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Design and fabrication of a cost-effective coil winding machine for slotless toroidal stators

J.M. Conde Garrido[1,2] and J.M. Silveyra[1,2]
[1]Universidad de Buenos Aires. Facultad de Ingeniería. Laboratorio de Sólidos Amorfos, Argentina
[2]CONICET - Universidad de Buenos Aires. Instituto de tecnologías y Ciencias de la ingeniería "Hilario Fernández Long" (INTECIN), Argentina
jmcondegarrido@fi.uba.ar, jsilveyra@fi.uba.ar

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Here, we demonstrate a cost-effective winding technology suited for Torus' stator prototypes. The device transfers the wire from the primary copper spool onto a secondary circular spool and then unwinds it onto the toroidal core. We designed 3D-printed accessories to achieve coils with good accuracy and repeatability. Our Torus winding machine is easy to build and use –yet, it keeps the prototyping process cost low.

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I. Introduction

With an increasingly electrified world, humanity needs to revolutionize its energy use. In particular, in the field of electric motors, which are the largest consumers of electrical energy [1]. Materials science can address the challenge of achieving higher-efficiency motors. A promising strategy is to replace traditional electrical steel with state-of-the-art nanostructured soft magnetic alloys. Due to their low coercivity and competitive saturation, high resistivity, and thin thickness [1, 2], these materials maintain low losses even in the kHz range [3-6].

In recent decades, amorphous Fe-based materials, and even more so nanocrystalline materials, have been shown to increase the efficiency of transformers by replacing the electrical steel cores. These devices have already moved beyond the demonstration prototype stage. They have become standard materials for many commercial applications, including magnetic shields, electronic filters, and mid-frequency transformer cores [7].

But, compared to steel, amorphous and nanocrystalline alloys are very hard. Moreover, in the nanocrystalline state, they can be excessively brittle. Also, the thin thickness of nanostructured laminates (~20 µm) is beneficial because it mitigates eddy current losses but is counterproductive for material handling. These mechanical characteristics make the manufacturing process difficult -and expensive- for the complex geometries of traditional stator and rotor cores. For example, the conventional stamping process used for steel radial stator cores would wear out the dies quickly if used for amorphous or nanocrystalline alloys. As a result, the manufacturing cost would be too high. Other investigated techniques, such as chemical etching or laser cutting, are not fast enough to be economically feasible at an industrial production scale.

Thus, there is a need for innovative motor designs with manufacturing processes that are both technically and economically feasible. Only then will electric motors with nanostructured cores meet the current demands of highly efficient electric machines.

In 1991, Spooner et al. proposed a novel electric motor topology coined Torus (which can also work as a generator) [8] (Fig. 1). The machine is an axial-flux device with one slotless toroidal stator core and two external rotors with permanent magnets. This topology is advantageous for applications that require short axial length and a high power-to-weight ratio. From the first published prototype in the early 1990s to the present, significant advances in the magnetic

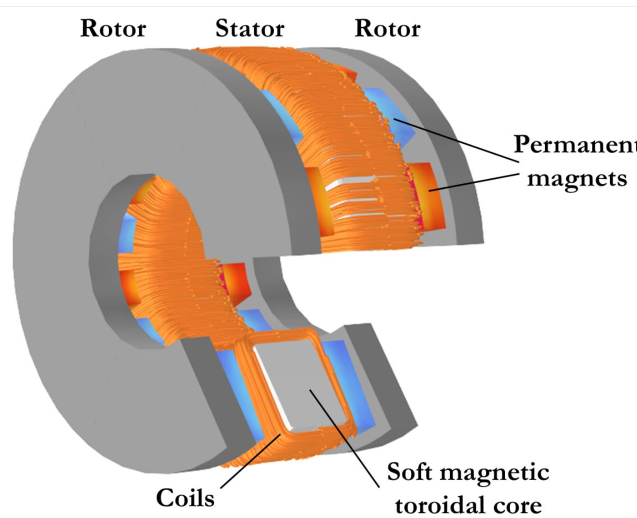

Fig. 1 Sliced 3D view of a Torus electric machine.

