Chapter 19

Rotary Transformer Design

Table of Contents

Introduction

There are many requirements to transfer signals and power across rotary interfaces. Most things that use slip rings or brushes can be replaced with a rotary transformer. Science instruments, antennas and solar arrays are elements needing rotary power transfer for certain spacecraft (S/C) configurations, such as a spin, stabilized (S/C). Delivery of signals and power has mainly been done by slip rings. There are problems in using slip rings for long life and high reliability: contact wear, noise, and contamination. Contact wear will lead to a conductive path to ground. This conductive path will generate noise and upset the original designed common-mode noise rejection. A simple slip ring assembly and a rotary transformer are shown in Figure 19-1. High data rates and poor slip ring life forced the Galileo (S/C) to replace the signal interface with rotary transformers. The use of a rotary transformer to transfer power on the Galileo (S/C) was contemplated, but it was thought the impact on the (S/C) delivery was too great. The rotary transformers on the Galileo (S/C) lasted the life of the spacecraft, from 1989 to 2003 without a glitch.

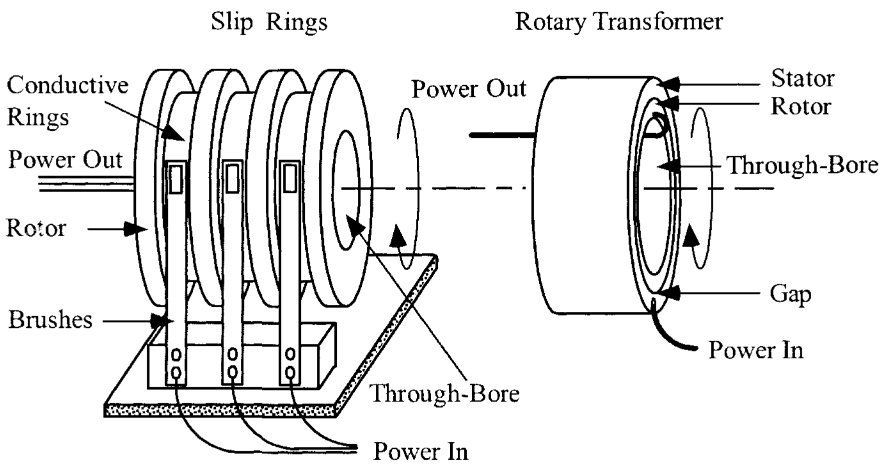

Figure 19-1. Comparing a Slip Ring Assembly and a Rotary Transformer.

Existing approaches to rotary power transfer use square wave converter technology. However, there are problems caused by the inherent gap in a rotary transformer, coupled with the fast rate of change in the square wave voltage. Undue stress is placed on the power electronics and the interface becomes a source of Electromagnetic Interference (EMI) that impacts the overall system's operating integrity.

Basic Rotary Transformer

The rotary transformer is essentially the same as a conventional transformer, except that the geometry is arranged so that the primary and secondary can be rotated, with respect to each other with negligible changes in the electrical characteristics. The most common of the rotary transformers are the axial rotary transformer, shown in Figure 19-2, and the flat plane, (pot core type), rotary transformer, shown in Figure 19-3. The power transfer is accomplished, electro-magnetically, across an air gap. There are no wearing contacts, noise, or contamination problems due to lubrication or wear debris.

