnetizing current is reactive and therefor lossless, in practice magnetizing current increases current in the primary winding, the cable, the reactive components and the switches in the inverter. All of this increases loss which is not acceptable during low power operation.

At high power levels the core loss is relatively low and the total loss is dominated by the winding loss. The charge current is limited by the loss in the windings, the means available to remove heat and the allowable temperature rise.

## IV. CORE DESCRIPTION

The transformer core was fabricated from MnZn ferrite. Other materials were considered but none gave the very low losses characteristic of ferrite. The shape of the core is shown in figure 4. The core is basically an E-E, with a round center leg[2]. Compared to a traditional 120 kW transformer, the

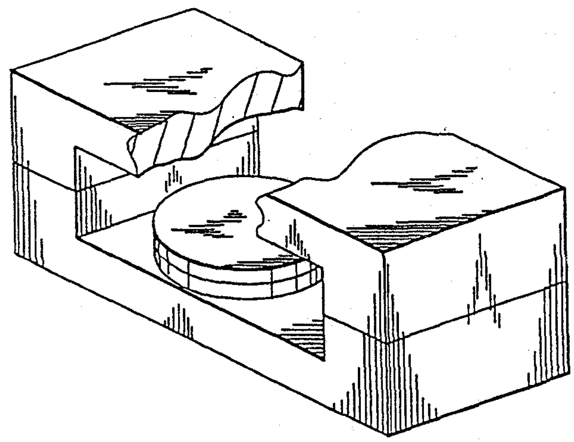

Figure 4. Core geometry.

high frequency ferrite core is tiny. However, when compared to commercial ferrite cores in common use for power electronics, the core is much larger than normal.

### A. Core fabrication

The size of the core presents a number of fabrication difficulties. There are three ways in which this core could be manufactured:

1. Machining from a block.
2. Assembly from smaller pieces glued together.
3. Direct pressing using custom dies.

Initial cores were machined from blocks of ferrite. This provided sample cores relatively quickly for electrical testing. However, this approach is much too expensive for volume production. There is also the problem of changing magnetic characteristics when extensive machining is performed on the ferrite. This is particularly a problem with low loss, high resistivity materials.

Core assembly from smaller ferrite pieces has several advantages. It is less expensive than direct machining, wastes less material, uses small simple shapes and provides the opportunity to use different materials in different places in the core. For example, the outer arms of the E-E core have a large surface area which is exposed to air flow for cooling. In these areas a lossier but lower cost material could be used. The center leg is much less accessible to cooling, being buried within the windings. The ferrite puck is especially isolated. These parts of the core can be made from more expensive, lower loss materials. Another possible advantage to piece-wise assembly is the ability to create optimized core shapes which may not be suitable for pressing.

There are of course disadvantages to piecewise assembly. Additional air gaps are introduced. In this application the small air gaps introduced from using multiple pieces were not a serious concern because of the large and unavoidable gap in the center leg. In other applications this might not be true. There is the problem of extensive handling during assembly which can lead to chipping, misalignment and increased cost.

Despite advantages, this approach is still too expensive for volume production but might be suitable for low volume military applications for example.

Producing cores of this size using standard industry technology presents a number of problems. A core of this size requires a very large press, larger than those commonly in use. Because substantial shrinkage during manufacturing is inherent in the process, maintaining dimensional tolerances is difficult. There are also problems with cracking and warping in such large cores. Die costs are very high and can be justified only for large volumes. These problems are being solved but considerable effort has been necessary. Large scale production of very large ferrite cores, while certainly practical, is still a developing technology.