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materials field make the Torus topology still worth exploring and optimizing. The ease of construction of Torus' slotless toroidal core facilitates the application of highly efficient state-of-the-art amorphous and nanocrystalline laminations, which can be easily wound into a toroidal shape. Also, the advent of rare earth permanent magnets may enable higher power densities in axial-flux machines [9] (especially in slotless machines, which have relatively larger air gap than slotted machines, because the effective air gap results from the mechanical clearance plus the stator winding).

However, the Torus topology does have a manufacturing challenge that can hamper its exploration, primarily at the prototyping stage. Winding the coils requires a purely manual process, a specific winding machine, or a segmented ferromagnetic core to insert them. Hand-winding using a sewing needle is both slow and unreliable (it requires high handling efforts, and it is possible to lose count of the number of turns being wound). Commercial machines are complex and, therefore, expensive [10]. The high initial investment would be rarely justified at a prototyping stage. Cutting toroidal stator cores to insert pre-wound coils, as conducted in [11], is a good idea from the fabrication point of view, but deteriorates the aimed excellent soft magnetic properties of the nanostructured material.

Thus, we sought an easy-to-build and easy-to-operate coil-winding technology that simplifies the fabrication of Torus's stator prototypes.

II. Proposed design

To wind a coil onto an annular or toroidal core, the end of the wire must describe one complete turn around the winding axis for every turn to be wound [12]. Thus, the wire cannot be supplied continuously from spools as in conventional winding machines. Instead, we first need to transfer the wire from the primary spool onto a shuttle spool of limited dimensions. The shuttle spool may be a small bobbin that travels around the winding axis, unwinding the wire onto the core. The core inner diameter limits the bobbin capacity. Alternatively, the shuttle spool may be a narrow grooved ring that encircles the toroidal core and rotates to unwind the wire. We used this second approach to design our winding machine.

The operation principle of our winding machine is illustrated in Fig. 2. First, a toroidal core T is positioned on a