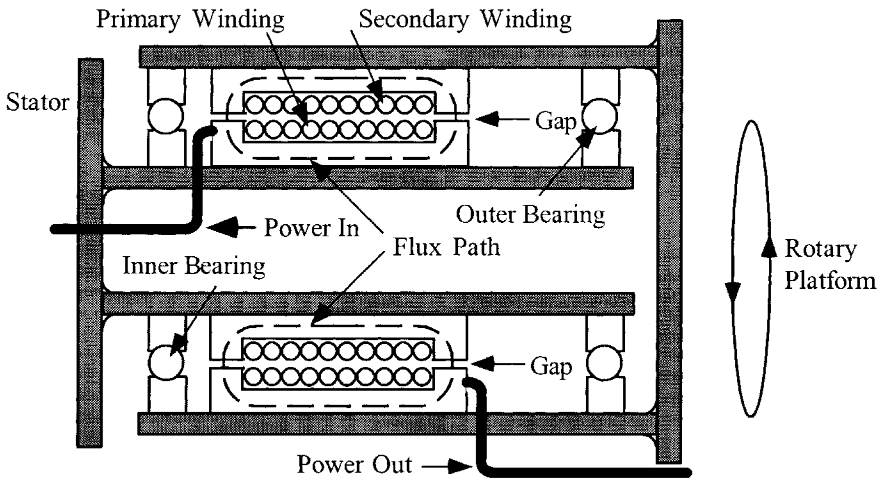

Figure 19-2. Pictorial of an Axial, type Rotary Transformer.

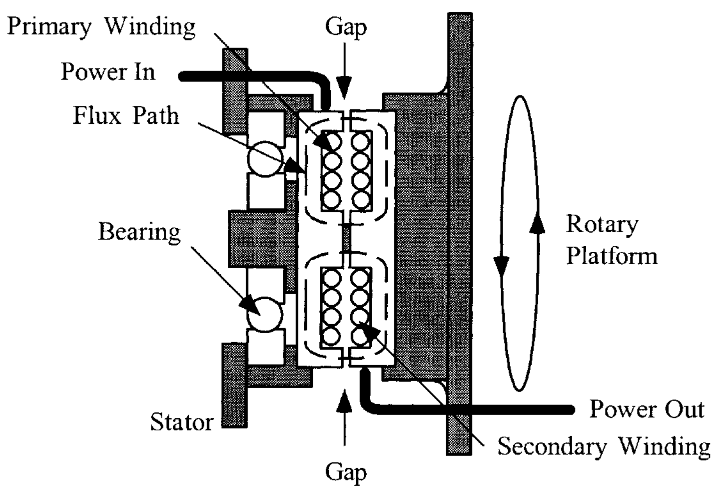

Figure 19-3. Pictorial of a Flat Plane, type Rotary Transformer.

Square Wave Technology

The ideal converter transformer would have a typical square B-H loop, as shown in Figure 19-4. A converter transformer is normally designed to have a minimum of leakage inductance. The voltage spikes that are normally seen on the primary of a square wave converter transformer are caused by the leakage inductance. To design a converter transformer to have a minimum of leakage inductance, the primary and secondary must have a minimum of distance between them. Minimizing the leakage inductance will reduce the need for power-wasting, snubber circuits. Although there are rotary power transformers designed with the use of square wave converter technology, they are not, without problems.

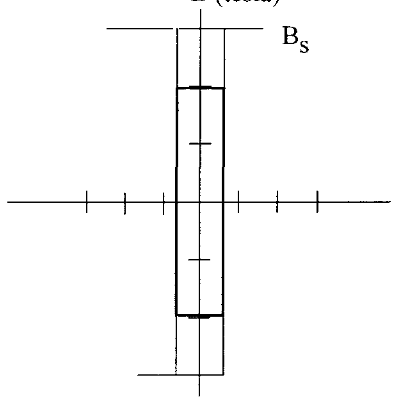

Figure 19-4. Typical, Transformer BH Loop.

There are two basic problems not found in the normal transformer: (1) the inherent gap in a rotary transformer is one problem, and (2) the required spacing between primary and secondary that leads to large leakage inductance is the other. These problems, along with a square wave drive, are what leads to a high loss, snubber circuit, and beccme a source of Electromagnetic Interference (EMI) that impacts the adjoining systems operating integrity. The rotary transformer, because of its inherent gap, has a B-H loop similar to an inductor, as shown in Figure 19-5. Basically, the transformer transforms power, and the inductor stores energy in the gap. The rotary transformer does not have any of the traits of an ideal transformer. It is, more accurately, a trans-inductor having a gap and a secondary, spaced away from the primary.