**B. Non-Uniform flux distribution**

In the small cores typically used for power conversion it is usually assumed that the flux distribution is uniform in any given cross section. While this is not strictly true the consequences of this assumption are usually minor. In a very large core the flux distribution is anything but uniform and does have significant consequences. The primary concern is the increase in losses and the concentration of losses in areas which are difficult to cool. There are several causes for non-uniform flux distribution:

1. Geometric effects.
2. Eddy current effects.
3. Electromagnetic (E-M) or dimensional resonance.

It is well known that in any practical core the effective path lengths will vary for different parts of the core. With a constant MMF applied this leads to different flux densities in different regions even if the cross sectional areas are equal. There will also be flux crowding around inside corners. None of this is any great mystery and these effects are present in cores of any size. Eddy currents and E-M resonance on the other hand are sensitive to core size becoming much more noticeable as core dimensions are scaled up.

We normally think about skin effect in the context of high frequency conductors where the skin depth is expressed by:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \qquad (1)$$

Where:
$\delta$ = the skin depth
$\rho$ = material resistivity in Ohm - meters
$\omega$ = $2\pi$ x frequency
$\mu$ = absolute permeability ($\mu_r$ x $4\pi 10^{-7}$ H/m)
$\mu_r$ = relative permeability

Inherent in the derivation of (1) is the assumption that displacement currents (D) can be ignored. In a good conductor that is a reasonable assumption. However, most ferrites are not very good conductors and (1) must be modified to take into account displacement currents especially for higher resistivities:

$$\delta = \left[\sqrt{\frac{2\rho}{\omega\mu}}\right] \bullet \left[\sqrt{(\omega\varepsilon\rho)^2 + 1} - \omega\varepsilon\rho\right]^{-1/2} \qquad (2)$$

Where:
$\varepsilon$ = absolute permitivity ($\varepsilon_r \times 8.854 \times 10^{-12}$ F/m)
$\varepsilon_r$ = relative permitivity
Note that (2) is in the form of (1) x a correction factor. The correction factor is close to 1 for resistivities below 10 $\Omega$-cm. For higher resistivities it becomes more important. In MnZn ferrites:
$\rho$ = .1 to 1000 Ohm - cm
$\mu_r = 10^3$ to $10^4$
$\varepsilon_r = 5 \times 10^4$ to $5 \times 10^5$

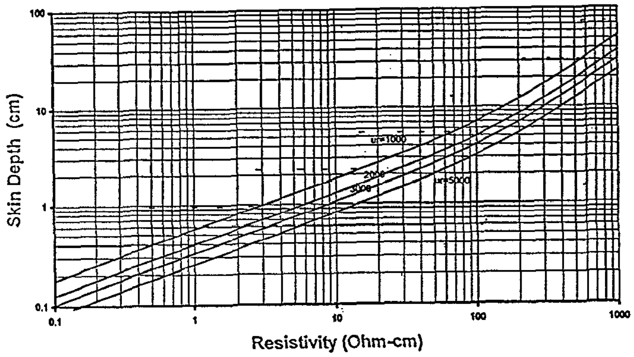

Figure 5. 80 kHz skin depth in MnZn ferrite.

A typical graph of (2) for $\varepsilon_r = 10^5$ and several values of $\mu_r$ is given in figure 5. Note that for $\rho < 10$ Ohm-cm, the skin depth is about 1 cm or less. The center leg in this core is about 5 cm in diameter and the rectangular portions of the core are about 2 cm thick. As a result the core is definitely large enough to have non-uniform flux distributions due to skin effect. It should also be kept in mind that while the DC resistivity, as given in a data sheet, may be higher than 10 Ohm-cm, resistivity can drop rapidly with increased temperature[3], frequency[3] and flux density.

In a large ferrite core flux distribution can be visualized by using finite element modeling (FEM) software. Figure 6 shows the flux density variation from the center to the outside of a 2" diameter center leg at 1 kHz (6a) and 80 kHz (6b). In both cases the excitation is 10 A-turns, with a sinusoidal waveform. Note how much less flux penetration there is at 80 kHz, due primarily to skin effect! Note also in figure 6b that in some areas the flux direction is reversed. This flux plot looks very much like the classical current distribution in a round conductor at high frequencies. In a transformer where the total flux is fixed by the winding voltage amplitude and waveform and the number of turns, the reduction of flux in one area requires an increase in another. This can lead to substantially higher losses, the creation of hot spots and even localized magnetic saturation.

