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Johnson et al.

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[54] **DYNAMIC BRAKING OF A GAS TURBINE POWERED SHIP PROPULSION SYSTEM UTILIZING A D. C. ELECTRIC DRIVE**

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[73] Assignee: **The United States of America as represented by the Secretary of the Navy,** Washington, D.C.

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[52] **U.S. Cl.** **318/376,** 290/17

[51] **Int. Cl.** **H02p 3/14**

[58] **Field of Search** 318/144, 147, 150, 151, 318/156–158, 253, 375, 376, 379, 381; 290/2, 4, 14, 17, 52

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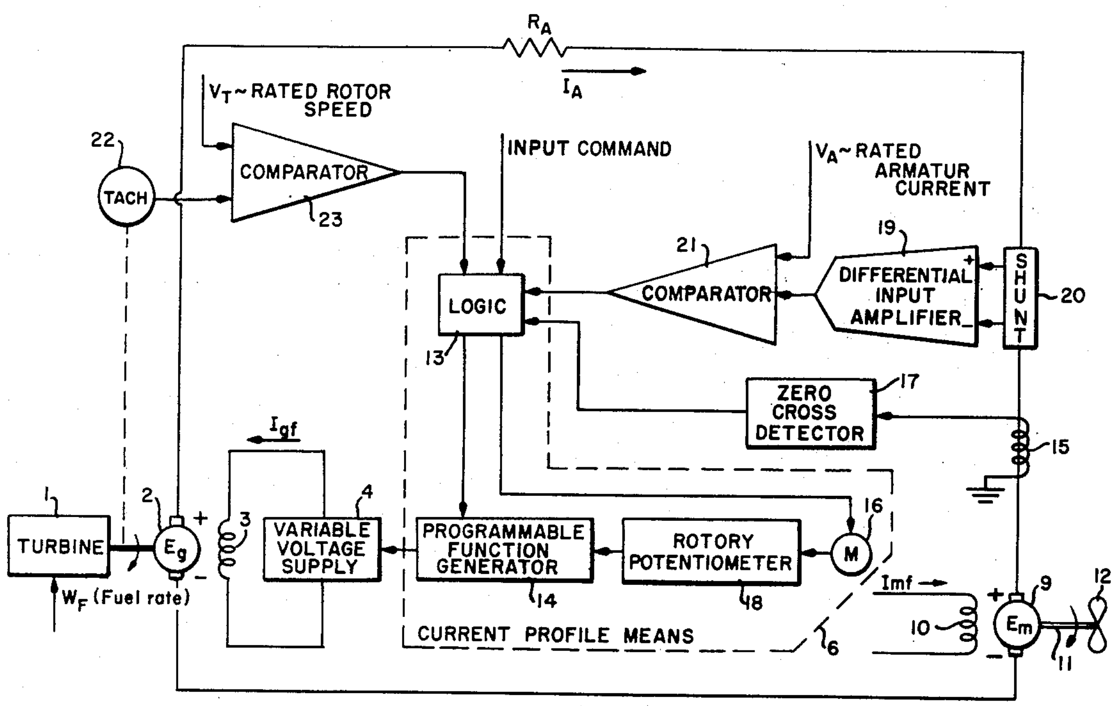
[57] **ABSTRACT**

Dynamic braking of a ship's propeller powered by a turboelectric drive system is achieved by dissipating the rotational energy of the propeller through the windage loss of the gas turbine rotor. Braking torque on the propeller is maximized by controlling the generator field current according to a predetermined profile so as to maximize armature braking current without exceeding rated armature current or rated rotor speed.