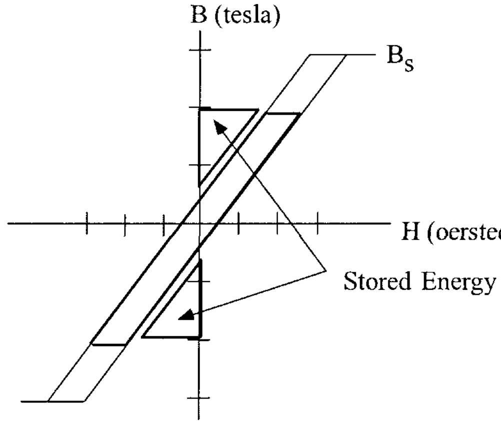

Figure 19-5. Typical, Rotary Transformer BH Loop.

Rotary Transformer Leakage Inductance

The rotary transformer has an inherent gap and spacing of the primary and secondary. The gap and spacing in the rotary transformer result in a low primary magnetizing inductance. This low primary inductance leads to a high magnetizing current. The leakage inductance, L_p, can be calculated for both axial and flat plane using Equation 19-1. The axial rotary transformer winding dimensions are shown in Figure 19-6. The flat plane rotary transformer winding dimensions are shown in Figure 19-7.

$$L_p = \frac{4\pi (MLT) N_p^2}{a}\left(c + \frac{b_1 + b_2}{3}\right)\left(10^{-9}\right), \quad \text{[henrys]} \quad [19\text{-}1]$$

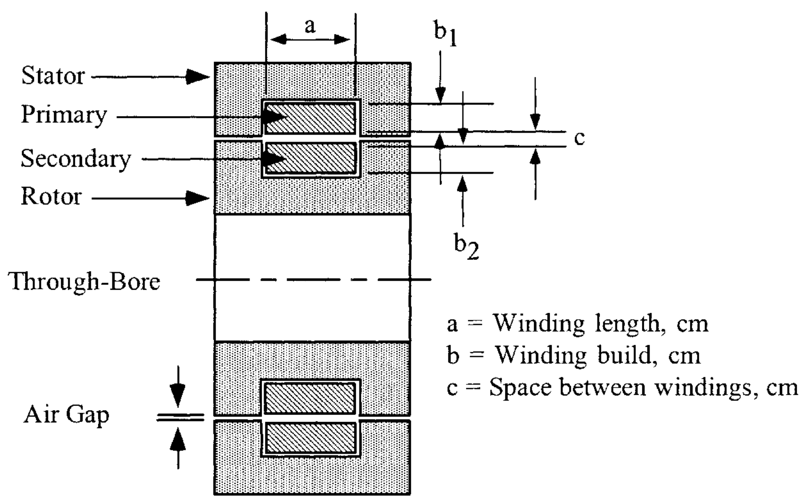

Figure 19-6. Axial Rotary Transformer, Showing Winding Dimensions.

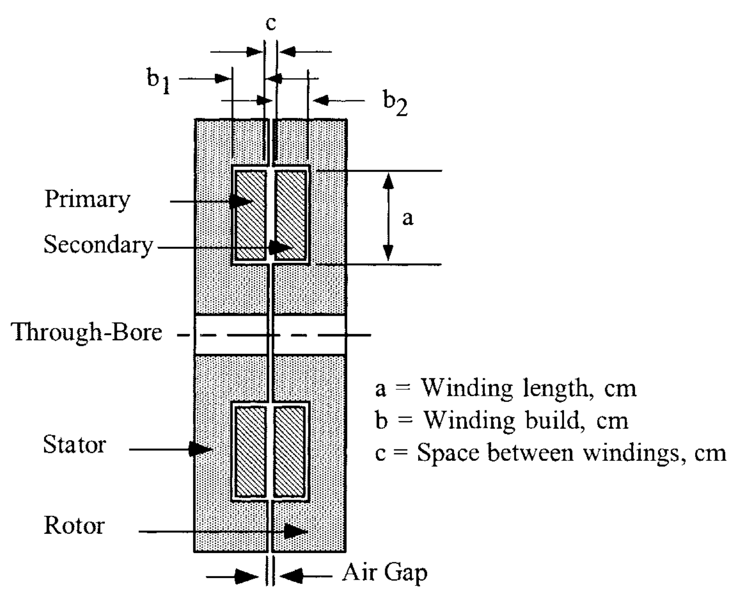

Figure 19-7. Flat Plane Rotary Transformer, Showing Winding Dimensions.

