A DC Transformer

Robert C. Youngquist[1], Curtis M. Ihlefeld, and Stanley O. Starr

Abstract

A component level dc transformer is described in which no alternating currents or voltages are present. It operates by combining features of a homopolar motor and a homopolar generator, both dc devices, such that the output voltage of a dc power supply can be stepped up (or down) with a corresponding step down (or up) in current. The basic theory for this device is developed, performance predictions are made, and the results from a small prototype are presented. Based on demonstrated technology in the literature, this dc transformer should be scalable to low megawatt levels, but it is more suited to high current than high voltage applications. Significant development would be required before it could achieve the kilovolt levels needed for dc power transmission.

This research has not been published in any other journal and has not been presented at a conference. Please consider this manuscript for publication as a Letter.

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Introduction

This letter presents an electro-mechanical component that transforms dc power, allowing dc voltages or currents to be stepped up or down. This dc transformer is a fundamental element, comparable to an ac transformer; it does not use internal electrical components, does not rely on switching or commutation, and does not require additional power to operate. As the theory section will show, this device is a dc counterpart to the well known ac transformer.

DC transformers are commonly referenced in the literature as being synonymous with dc converters [1,2,3,4], utilizing internal switching to create an ac waveform that can be stepped up or down with inductors or an ac transformer, and then switched back to a new dc voltage. Yet, this nomenclature is relatively new. A generation ago dc transformers were regarded as a fundamental component, with no internal elements, and were considered to be fictional until a superconducting version appeared [5] in the 1960s. In this letter a true component level dc transformer is presented, not a dc converter.

The device presented here is based on a combination of principles exhibited by homopolar motors [6,7] and homopolar generators [8,9]. The underlying idea does not appear to be in the recent literature however a patent was found describing a "homopolar transformer" [10], which appears to be related to the present concept, although no analysis or results are given in the patent and the design is more intricate than that developed below. Consequently, the authors believe that the dc transformer described in this letter is worth consideration not only for its novelty, but for possible further development. There is a need for high power dc transformers

[1,2] and this device should be capable of handling megawatt dc power levels by extending engineering already developed for homopolar motors and generators.

Theory

The simplest, isolated, form of the dc transformer consists of two conductive disks, radius a_1 and a_2 resp., that are spinning at frequency, ω, in a uniform magnetic field, $\vec{B}$, as shown in Figure 1. Voltage leads are connected to sliding contacts on the disk edges and the returns are connected to the two electrically isolated axels. If the voltages do not need to be isolated a simpler, single disk form exists, as shown in Figure 2, where the contacts are located on the disk face. It will be assumed below that $V_{1,ret} = V_{2,ret} = 0$ so that the analysis will apply to either configuration.
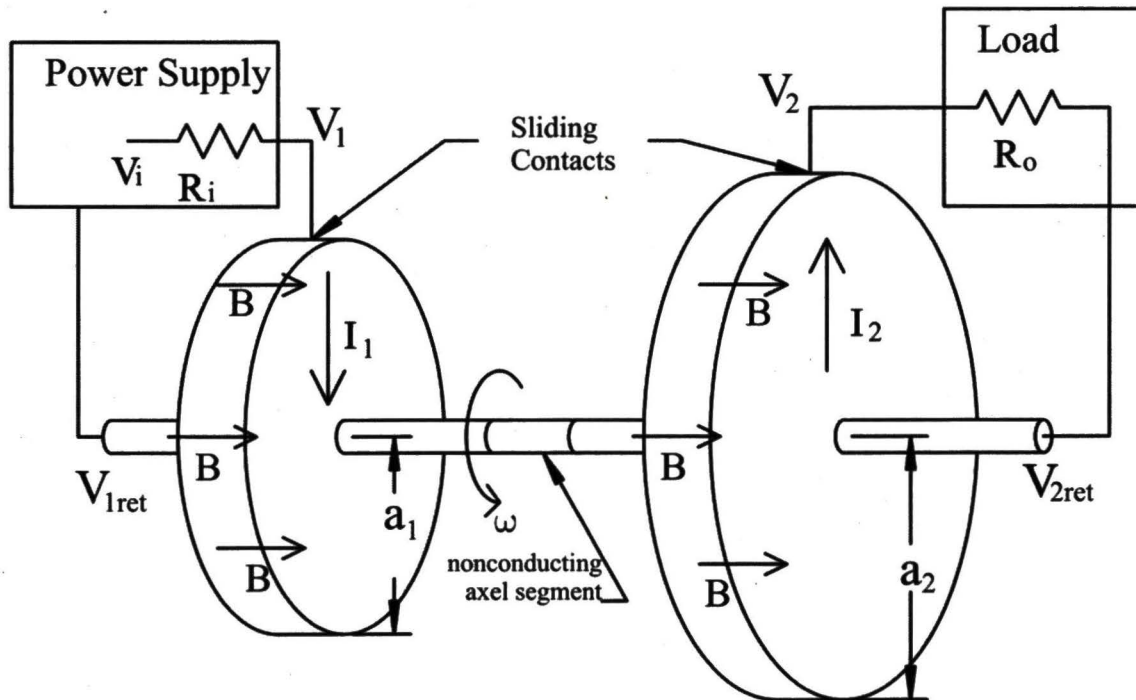

