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A ROTATING ARC PLASMA INVERTOR

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A Rotating Arc Plasma Invertor

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Abstract

A device is described for the inversion of direct current to alternating current. The main feature is the use of a rotating plasma arc in crossed electric and magnetic fields as a switch. This device may provide an economic alternative to other inversion methods in some circumstances.

One constant feature of plasma technology is the surprising variety of uses which can be made of this remarkable state of matter. One of the earliest and most frequent applications is that of electrical switching. Although solid state thyristors have increasingly replaced plasmas in high power switching applications, the use of plasmas for switching megawatts of power and kiloamperes of current persists. In contrast with solid state devices, a plasma is an inherently high power object. It is an energetic extreme of material for the energy ranges of interest here, and adding more energy to it just makes more plasma. A gaseous plasma is, in fact, the final state of an overloaded transistor.

Specialized devices exist for the initiation and interruption of current flow but the workhorse plasma switch is the mercury arc rectifier [1]. A simple three electrode version of this switch is shown in Fig. 1. A quartz or ceramically insulated steel envelope surrounds an evacuated cavity in which the remaining atmosphere is mostly mercury vapor. The negatively charged cathode. which is subject to the destructive bombardment of positively charged ions. is made of liquid mercury. The positively charged anode is made of tungsten or graphite. A third ignition electrode near the cathode is used to initiate the discharge.

In the non-conducting state,several kilovolts can be applied across the anode to cathode gap. To initiate the discharge, a small spark is drawn between the ignition electrode and the cathode. An electron-emitting spot then forms on the cathode from which some electrons reach the anode precipitating the main discharge.

Once established. this plasma arc conducts kiloamperes of current with voltage drops of one hundred volts or less. To shut the device off and bring it back to the non-conducting state, this current must be brought to zero by lowering the anode to cathode voltage to less than this one-hundred-volt drop. This need for close to zero commutation voltage severely restricts the design of mercury arc invertors.

Two other problems plague this device: backfiring when the anode is at a higher voltage than the cathode and spontaneous firing of the device in the forward direction at the wrong moment.

Figure 2 details a simple single phase invertor circuit using two mercury arc rectifiers. A direct current power supply is connected in parallel with the rectifiers which then connect to opposite ends of a transformer winding which has a central tap. This tap leads back to the power supply. The output winding of the transformer is connected in parallel with a tuning capacitor and a load reactance. This circuit operates by alternately switching the two rectifiers on and off so that current flows first one way and then the opposite way through the transformer input winding. The output winding is then inductively driven by this alternating current, transferring it to the tuning capacitor and load. The tuning capacitor provides a back voltage which eventually drives the currents in the transformer downwards, thus transferring this back voltage to the rectifier. This shuts off the discharge at the appropriate moment. The tuning capacitor is usually a necessary element of this circuit.

Elaborate schemes exist for improving the output waveform, controlling the phase, and making the circuit of Fig. 2 more dependable. These schemes will not be discussed here.

Figure 3 schematically illustrates a rotating arc plasma invertor [2] which replaces the two mercury arc rectifiers in the circuit of Fig. 2. It consists of a single cylindrical cathode and two anodes made out of a symmetrically split annulus. A magnetic field is applied along the axis of the cylindrical cathode. The cathode is connected to the negative pole of the direct current power supply. The anodes are connected to the opposite ends of the input transformer winding and the central tap to the remaining power supply lead. The principle of operation is quite simple.

An arc is struck between the cathode and one of the anodes. Under quite general conditions it forms a single spoke of plasma between the two, which then rotates around the device at a velocity that depends on the applied magnetic field and the spoke current.

When the spoke encounters the gap between the pieces of the split annulus, it jumps across, transferring the flow of current in an alternating manner between the pieces.

The idea of splitting the annular electrode in a rotating arc crossed field device is one of the authors (K.J.), who thought of it in order to measure the spoke velocity in such a device. Its use as an inversion method followed immediately.