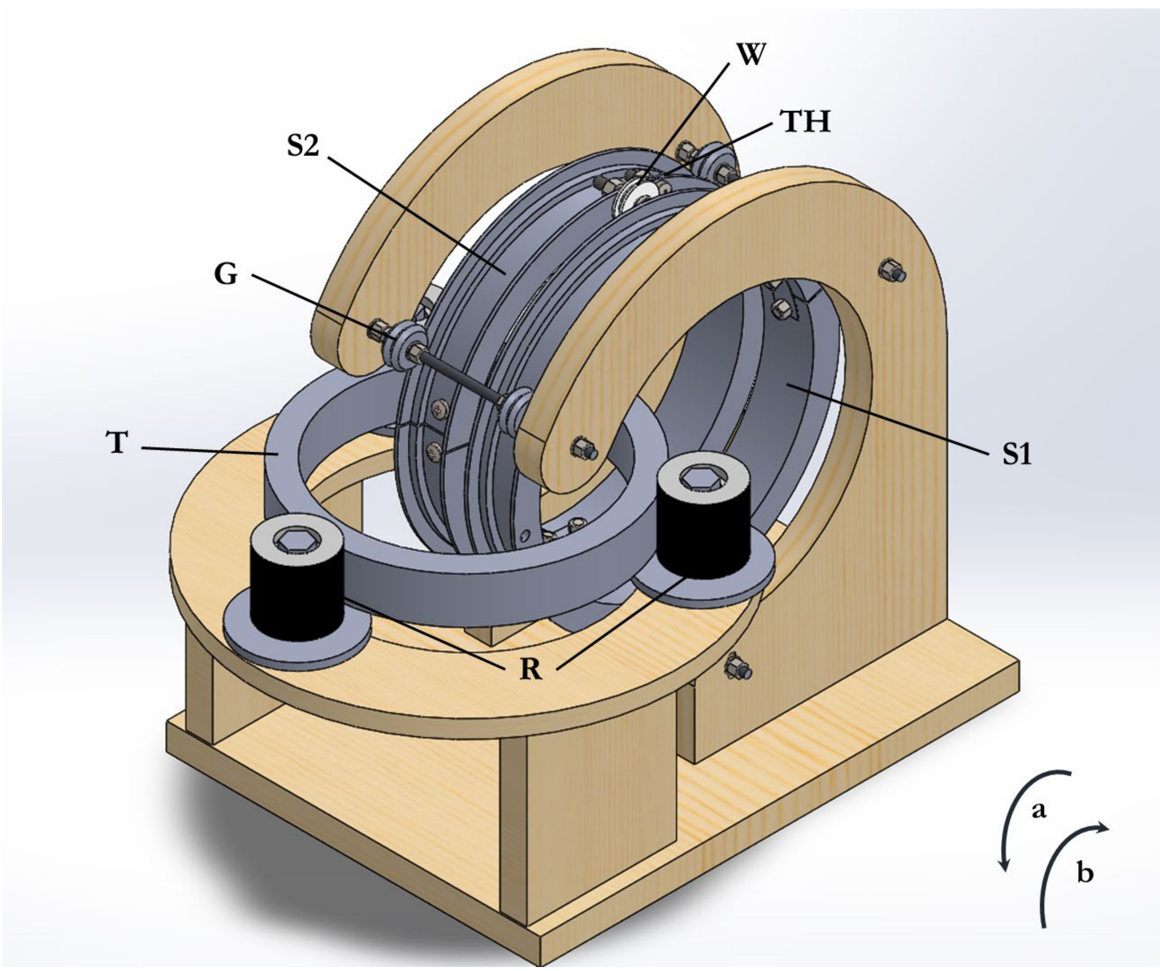

Fig. 2 Schematic of our winding machine design. The capital letters point out the components out the device mentioned in the text. The arrows “a” and “b” denote, respectively, the secondary ring spinning direction during the winding operation and the shuttle ring spinning direction during the loading operation.

three-point roller support R mounted on a winding table. These rollers hold the core in place and help to rotate it about its axis without any slippage when needed [13]. A grooved shuttle ring S1 and a secondary ring S2 encircle the toroidal core. The rings are supported by three small guide rollers G on their circumference and have a detachable section to introduce and withdraw the core. Then, the wire is transferred from a primary supply spool onto the shuttle ring by manually spinning it in the direction “b” of the schematic. When sufficient wire has been loaded on the groove, it is cut at the supply spool. After finishing the loading, the winding operation begins. The free end of the wire is passed through a threader TH, over a small wheel W free to rotate attached to the secondary ring S2, and immobilized using a hanger system for the first couple of turns. The secondary ring is then manually spun in the direction “a” of the schematic. As the wire is unwound from the shuttle ring and transferred onto the core, the shuttle and the secondary rings rotate independently [14]. In our machine, both rings are located side by side. Alternatively, the design could have one ring inside the other or have the small wheel mounted on a carriage free to travel around the shuttle ring [12]. Either of these options is more complex to build. Finally, the wound toroidal core may be withdrawn by removing the detachable section of the rings.

The best choice for the shuttle ring needs to consider the following issues. A wide diameter maximizes wire storage capacity. However, Mirza has pointed out [13] that this also reduces the winding speed. Yet, what is even more critical, the toroidal core ends up being placed too eccentrically on the coil winding machine. Planer has demonstrated [12] that a large eccentricity causes large accelerations in the shuttle ring that may result in high strains upon the wire and can eventually break it. Regarding the width of the ring, it needs to provide adequate wire capacity and have the ability to pass through the inner diameter of the finished core.

A crucial feature of the shuttle ring is its need for a braking mechanism. During the winding process, the shuttle ring experiences deceleration periods that change the wire’s tension. Our design implements a friction brake applied onto the shuttle ring, which yields a more uniform strain and avoids the dislocation of the wire from its path along the shuttle ring.