11 Claims, 3 Drawing Figures



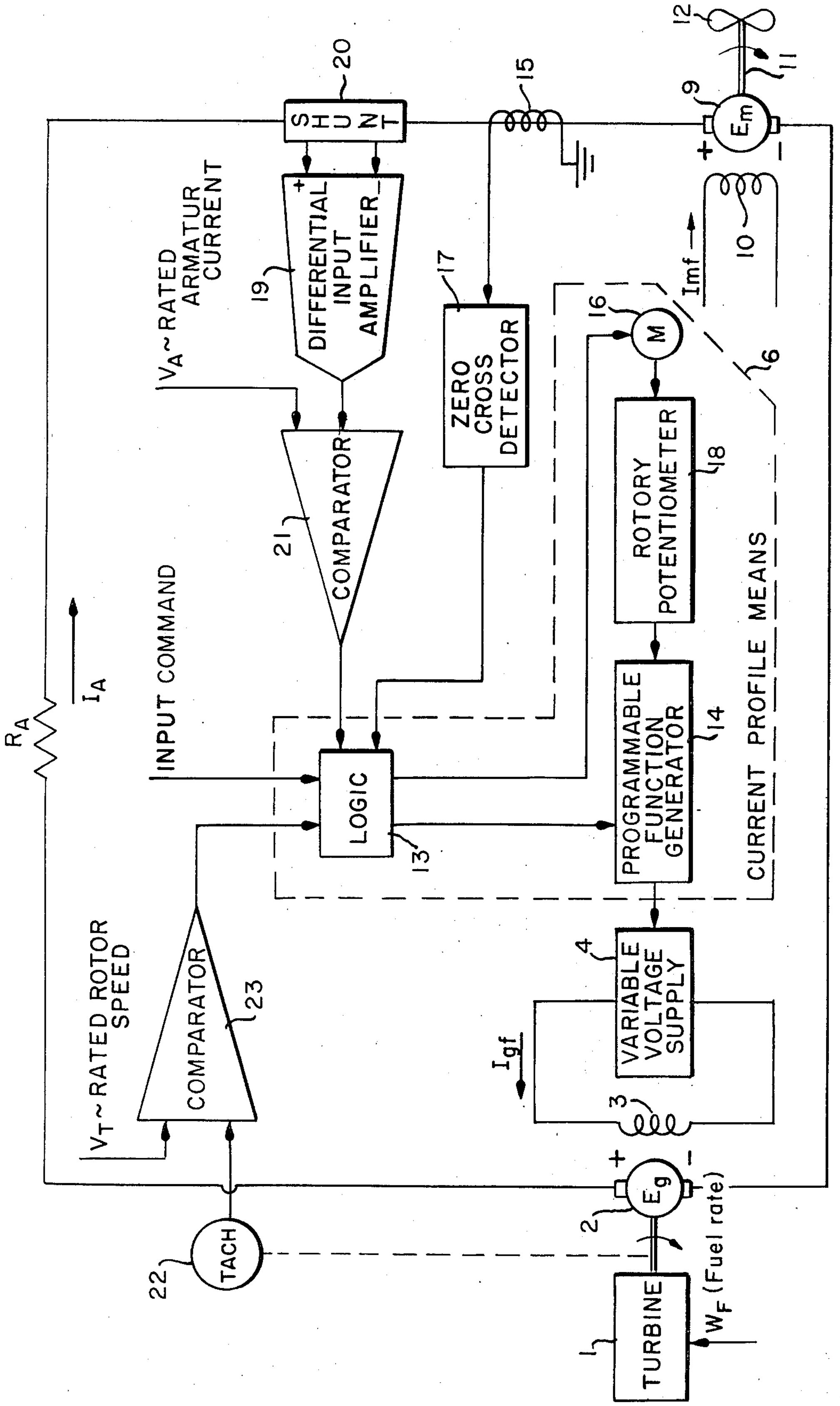

SHUNT
20
15
12
11
9
E_m
10
I_{mf}
DIFFERENTIAL INPUT AMPLIFIER
19
V_A ~ RATED ARMATUR CURRENT
17
ZERO CROSS DETECTOR
16
M
6
ROTORY POTENTIOMETER
18
COMPARATOR
21
INPUT COMMAND
I_A
R_A
LOGIC
13
PROGRAMMABLE FUNCTION GENERATOR
14
CURRENT PROFILE MEANS
VARIABLE VOLTAGE SUPPLY
4
I_{gf}
3
COMPARATOR
23
V_T ~ RATED ROTOR SPEED
E_g
2
TACH
22
TURBINE
1
W_F (Fuel rate)

FIG. 1.