Three invertors have been constructed and operated at low currents and voltages. One of them with ten amperes of current and one hundred volts was used to power an ordinary household electric fan and vary its speed from one to one hundred hertz by changing the applied one hundred gauss magnetic field. All three of these devices had solid metallic electrodes and operated at a relatively high pressure of one atmosphere.

The rotating arc plasma invertor would presumably find a niche in high power applications where the deficiencies of solid state devices are most evident. One example is in the substations of high voltage direct current power distribution systems [3] where conversion to alternating current is necessary both to step down the voltage and for distribution over the local alternating current systems.

A prototype rotating arc invertor for such an application is shown in Fig. 4. It borrows heavily on the extant technology of mercury arc rectifiers. The cathode is liquid mercury, the anode is tungsten or graphite, and the applied magnetic field is radial.

The practicality of the rotating arc invertor in such an application is at present unknown. A number of questions need to be answered experimentally since spoke formation, rotation, and stability are complex three-dimensional phenomena and are not completely understood theoretically[4]. Its advantages over the ordinary rectifier may include an absence of backfiring, a higher permissible commutation voltage, and a longer lifetime.

The existence of a single spoke is due to the pinch effect and localized cathode spots. The actual size of the spoke has a complicated dependence on plasma conditions.

The speed of spoke rotation is determined by the interplay of a number of factors: the drift velocity of charged particles, the presence of finite flows in the plasma, the motion of hot spots on the electrodes, and plasma surface interactions. A number of competing theories exist. The spoke does not always rotate at the E cross B drift velocity and indeed under certain avoidable circumstances may rotate in the opposite direction. Usually its dependence on the applied magnetic field strength and spoke current is nonlinear and monotonic,

$$V \sim I^{\alpha} B^{\beta}$$

where α and β are larger than 1.

The details of the process by which the spoke jumps across the anode gaps are not clear. Although the crossed field drift forces electrons to cross the gap, the presence of a finite voltage between the split annuli at the time of commutation should inhibit this jump and the maximum back voltage at which the jump will proceed is a critical parameter of the device.

The rotating arc invertor may not suffer from the inverse conduction problems of the mercury arc rectifier but may incur anode to anode conduction at commutation time. This would dissipate energy stored in the transformer and result in reduced efficiency, but may actually help the spoke to jump by reducing any extant voltage between the annuli. Such anode to anode conduction was not observed in the invertors built to date. In any event it could be eliminated by the inclusion of a tuning capacitor.

More experiments based on the device in Fig. 4 are necessary to answer some of these questions.

Other applications of the rotating plasma invertor are discussed in Ref. [2]. Multiphase versions of the device, phase locking of multiple devices, and output frequency control are all possible. One interesting extension replaces the transformer with an antenna and splits the anode into a number of segments connected in an alternating fashion to the poles of the antenna. This results in the multiplication of the rotation frequency by half the number of anode segments. Such a system may be able to produce very high power radio frequency electromagnetic waves.

Another application of multiple segment anodes in a single phase device would wire sucessive segments to the input winding of the transformer so that sucessive segments gradually couple to more and more turns, and then fewer and fewer turns of the input winding. This decreases the segment to segment voltage at commutation time by splitting it into several steps.

We have sketched out the basic idea of a rotating plasma arc invertor and some of the problems which need to be investigated in order to establish its usefulness. It could potentially reduce the cost of energy distribution in electrical power systems and has a number of other industrial and scientific applications. Further experimentation is necessary and seems justified.

References

1. D.G.Fink and J.M. Carroll, Standard Handbook for Electrical Engineers , Tenth Edition, Secs. 12 and 14. (McGraw-Hill, New York, 1968).
2. K. Jayaram and M. F. Reusch, Electrical Invertor Apparatus, U.S. Patent 4,194,239, (Mar. 18, 1980).
3. C. Adamson and N. G. Hingorani, High Voltage Direct Current Power Transmission, (Garraway Limited, London, 1960).
4. IEEE Trans. Plasma Sci., Vol. PS-1, No. 3, Special Section on Arcs, (1973).