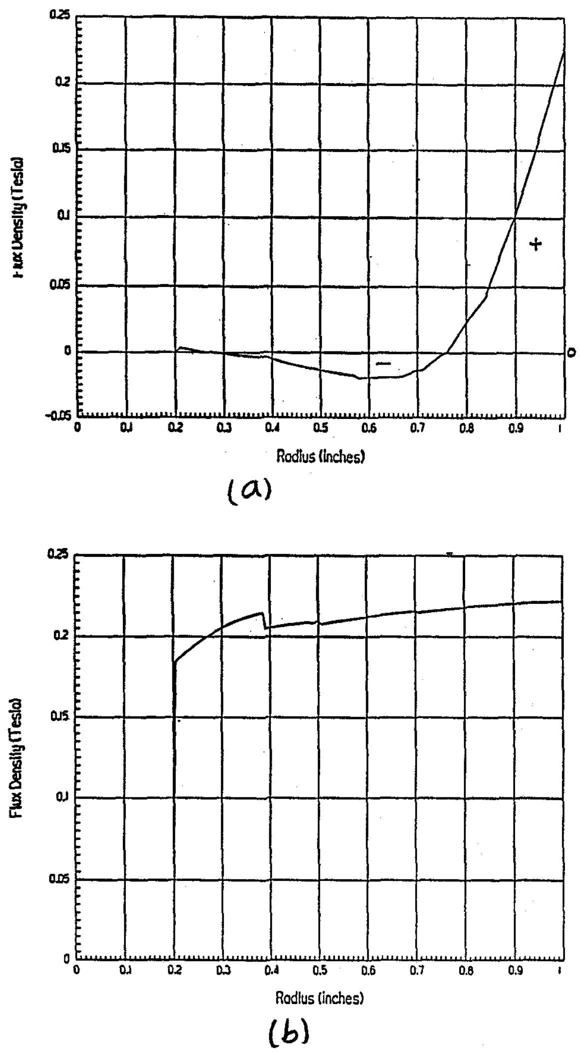

Figure 6. Flux density. (a) 1kHz, (b) 80kHz

Another effect which is possible in cores of this size is dimensional resonance. The wavelength ($\lambda$) in an isotropic material is:

$$\lambda = \frac{V}{f_s} = \frac{C}{f_s\sqrt{\mu_r\sqrt{\varepsilon_r^2 + \left(1/\rho\omega\varepsilon_o\right)^2}}} \quad (3)$$

Where C= speed of light, $\approx 3 \times 10^8$ m/sec

Resonance can occur when the minimum dimension, perpendicular to the flux, is $\geq\lambda/2$. One way to visualize the resonant modes is to view the core as equivalent to an unterminated waveguide or a cavity resonator. In a waveguide the cutoff frequency is determined by the minimum dimension perpendicular to the power flow. Like a waveguide or a cavity, multiple modes and standing wave patterns are possible as the excitation frequency is raised above cutoff. A graph of (3) is given in figure 7 for $\varepsilon_r = 10^5$ and several values of $\mu_r$. The present core has dimensions smaller than $\lambda/2$ (for the expected resistivity) but if it were larger there would be a real possibility of resonance effects. Even though this core is not resonant at 80 kHz, the high power operating point, it may be excited at lower powers with frequencies up to 300 kHz. It is possible that substantially higher than expected power loss may be observed.

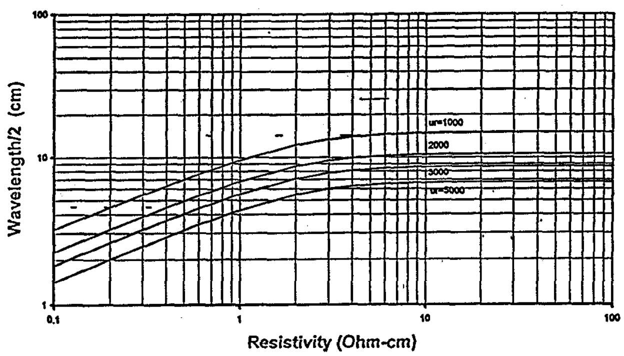


Figure 7. $\lambda/2$ at 80 khz in ferrite.