Current-fed Sine Wave Converter Approach

The current-fed, sine wave converter topology is a good candidate to power the rotary transformer. The design would be a current-fed, push-pull, tuned tank converter requiring a gapped transformer. A comparison between a standard, square wave converter, shown in Figure 19-8, and a current-fed, sine wave converter, is shown in Figure 19-9. Using the rotary transformer in this topology, the energy that is stored in the rotary gap that causes so much trouble in the standard square wave driving a rotary transformer, is recovered and is used in the tank circuit. There would not be any need of power-wasting snubbers using the rotary transformer approach. See Chapter 18.

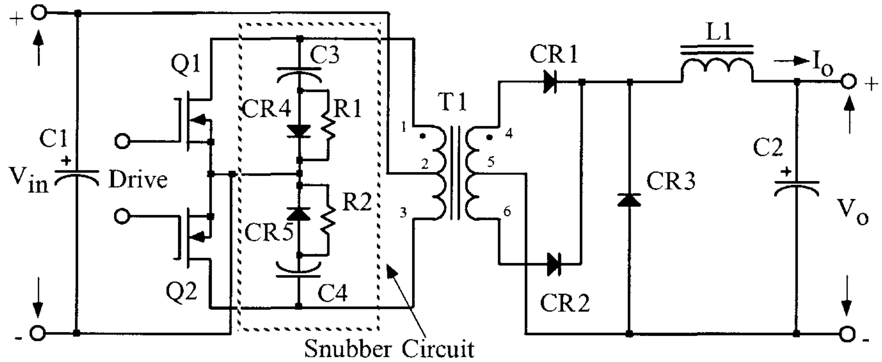

Figure 19-8. Typical, Voltage-fed, Square wave Converter Circuit with Snubbers.

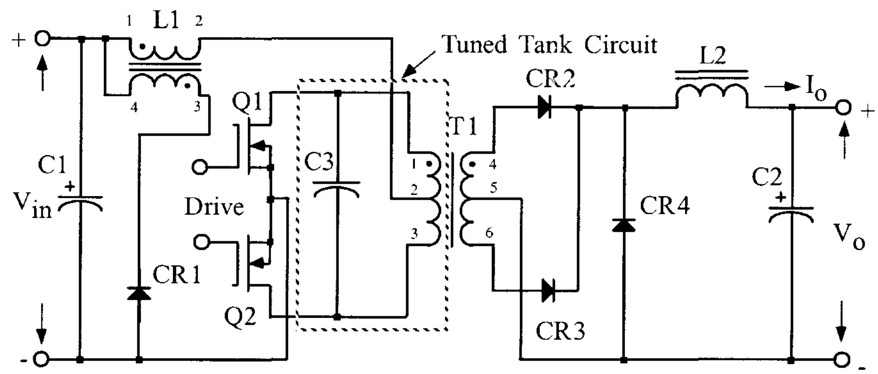

Figure 19-9. Typical, Current-fed, Resonant Converter Circuit.

The current-fed sine wave converter requires a resonant, LC, tank circuit to operate properly. The primary of the rotary transformer would be the ideal inductor, because of the inherent gap of the rotary transformer. There are several advantages to incorporating the resonant tank circuit into the rotary transformer. First, it minimizes the number of components in the power stage. Secondly, the output of the inverter is a natural sine wave, as shown in Figure 19-10, and usually requires no additional filtering. Thirdly, energy stored in the gap of the transformer is released when either power switch is turned off. This energy is commutated in the resonant tank circuit. This provides the capability for direct exchange of power between the tank circuit and the load. There is not a noticeable drive torque in a rotary transformer. The tuning or tank capacitor must be of high quality, stable, and with low ESR.