Figure Captions

Figure 1 - Simple Mercury Arc Rectifier

Figure 2 - Simple Invertor Circuit

Figure 3 - Rotating Arc Invertor Circuit

Figure 4 - Prototype Rotating Arc Invertor

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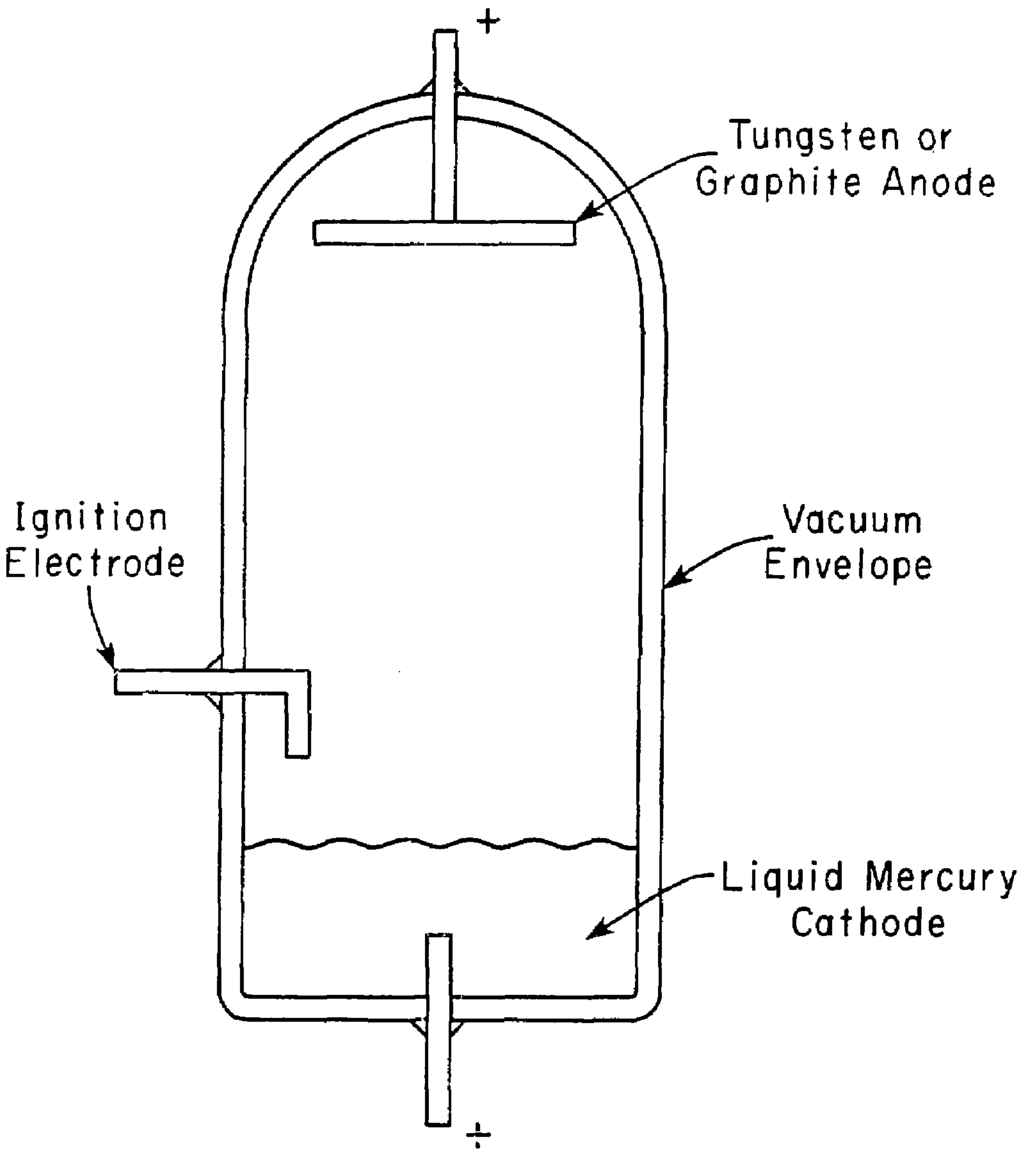