Since slotless toroidal stators do not have slots, we designed mechanical guides to aid the manual task of spreading the wire of each coil (Fig. 3). These guides need to be accommodated in place before the winding operation begins and are removed to be reused for winding the next coil (which may or may not be directly adjacent to the previous one). Before the winding operation begins, positioning lines should be drawn on the core surface to place the guides appropriately. To wind a new coil the core needs to be manually rotated about its axis. At certain times, the position of the middle guide roller may need to be readjusted (as the external diameter of the core increases with the wound coils).

Manual counters need great vigilance from the operator [10]. Instead, our machine has a permanent magnet attached to each ring (in the shuttle ring, the magnet is placed on the interior surface to avoid entangling the wire loaded in the groove). A magnetic field counter registers each time the permanent magnet passes nearby.

III. Fabrication Procedure

We aimed for a simple fabrication procedure with commonly available items and manufacturing processes. Our coil winding machine was designed for slotless toroidal stators

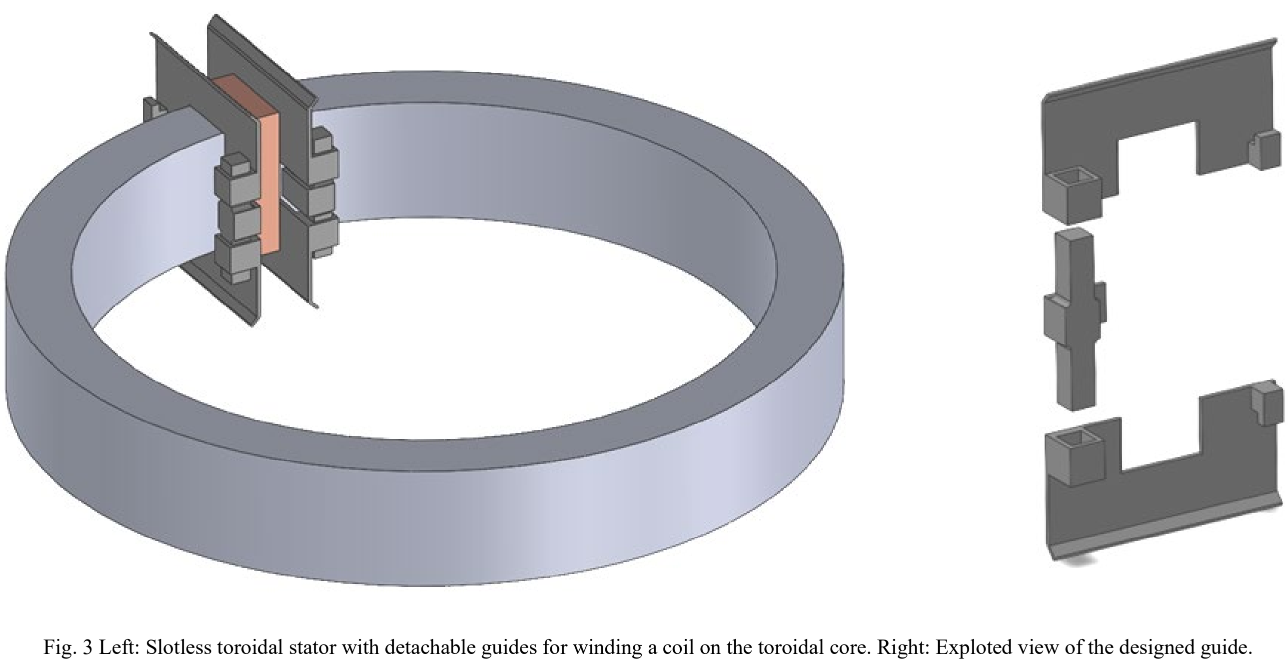

Fig. 3 Left: Slotless toroidal stator with detachable guides for winding a coil on the toroidal core. Right: Exploted view of the designed guide.

with a minimum internal diameter of ~100 mm, a maximum external diameter of ~200 mm, and a maximum height of ~60 mm. But the design can be easily adapted for other dimensions.