Figure 1. The simplest isolated form of the dc transformer consists of two mechanically connected spinning disks located in a uniform magnetic field.
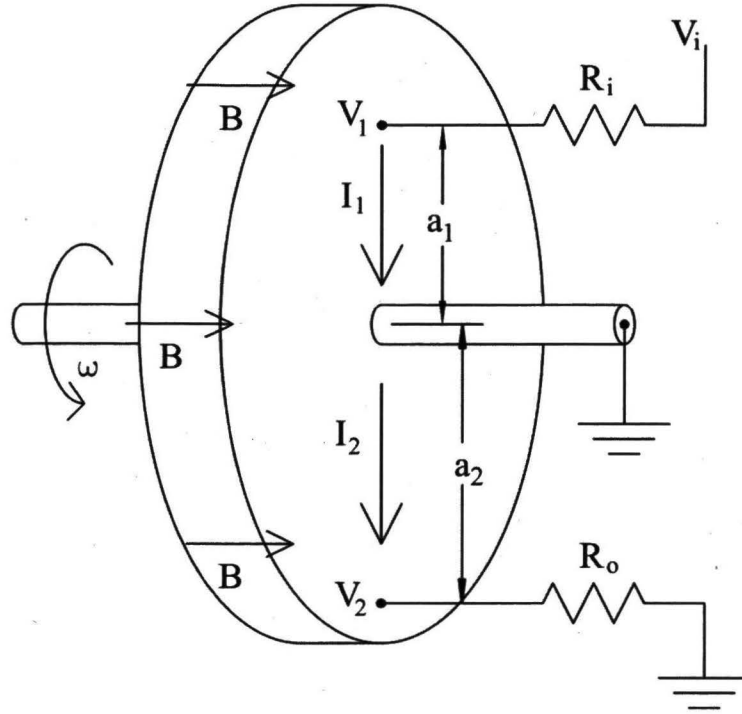
Figure 2. The simplest form for the dc transformer is composed of a single spinning disk in a magnetic field with two sliding contacts on the disk face.

The operation of this device is based on a combination of homopolar motor and homopolar generator concepts. Homopolar motors operate by flowing current in the presence of a magnetic field to generate torque [11]. The total torque, τ, is the sum of the torques generated by each disk current and is given by

$$\tau = \frac{1}{2} I_1 a_1^2 B - \frac{1}{2} I_2 a_2^2 B \qquad (1)$$

where I_1 and I_2 are the currents in each disk. In the steady state, ideal case where the rotational velocity is constant and there is no friction, the total torque is zero and equation (1) reduces to

$$I_1 a_1^2 = I_2 a_2^2 \qquad (2)$$

showing that the disk radii scale the current ratios similar to the coil winding number in an ac transformer.

Homopolar generators operate by rotating a conductor in a magnetic field to generate a voltage, i.e. a back emf [11]. In the configurations shown in Figure 1 and 2 voltages, V_1 and V_2 respectively, are generated at the disk radii, a_1 and a_2 according to

$$V_1 = \frac{1}{2}\omega a_1^2 B \quad \text{and} \quad V_2 = \frac{1}{2}\omega a_2^2 B \quad \Rightarrow \quad V_1 a_2^2 = V_2 a_1^2 \tag{3}$$

where ω is the rotational velocity of the two disk system. The last relation in equation (3) shows how the disk radii scale the ratio of the voltages on the two disks. Combining equations (2) and (3) yields the fundamental equation for the operation of an ideal dc transformer;

$$V_1 I_1 = V_2 I_2 \tag{4}$$

which is the same power conservation relationship produced when analyzing an ideal ac transformer. In addition, like an ac transducer, the input and output connections can be interchanged turning, for example, a voltage step up device into a voltage step down device.

The figures show a power supply with voltage, V_i , impedance, R_i, and a load R_o . One purpose of a transformer is to match load impedance to power supply impedance in order to maximize power delivery. In the case of the dc transformer shown in Figure 1 the power supply sees an impedance given by V_1 / I_1, which can be rewritten as

$$\frac{V_1}{I_1} = \frac{(V_2 a_1^2 / a_2^2)}{(I_2 a_2^2 / a_1^2)} = \left(\frac{a_1}{a_2}\right)^4 R_o$$

showing the significant role that the disk radii play in converting the load impedance.