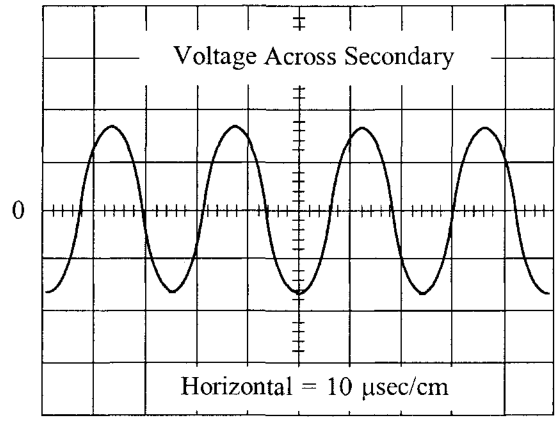

Figure 19-10. Current-fed Converter, Secondary Sine Wave Secondary Voltage.

Rotary Transformer Design Constraints

The rotary transformer requirements pose some unusual design constraints compared to the usual transformer design. The first is the relatively large gap in the magnetic circuit. This gap size depends on the eccentric dimension and the tolerance of the rotating shaft. The gap results in a low primary magnetizing inductance. Secondly, the large space separating primary and secondary windings results in an unusually high primary-to-secondary leakage inductance. Thirdly, the large through-bore requirement results in an inefficient utilization of the core material and copper, due to the fixed mean-length turn. This large diameter results in requiring more copper area for the same regulation. Finally, the core has to be more robust than the normal transformer because of the structural requirement. See Figure 19-11.

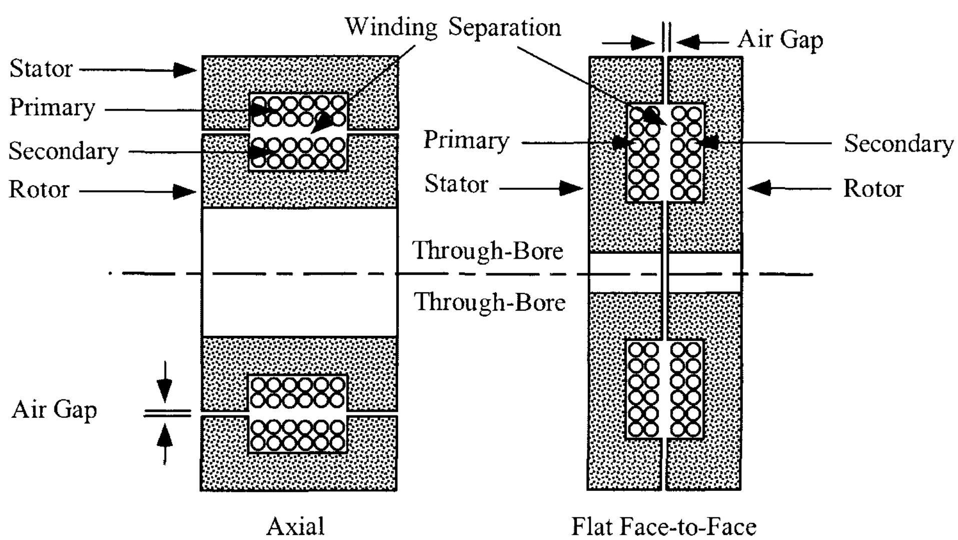

Figure 19-11. Geometries of the Basic Type Rotary Transformers.

Rotary transformer dimensions are usually governed by the mechanical interface, in particular the relatively large gap and the large through-bore, resulting in a long Mean Length Turn (MLT). The rotary transformer is not an ideal magnetic assembly. A toroidal core is an ideal magnetic assembly. Manufacturers use test data, taken from toroidal cores, to present magnetic material characteristics. The magnetic flux in a toroidal core travels through a constant core cross-section, A_c, throughout the whole Magnetic Path Length, MPL, as shown in Figure 19-12, and provides ideal magnetic characteristics. It can be seen that the core cross-section throughout the rotary transformers, shown in Figure 19-13 and Figure 19-14, does not provide constant flux density or an ideal magnetic assembly. The rotary transformers for the Galileo spacecraft were about 10 cm in diameter, and manufactured by CMI (Ref 4.)