The structure of the winder was manually machined out from MDF (medium-density fiberboard), which is an inexpensive building material made of recycled wood. For this purpose, we used a circular saw for straight cuts, a jigsaw for curved cuts, and a drill. Each of the parts was mounted with wood screws.

The three rollers for supporting and rotating the toroidal core are reinforced Nylon rollers (41 mm wide and 43 mm long) commercially available as stabilizers for sliding-type gates. We covered them with 1 mm thick EVA (ethylene-vinyl acetate) rubber and 3D-printed 100 mm wide discs made of PETG (polyethylene terephthalate glycol) with 100 % infill to support the core.

We used the same geometry for the shuttle and the secondary rings: aluminum 6061-T6 12” wide fat bicycle rims. Even though only the shuttle ring required a channel to load the wire, using equal parts enabled using the same holding and rotating mechanism for both. We cut a ~150 mm long section using a Dremel rotary tool from each ring. These sections can be detached and reattached with a rectangular curved piece, machined from a thin steel sheet, using screws, washers, and nuts. This ferromagnetic piece also serves the purpose of holding a permanent magnet in each of the rings. Then, a mobile phone placed beneath or at the back of the secondary ring during the winding operation detects when the magnet passes nearby and counts the number of turns with the “Magnetic field counter” application developed and freely distributed by Keuwlsoft [15] (the same strategy of placing the mobile phone beneath or at the back of the shuttle ring is used during the loading operation to calculate the wire length to load).

The small wheel mounted on the secondary ring is a Nylon grooved wheel with bearing and bolt used for mosquito sliding nets (25 mm wide, 5 mm wide, and with a 4 mm wide round channel). The threader was manually shaped from a paper clip and mounted close to the small wheel.

The three small guide rollers that support each ring are plastic V-pulleys with bearing (with an external diameter of 24 mm, an internal diameter of 5 mm, and a thickness of 11 mm). These are held with threaded rods, washers, and nuts.

A thick foam board placed under the shuttle ring during the winding operation serves as the friction brake needed for this stage.

The pair of detachable mechanical guides for winding each coil were designed ad hoc and 3D-printed in PLA (polylactic acid). We used 60 % infill for the central part of each guide and 100 % infill for the other ones. An elastic band between the tabs of the guide holds its strain. A paper stencil helps to draw the positioning lines for winding each coil.

Figure 4 shows the components described above and the assembled winding machine. Finally, Fig. 5 shows the

Fig. 4 Fully assembled winding machine.

Fig. 5 Operation steps of the developed device to wind a slotless toroidal stator. 1) loading operation, 2) feeding the wire through the threader and small wheel, 3) holding the wire for the first couple of turns, 4) placing the friction brake, 5) winding the coil, 6) counting the number of turns.

operation steps of the built device: 1) loading the wire from a primary supply spool onto the shuttle ring (the wholes of the bicycle rim allow to easily hold the end of the wire), 2) feeding the free end of the wire through the threader and the small wheel attached to the secondary ring, 3) holding the wire for the first couple of turns, 4) placing the friction brake under the shuttle ring (to yield a more uniform wire strain and to avoid the dislocation of the wire from its path along the shuttle ring), 5) winding the coil around the slotless toroidal core and in-between the pair of coil guides, 6) counting the number of turns using a smartphone with an internal magnetic field sensor and the “Magnetic field counter” mobile application (the smartphone can be placed beneath or at the back of the secondary ring).

IV. Conclusions

We developed a coil winding machine suitable for slotless toroidal stators that is easy and cost-effective to build. The device is also easy to use and helps to wind the coils with precision and consistent quality. We have described the working principles of toroidal coil winding, which is rarely found in the literature, and explained a feasible fabrication procedure. Although the presented design needs to be operated manually, it can be partially automated by motorizing the wheels and the roller support (the handling of the start and end wires are manual processes even in commercial winding machines). However, this would increase the complexity and cost of the device. We hope our design to ease the prototyping stage of slotless toroidal stators like the ones used in the Torus electric machines.

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