Fig. 1

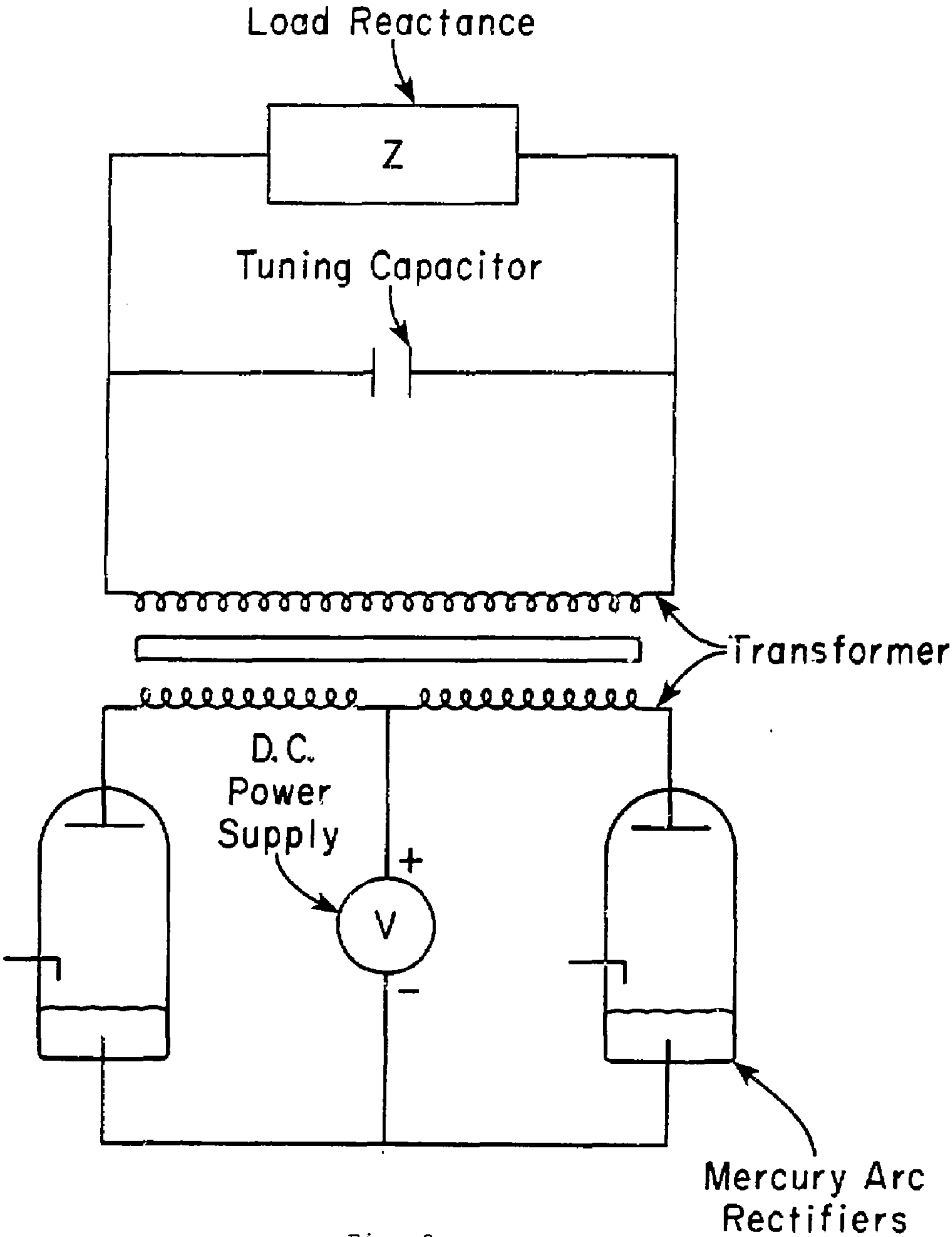
Load Reactance
Z
Tuning Capacitor
Transformer
D.C.
Power
Supply
+
V
−
Mercury Arc
Rectifiers