Resonance effects should be kept in mind when working with large MnZn ferrite cores.

### C. Core loss computation

Because of the non-uniform nature of the flux distribution and poorly defined values for $\mu_r$, $\varepsilon_r$, $\rho$ and measured specific power loss, accurate power loss calculations are really not possible. Approximations can be made to estimate the total loss but these become progressively less accurate as the size of the core increases. Direct measurements of core loss are however, possible using a variety of techniques[8,9]. The measured total core loss was $\approx$100 W.

The calculation of core loss in large cores is an art yet to be perfected!

## V. WINDINGS

The primary and secondary turns ratio was 8:4, for high power operation. Other turns ratios are of course possible to accommodate different battery voltages and input power sources.

Because the primary limitation on charging current is loss in the windings and the ability to remove the resulting heat, as few turns as possible are desired for high power operation. Unfortunately, the transformer must also be used for low power charging where very low magnetizing inductance is not acceptable. Eight turns on the primary, were adopted as a compromise to allow operation over a wide range of powers but the cost of this compromise is higher winding loss and complexity in cooling arrangements. The higher primary turns also reduced the cable current by a factor of two by using a higher drive voltage from the charger.

### A. Secondary Winding

The secondary winding is divided into two symmetrical halves, one on each side of the primary. Symmetry was adopted to minimize leakage inductance and to minimize field distortions which would increase the eddy current losses in the windings. The division also reduces the effective number of layers, in both the primary and secondary, which significantly reduces proximity loss. Loss in the windings is the fundamental factor limiting power transfer through the port. Everything possible must be done to limit losses for 120 kW operation to be practical.

The AC resistance of the windings was determined using FEM. This resistance was minimized by optimizing the winding dimensions using FEM. For a battery voltage of 400 V, the charge current was 300 A. This translates to 333 A rms in the winding if the winding current is a sinusoid, which it very nearly was. The total winding loss for primary and secondary was $\approx$700 W.

The current waveform in the winding can have an important effect on losses especially if there is significant harmonic content. For that reason every effort was made to use near sinusoidal waveforms. The need to accommodate low magnetizing and relatively high leakage inductances also indicated the use of resonant rather than switchmode charger technology.

### B. Primary Winding

The primary used a helical winding. The presence of the insulated puck, in the center of the winding, complicated the problem of removing the heat.

### C. Cooling Arrangements

Ultimately, the capability to remove heat from the windings determines the power transfer capability of the transformer. At the power level discussed here, non-refrigerated liquid cooling on both primary and secondary was required.

The secondary cooling is tied into the vehicle on-board cooling system. The primary is cooled with oil supplied from the charger and pumped through the charge cable. This provides cooling for the cable as well as the primary winding. When running at full power the observed temperatures were all within requirements as shown in table 1.

The cooling liquid circulated through the windings. It was necessary to place the cooling in locations where the magnetic field is low. Otherwise large losses due to eddy currents may occur.

Table 1, Temperatures at selected points.

| Location | Temperature °C |
|---|---|
| Puck | 46 |
| Secondary | 38 |
| primary * | 88 |
| Cable | 35 |

* measured directly on the winding

## VI. CONCLUSION

The many new resonant and soft switching techniques which have been demonstrated in recent years have made it possible to generate powers of hundreds of kW with switching frequencies of 80 to 300 kHz. This brings with it new demands and opportunities for transformer design. By using ferrite cores and suitable cooling techniques, very small, light weight and efficient transformers can be built. The size of the ferrite cores, while very small compared to past technologies using other materials at these power levels, is still much larger than common practice for power electronics equipment. This leads to a number of concerns in both fabrication and power loss. All of these problems can be addressed but they must be understood before embarking on such a project.

## ACKNOWLEDGMENT

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