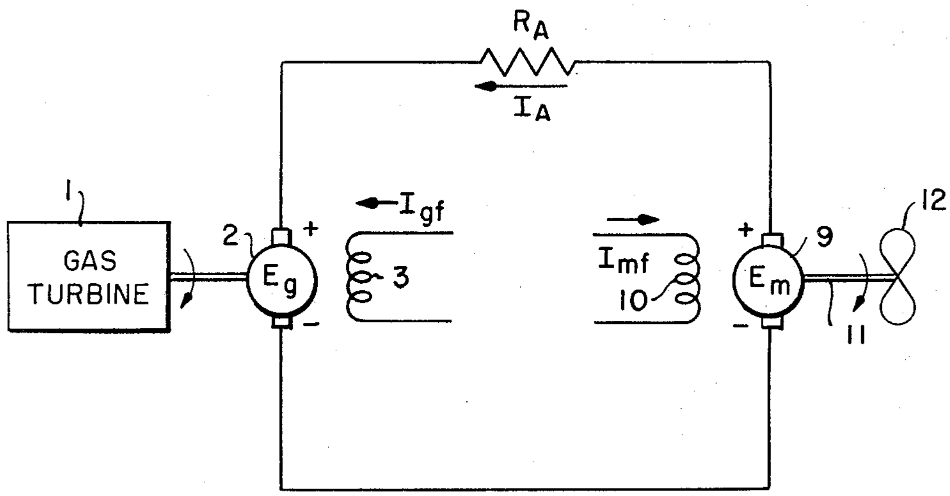

R_A
I_A
1
GAS TURBINE
2
E_g
I_{gf}
3
I_{mf}
10
9
E_m
11
12

FIG. 2.

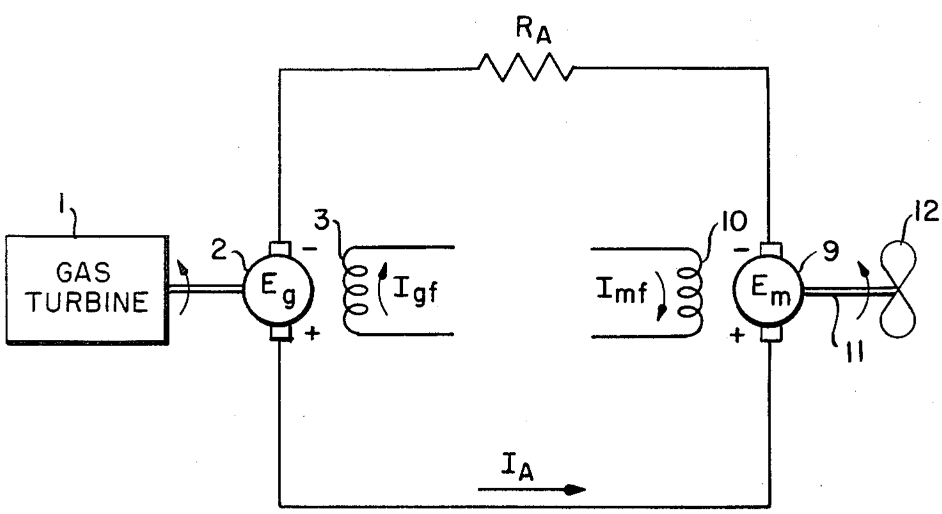

R_A
1
GAS TURBINE
2
E_g
3
I_{gf}
I_{mf}
10
9
E_m
11
12
I_A

FIG. 3.

DYNAMIC BRAKING OF A GAS TURBINE POWERED SHIP PROPULSION SYSTEM UTILIZING A D. C. ELECTRIC DRIVE

BACKGROUND OF THE INVENTION

This invention relates to an electromechanical propulsion system and more particularly to apparatus for dynamically braking a ship's propeller which is driven by a gas turbine powered d. c. electric generator-motor set.

In the conventional method of dynamic braking an adjustable resistance is connected across the motor terminals. When the fuel rate to the turbine is reduced to the idle condition, power is no longer delivered to the propeller. Instead, the propeller which continues to rotate due to total drive system inertia and the "windmilling" effect as it is being dragged through the water, delivers power to the motor. The motor then acts like a generator and delivers current to the braking resistor which dissipates the propeller's kinetic energy in the form of heat. The armature current that flows through the motor exerts an electromagnetic braking torque, Q_B, on the propeller in accordance with the equation:

$$Q_B = K_{QM} Q_M I_A \quad (1)$$

Where Q_M is the motor field flux,

K_{QM} is the motor torque constant.