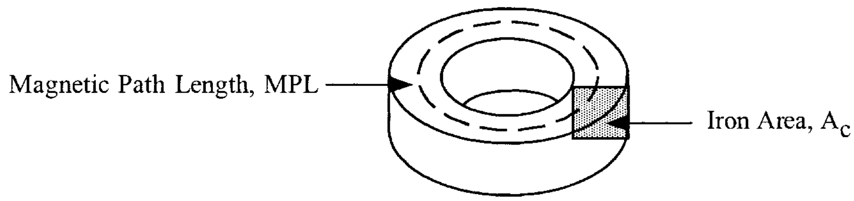

Figure 19-12. Typical Perspective View of a Toroidal Core.

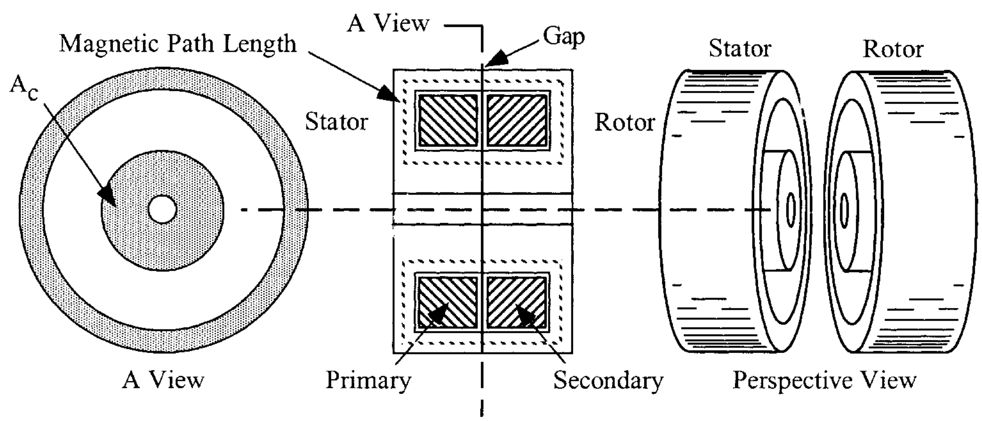

Figure 19-13. Open View of a Flat Plane, Type Rotary Transformers.

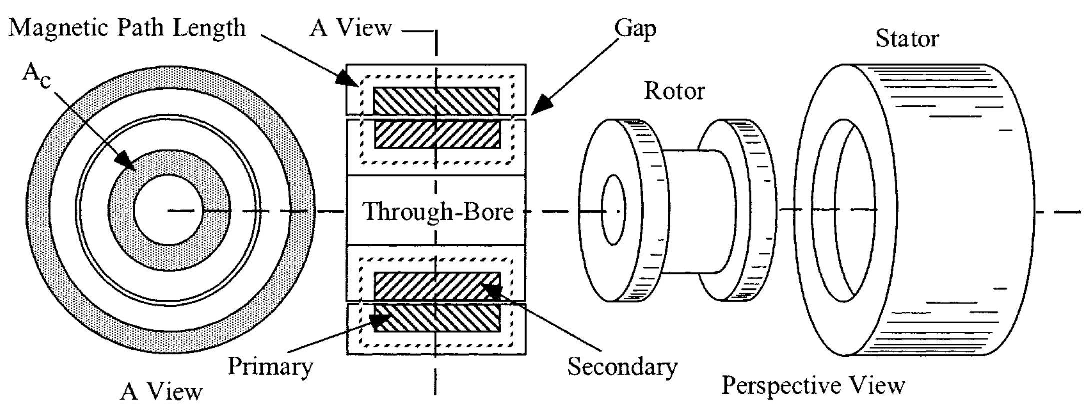

Figure 19-14. Open View of an Axial Type Rotary Transformers.

References

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3. S. Marx, "A Kilowatt Rotary Power Transformer." Philco-Ford Corp., IEEE Transactions on Aerospace and Electronic Systems Vol. AES-7, No. 6 November 1971.
4. Ceramic Magnetics, Inc. 16 Law Drive Fairfield, NJ 07006. Tel. (973) 227-4222.