The analysis above can be generalized to include friction by the addition of a frictional torque, τ_f, acting to decelerate the disks yielding a modified version of equation (1)

$$\tau = \frac{1}{2}I_1 a_1^2 B - \frac{1}{2}I_2 a_2^2 B - \tau_f \qquad (5)$$

Making the steady state assumption, where the total torque is set equal to zero, this expression can be simplified significantly by the incorporation of a frictional current, I_f defined by $I_f = 2\tau_f / (a_1^2 B)$. This allows equation (5) to be rewritten as

$$\frac{1}{2}I_1 a_1^2 B = \frac{1}{2}I_2 a_2^2 B + \frac{1}{2}I_f a_1^2 B \quad \Rightarrow \quad I_{1,f} a_1^2 = I_2 a_2^2 \quad \text{where} \quad I_{1,f} = I_1 - I_f$$

and permits the rest of the analysis to proceed as above yielding $V_1 I_{1,f} = V_2 I_2$. Physically this states that friction requires a current penalty, but after paying this the device operates ideally. Note that the frictional torque and the frictional current are not necessarily constant, for example, they can vary with rotational speed in the case of air resistance.

In the presence of friction the induced voltage equations (3) are unaffected. Combining these with equation (5) yields

$$\tau\omega = I_1 V_1 - I_2 V_2 - \tau_f \omega$$

which states that the total mechanical power entering the two-disk system is equal to the incoming electrical power minus the outgoing electrical power minus the power loss to friction. In other words, the device operates by using differences in electrical power to ramp up or down mechanically stored energy after paying a frictional penalty. Energy lost to resistance in the device could also be explicitly handled, but it can be lumped in with the energy lost in the power supply and the load resistances.

The rotary inertia of this dc transformer can be substantial, such that a sudden change in load resistance will change the output current, but the output voltage and input current will not change until the rotational speed begins to change. If the load impedance decreases and more current flows out of the transformer, rotational energy will be converted into electrical energy until a new, slower, steady state, rotational speed is reached. This high frequency filtering effect may be advantageous to protecting the power source.

There are alternative configurations for this dc transformer. For example, the device could utilize cylindrical conductors and radial magnetic fields instead of disks, a common approach in the literature and the equations for this cylindrical version would now be functions of the radii and the length of the cylinders. Alternatively, the two rotating disks or cylinders could be coupled using belts or gears yielding a wide variety of devices and performance characteristics.

Prototype Device

Significant engineering has gone into developing large scale homopolar generators and motors [6-10], but a dc-dc converter using these has not been demonstrated. So, we decided to construct a small scale, non-optimized, device—a toy compared to systems in the literature—to demonstrate the concept. Figure 3 shows our dc-dc transformer, consisting of one 3-inch and one 4-inch diameter aluminum disk spinning on a common axle in a magnetic field generated by a pair of fixed rare earth magnets. The magnets are located inside of the large aluminum cylinders and generate an approximately uniform magnetic field of about 0.2 Tesla across the disks.

A high current capacity graphite brush was used to provide 30 Amps of current to the 3-inch disk (left disk in the Figure) with the return path passing through the system axel, across the bearings, and down the center pedestal. This current caused the two-disk structure to accelerate up to a

17.5 Hz rotational speed generating about 16 mV $\pm$ 1.5 mV of voltage across the 3-inch disk and about 30 mV $\pm$ 1.5 mV across the 4-inch disk (the right disk in Figure 3). Higher speeds were not possible due to friction in the sliding contacts and by slight imperfections in the disks causing the sliding contacts to lose contact at higher rotational speeds, but this result does demonstrate a voltage increase approximately equal to the ratio of the radii squared $(4/3)^2 \approx 30\text{mV}/16\text{mV}$ as predicted by Equation 3 above.
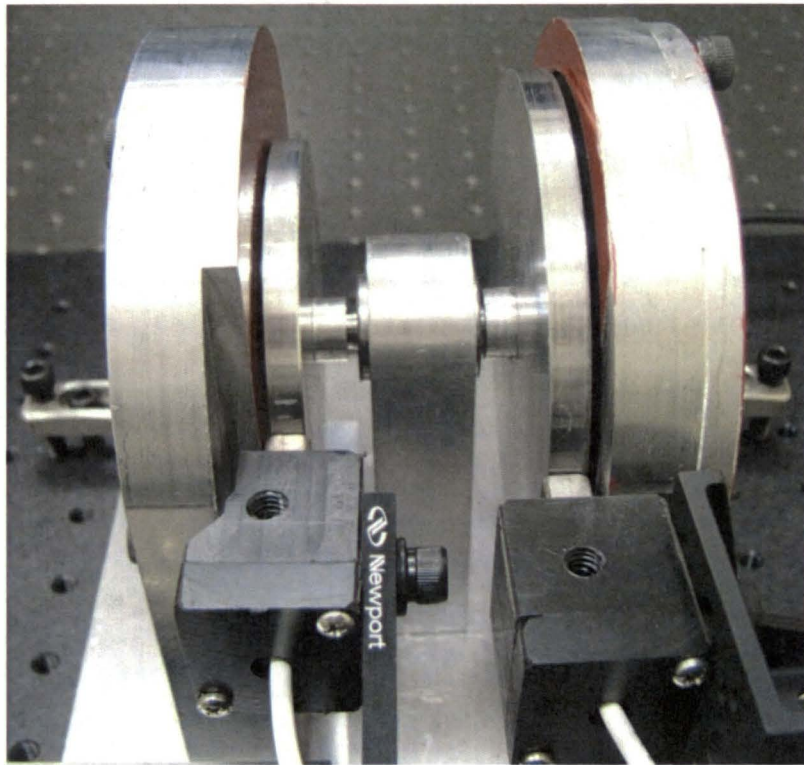