To maintain rated braking torque, a control system assures that rated current flows in the motor by lowering the braking resistance as the propeller speed decreases.

There are several disadvantages of the above braking method. The braking resistor must be very large to dissipate the required power. New development costs would be necessary to provide an adjustable resistance at the high current levels (100,000 amperes or more) of homopolar motors. And the necessary switching and control of the braking resistor requires additional complexity.

SUMMARY OF THE INVENTION

It is therefore an object of this invention to provide a simple method of dynamically braking a ship propulsion system which utilizes turboelectric power.

It is another object of this invention to eliminate the braking resistor and its disadvantages by efficiently utilizing the existing structure of a turboelectric propulsion system for dissipating the energy of the propeller during braking.

Accordingly, it is a feature of this invention to utilize the turbine rotor windage loss to absorb power from the propeller during braking. Use is made of the concept of generator field weakening to permit maximum windage loss of the turbine rotor and to control the braking current.

Various other objects and advantages will appear from the following detailed description taken in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a preferred embodiment of the invention.

FIGS. 2 and 3 show the direction and polarity of current and voltage respectively of FIG. 1 at different times after braking is initiated.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now specifically to FIG. 1 the rotor output of a conventional gas turbine **1** is mechanically coupled to the armature of a homopolar generator **2.** As is well known, a homopolar generator provides a continuous and direct armature current. The direction and magnitude of the armature current is controlled by the magnetic field produced by the generator field coil **3.** The generator field current I_{gf} is derived from a variable voltage source **4.** During braking, I_{gf} is controlled by current profile control circuitry **6** to optimize dynamic braking. The generator armature is electrically coupled to the armature of a homopolar motor **9.** The motor field coil **10** is supplied with a direct current from a source not shown. Shaft **11** of propeller **12** is connected to the armature of motor **9.**

The current profile control circuitry **6,** as stated above, operates to maximize braking by controlling the generator field current I_{gf}. The logic circuit **13** in response to an input command signal sets the programmable function generator **14** and motor **16** for a desired profile and speed, respectively. At the beginning of dynamic braking, current I_A is caused to reverse direction for reasons to be described. As I_A decreases in value, passes through zero and then increases in value in the opposite direction, a corresponding induced voltage in coil **15** will change polarity at the point in time that I_A passes through zero. Zero cross detector **17** senses the polarity change and produces an output which is processed by logic circuit **13** to activate motor **16** at the speed set by the input command signal. The motor **16** drives rotary potentiometer **18** so as to produce a linear ramp voltage at the output thereof. The ramp voltage output of the potentiometer **18** is processed by the function generator to give the desired voltage vs time profile to control the variable voltage supply **4,** which in turn gives rise to the desired generator field current I_{gf}.

Programmable function generators are well known in the art. Preferably, generator **14** should be capable of producing a piecewise linear approximation of a predetermined profile in response to the potentiometer ramp voltage. As an example, between 0 volts and 1 volt on the ramp voltage the function generator might be programmed to produce a voltage with a slope of two. Between 1 and 2 volts of the ramp voltage the function generator might be programmed to produce a voltage with slope of one half, and so on. The slope of the ramp voltage, which is controlled by the motor speed, is determinative of how quickly the function generator will run through a particular programmed voltage profile.

To develop a desired field current profile during dynamic braking an arbitrary first estimate of the I_{gf} profile would be generated in a simulation run by appropriately programming function generator **14** and by setting the speed of motor **16.** During the simulation the armature current, I_A, and turbine rotor speed are monitored. Successive profiles are incorporated in the simulation until one is found that results in maximum armature braking current for the greatest extent of the braking period without exceeding the rated armature current or rated rotor speed.

In most cases, the variable voltage supply would be programmed to avoid exceeding rated armature current and rated rotor speed. However, to prevent accidental overrating two comparator circuits are employed to monitor these parameters. To monitor the armature current a differential input amplifier **19** is connected across shunt **20.** The output voltage of amplifier **19** is proportional to the actual armature current and is applied to one input of comparator **21.** The other input to comparator **21** is a voltage corresponding to rated armature current. When I_A is below rated value the comparator output is zero with no effect on the voltage supply **4.** If I_A exceeds rated value, the comparator output becomes positive and is fed to logic circuit **13.** In response to the positive comparator input the logic circuit **13** causes the function generator **4** to drive the voltage supply **4** in a direction to reduce I_A. The comparator returns control to the function generator when I_A again becomes less than rated value.