Fig. 2

#86P0242

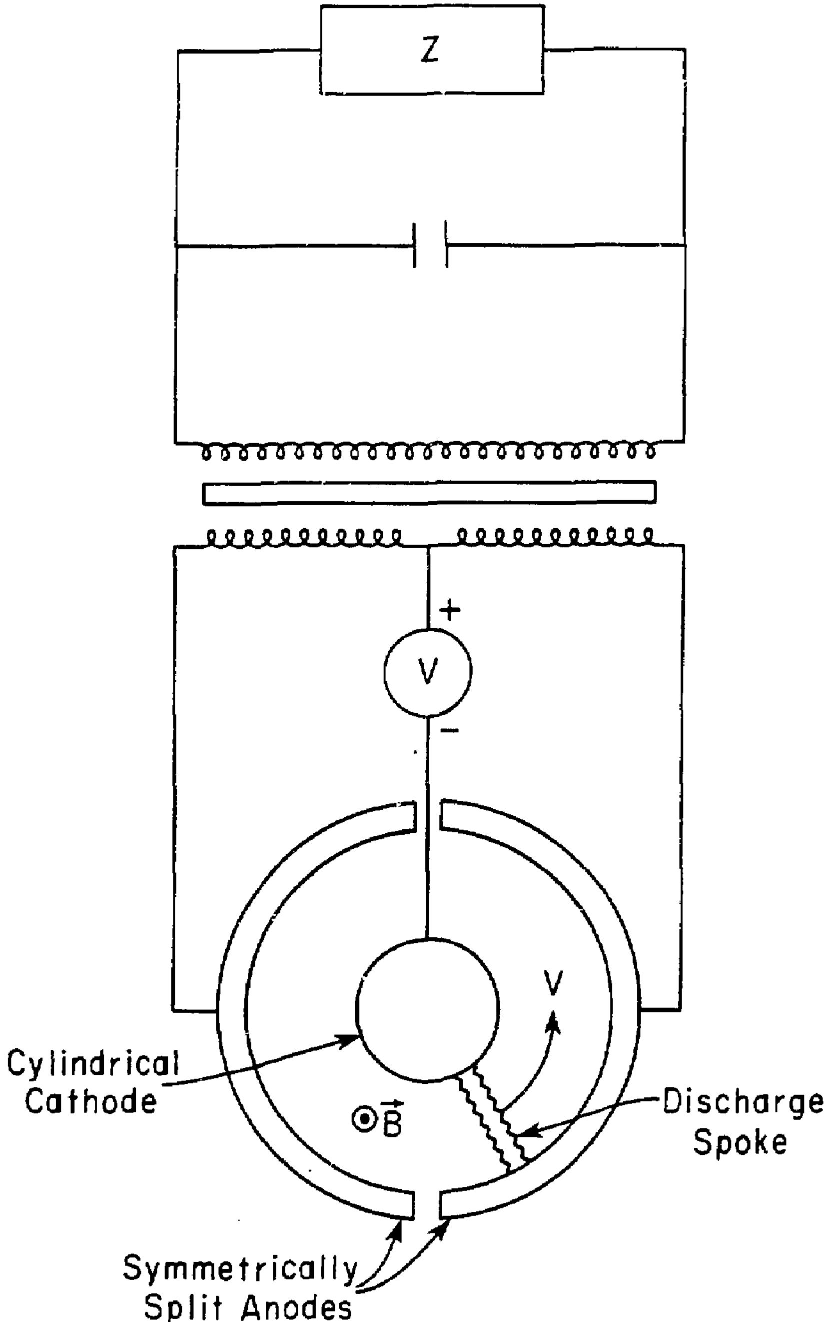

Fig. 3

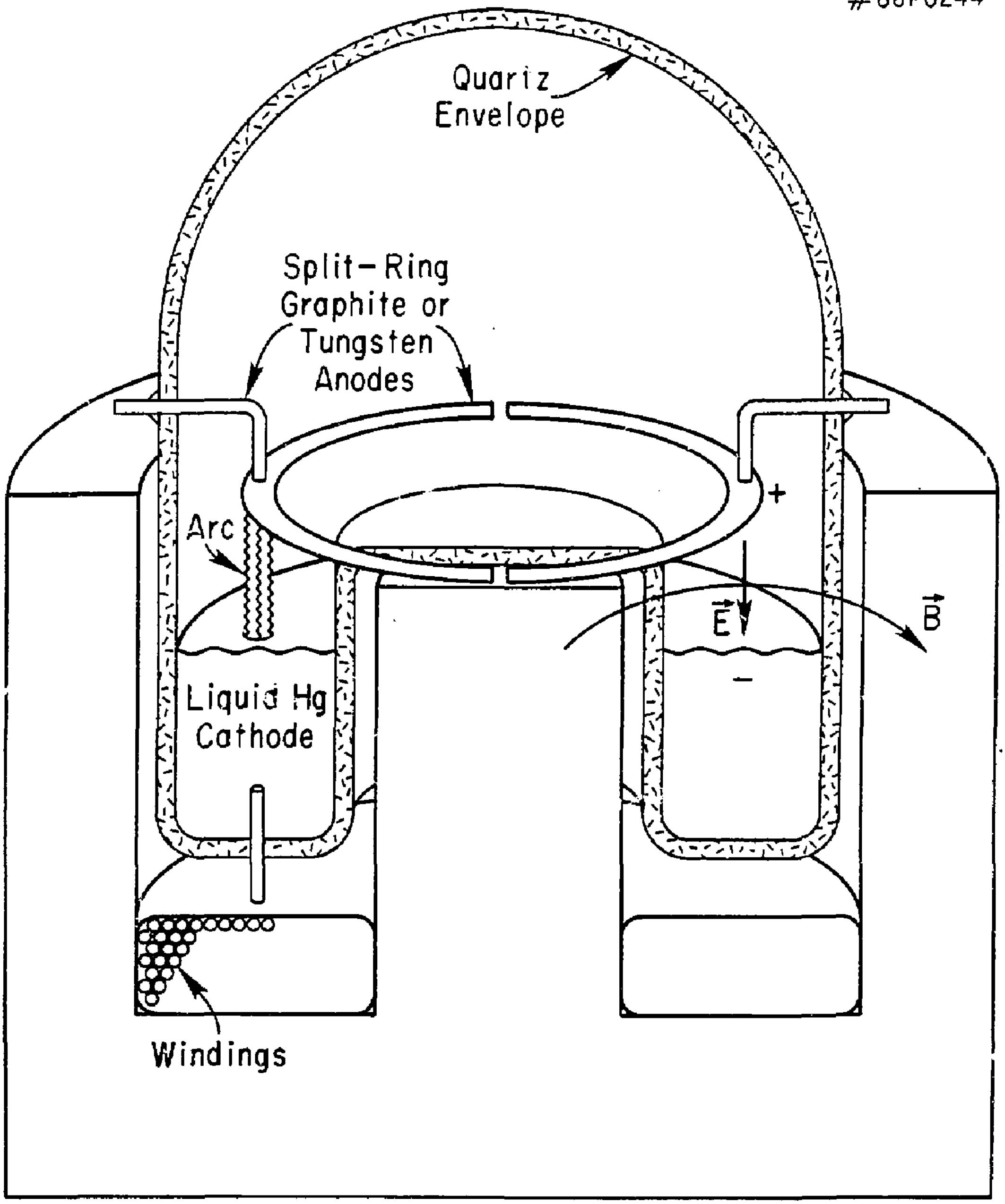
Quartz
Envelope
Split-Ring
Graphite or
Tungsten
Anodes
Arc
+
E
B
–
Liquid Hg
Cathode
Windings

Fig. 4

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