Figure 3. A small scale device was constructed to demonstrate the dc-dc transformer concept using a pair of conducting disks spinning in a magnetic field.

The voltage from the 4-inch disk was fed across a low impedance load generating a current that peaked at about 40 mAmps, but due to variations in the sliding contacts the expected increase in the input current could not be measured—the variations in the frictional current, I_f, were greater than the ideal device input current. Even so, power was generated and delivered, albeit only

about 1 mW, with about 400 mW being used to overcome friction. Increased scaling would be necessary to create an efficient, high power, device, but this "toy" device has demonstrated the basic operation of the concept, by shifting voltage up and delivering power.

Conclusions

A true dc transformer has been described and demonstrated, but its utility is unclear. These devices cannot compete with low power semiconductor based dc converters, however, they can be scaled to high power, where the primary need is for high voltage converters (kilovolts) for dc power transmission [2]. The difficulty is that homopolar generators are more suited to high current, rather than high voltage, applications and have only been demonstrated up to 750 volts [8]. Even so, with engineering this may be extended and they may find a role where their dc conversion potential coupled with their power filtering/storage capability may solve a need in the rapidly growing area of high dc power transmission.

Acknowledgements

References

1. N. Denniston, A. M. Massoud, S. Ahmed, and P. N. Enjeti, "Multiple-Module High-Gain High-Voltage DC-DC Transformers for Offshore Wind Energy Systems," IEEE Trans. Industrial Electronics, vol. 58, pp. 1877-1886, May 2011.

2. D. Jovcic, "Bidirectional, High-Power DC Transformer," IEEE Trans. Power Delivery, vol. 24, pp. 2276-2283, Oct. 2009.

3. W. Feng, P. Mattavelli, and F. C. Lee, "Pulsewidth Locked Loop (PWLL) for Automatic Resonant Frequency Tracking in LLC DC-DC Transformer (LLC-DCX)," IEEE Trans. Power Electronics, vol. 28, pp. 1862-1869, April 2013.

4. A. Ambramovitz and K. Smedley, "A Resonant DC-DC transformer with Zero Current Ripple," IEEE Trans. Power Electronics, vol. 22, pp. 2344-2351, November 2007.

5. I. Giaver, "A dc transformer," IEEE Spectrum, pp. 117-122, September 1966.

6. A. Arkkio, P. Berglund, J. T. Eriksson, J. Luomi, and M. Savelainen, "A 50 kW Homopolar Motor with Superconducting Field Windings," IEEE Trans, Magnetics, vol. MAG-17, pp. 900-903, January 1981.

7. R. J. Thome, W. Creedon, M. Reed, E. Bowles, and K. Schaubel, "Homopolar Motor Technology Development," in 2002 IEEE Power Engineering Society Summer Meeting, 2002, pp. 260-264.

8. H. Devred, M. Martinez, and J. Huonic, "150 kVA, 56000 rpm, Turbo Engine Integrated Homopolar Electrical Generator," in International Conference IEMD '99, Electric Machines and Drives, 1999. Pp. 749-751.

9. J. H. Price, J. H. Gully, and M. D. Driga, "The High Voltage Homopolar Generator," IEEE Trans. Magnetics, vol. 22, pp. 1690-1694, November 1986.

10. R. C. Smith, "Homopolar transformer for conversion of electrical energy," Patent 5821659, Issued Oct. 13, 1998.

11. P. Lorrain and D. Corson, Electromagnetic Fields and Waves, 2nd Edition. San Francisco: W. H. Freeman and Company, 1970, Chapter 8-Magnetic Fields II—Induced Electromotance and Magnetic Energy and Appendix C-Induced Electromotance in Moving Systems.