In a similar manner the turbine rotor speed is monitored. Tachometer **22** develops a voltage proportional to actual rotor speed. The tachometer voltage is compared with a voltage proportional to rated rotor speed in comparator **23.** The output of comparator **23** operates to reduce armature current if rated rotor speed is exceeded in a similar manner as the output of comparator **22.**

Now assume that a ship is proceeding full speed ahead with the propulsion system as shown in FIG. **1.** A crash reverse maneuver would begin by employing a dynamic braking to bring the propeller speed quickly to zero. The braking phase is initiated by reducing the fuel rate W_F to the gas turbine to idle condition, thereby cutting power to the propeller. The total drive system from the free turbine to and including the propeller quickly gives up some of its kinetic energy before reaching a relative steady state condition in which the propeller rotation will be attributed solely to "windmilling" as it is dragged through the water by the ships inertia movement. As this steady state condition is reached, the direction of energy flow in the propulsion system will be reversed. The windmilling propeller will deliver power to the motor **9** causing it to act as a generator thus reversing the direction of armature current flow as shown in FIG. **2.** The generator **2,** concomitantly, will act as a motor so as to drive the turbine rotor in the same direction as prior to the reduction to the fuel rate. This is because the electromagnetic torque of the generator **2** has changed direction in response to the armature current's direction change, and now instead of bucking the rotation of the turbine rotor, it acts to drive it.

Similarly, the electromagnetic torque of the motor **9,** now instead of driving the propeller, resists its rotation and therefore acts as a brake.

The power being withdrawn from the propeller is primarily consumed by the windage loss of the rotor of the gas turbine. Power dissipation in the armature resistance is negligible. As the propeller speed is reduced by the braking torque, Em is continually decreased (since Em is directly proportional to rpm) and this would ordinarily reduce the braking current I_A and hence decrease the braking torque. To maintain the braking torque on the propeller shaft at a significant level, the field current of the generator **2** (acting as a motor) is decreased by current profile control circuitry **6** which is activated when zero crossing detector **8** indicates I_A has changed direction as previously explained. This immediately results in a decrease in the back E.M.F., Eg, of the generator **2,** thus allowing an increase in armature braking current I_A. The increase in current I_A effects an increase in braking torque, Q_B, of motor **9** in accordance with equation (1) as Q_B is directly proportional to I_A.

By the same reasoning, as I_A increases, generator **2** applies a greater electromagnetic torque to the rotor on the free turbine, thus increasing the turbine rotor speed and windage loss. It is desirable that the braking current I_A be maintained as close as possible to its rated value without exceeding the rated speed of the turbine rotor. These last conditions determine the rate of field weakening in generator **2** or in other words, the shape of the current profile produced by current profile circuitry **6.** That is, the current profile of the generator field current during braking must be shaped so that it allows armature current I_A to be maximized, so as to effect maximum braking torque on the propeller (1) without exceeding I_A rated current value and (2) without allowing rated speed of the turbine rotor to be exceeded.

As an example, suppose that the rated windage loss of the turbine rotor is 4,000 hp at rated speed of 4,000 rpm. The power delivered to the turbine rotor by generator **2** (acting as a motor) is given by the relation

$$Pg = E_g I_A \tag{2}$$

The braking current is then

$$I_A = Pg \times 746 \quad \text{watts/hp}/Eg = 4000 \times 746 \quad \text{Amps.}/Eg \tag{3}$$

As Eg is reduced by programmed field weakening, equations (1) and (3) give the profiles of the braking torque and current respectively. With continuing field reduction, the current I_A will be maximized within the limits set out above.

At the end of the dynamic braking phase the propeller has been slowed to near zero speed. At the same time the field current I_{gf} is near zero. Under zero field conditions the turbine-generator is theoretically decoupled from the motor and propeller. The only load presented to the motor is the extremely low armature resistance. Consequently, the braking current I_A, and torque, Q_B required to oppose the windmilling torque can be achieved by a very low generated voltage at the motor terminals. The low voltage E_m implies a very low motor and propeller speed.

When the propeller is brought to a halt, the field current I_{gf} is reversed thus reversing the polarity of the generator and initiating a motor torque which soon turns the propeller in the opposite direction as shown in FIG. **3.** The fuel rate W_F to the gas turbine and the generator field current are simultaneously increased to provide an increase of power to the reversing propeller without overspeeding the turbine or exceeding the rated armature current.

It is contemplated that superconducting field coils may be provided in both the homopolar generator and homopolar and motor field circuits. The superconducting coils are constructed in a manner well known in the art. For instance, they may comprise coiled copper tubing appropriately insulated with a source of cryogenic fluid for passage through the tubing. The purpose for employing superconducting field coils is that they can produce intense magnetic fields in a small package.

It will be understood that various changes in details, materials, steps and arrangements of parts, which have been herein described and illustrated in order to explain the nature of the invention, may be made by those skilled in the art within the principle and scope of the invention as expressed in the appended claims.

What is claimed is:

1. An electromechanical propulsion system for a ship's propeller utilizing dynamic braking comprising, in combination:

a gas turbine including a rotor;

a homopolar d. c. electric generator and a homopolar d. c. electric motor, said generator being mechanically coupled to said turbine rotor and electrically coupled to said motor, said motor being mechanically coupled to said propeller;

electrical energy coupling means between said turbine rotor and said propeller which, during propulsion, transmits energy produced by said turbine to drive said propeller and, during dynamic braking of said propeller, transmits energy from said propeller to drive said rotor of said turbine in the same direction it was moving during propulsion for dissipating the propeller's energy through rotor windage loss;

wherein said turbine rotor is mechanically coupled to the armature of said homopolar generator, the armature of said homopolar generator is electrically coupled to the armature of said homopolar motor, and the armature of said homopolar motor is mechanically coupled to said propeller so that said motor functions as a generator during braking of said propeller, thereby developing a reverse electromagnetic braking torque on said propeller, while said generator simultaneously functions as a motor, thereby driving said turbine rotor;

and further including generator field current profile means for controlling, according to a predetermined profile, the current in said generator field coil circuit during braking, at a value which will compatibly maximize both armature current, up to armature current rated value, and power delivered to said turbine rotor up to rated windage loss at rated speed of said turbine rotor.

2. The combination of claim **1**, wherein,

the field coils of said homopolar generator and said homopolar motor are superconducting.

3. The combination of claim **1**, including:

means to activate said current profile means for commencing said predetermined current profile in said generator field circuit in response to a change in a particular parameter of said propulsion system.

4. The combination of claim **3**, wherein:

said parameter is the common armature current of the homopolar generator and motor, and

said change is a reversal in direction of said common armature current.

5. The combination of claim **4**, including:

a variable voltage supply in the generator field coil circuit for supplying current to said field coil;

wherein said current profile means is coupled to said variable voltage supply for controlling the voltage thereof.

6. The combination of claim **5** wherein said current profile means includes:

a programmable function generator coupled to said variable voltage supply; and

said means to activate is coupled to said function generator.

7. The combination of claim **6** including armature current comparator means for comparing a signal proportional to actual armature current with a signal proportional to rated armature current and for supplying an output signal coupled to said function generator to effect a decrease in armature current when said armature current equals or exceeds its rated value.

8. The combination of claim **7** including rotor speed comparator means for comparing a signal proportional to said actual rotor speed with a signal proportional to rated rotor speed and for supplying an output signal coupled to said function generator to effect a decrease in rotor speed when said rotor speed exceeds its rated value.

9. A method of dynamically braking a ship's propeller which is driven by a turbine powered d. c. electric generator motor drive system including the steps of:

cutting power to said turbine;

transmitting the energy in said propeller via said d. c. electric drive system to said turbine; and

dissipating said energy in the windage loss of the rotor of said turbine by controlling the current in said generator field circuit according to a predetermined profile so as to compatibly maximize both armature current, up to armature current rated value and power delivered to the rotor of said turbine up to rated windage loss at rated rotor speed.

10. The method of claim **9** including the steps of:

initiating the step of controlling the current in said generator field circuit in response to a change in a particular parameter of said system.

11. The method of claim **10**, wherein:

said parameter is the armature current; and

said change is a reversal of direction of said armature current.

* * * * *