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(54) FLYWHEEL SYSTEM WITH SYNCHRONOUS RELUCTANCE AND PERMANENT MAGNET GENERATORS

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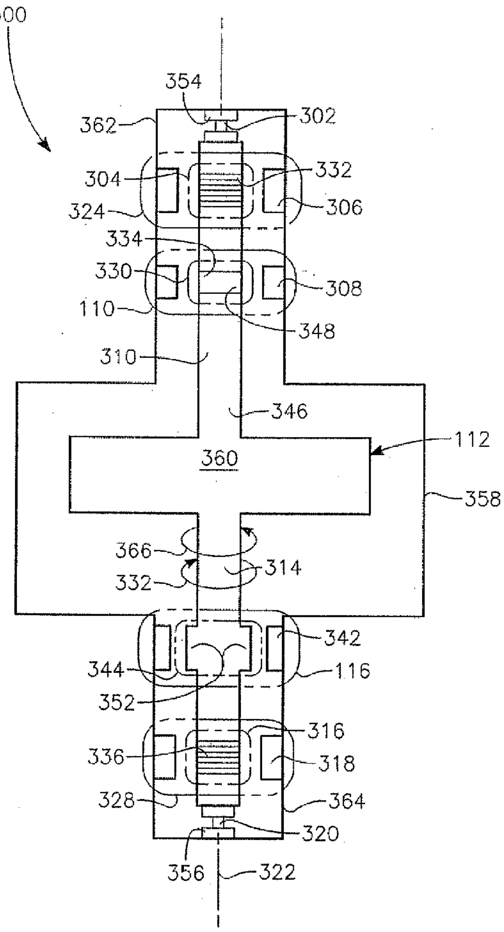
(57) ABSTRACT

The present invention provides a flywheel system with a variable speed synchronous reluctance motor-generator and a variable speed permanent magnet generator for providing backup power. The flywheel system incorporates rotating elements supported by electromagnetic bearings. Electric power provided by the backup generator maintains electromagnetic bearing operation during that portion of the coast down period when shaft speed falls below the minimum required for operation of the synchronous reluctance motor-generator.



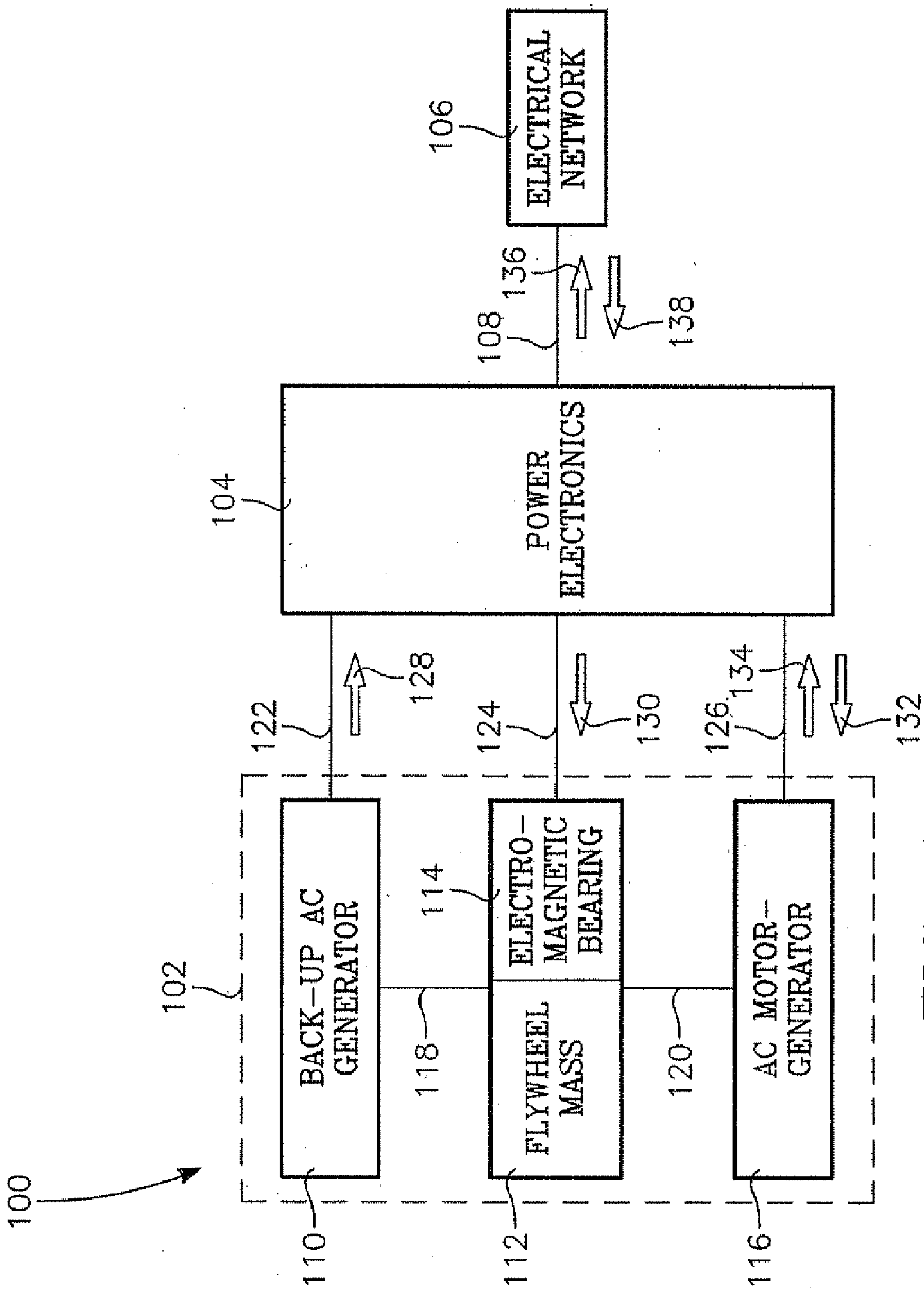

ELECTRICAL NETWORK
106
136
138
108
POWER ELECTRONICS
104
122
128
124
130
126
134
132
BACK-UP AC GENERATOR
ELECTRO-MAGNETIC BEARING
114
FLYWHEEL MASS
AC MOTOR-GENERATOR
102
118
120
100
110
112
116

FIG. 1

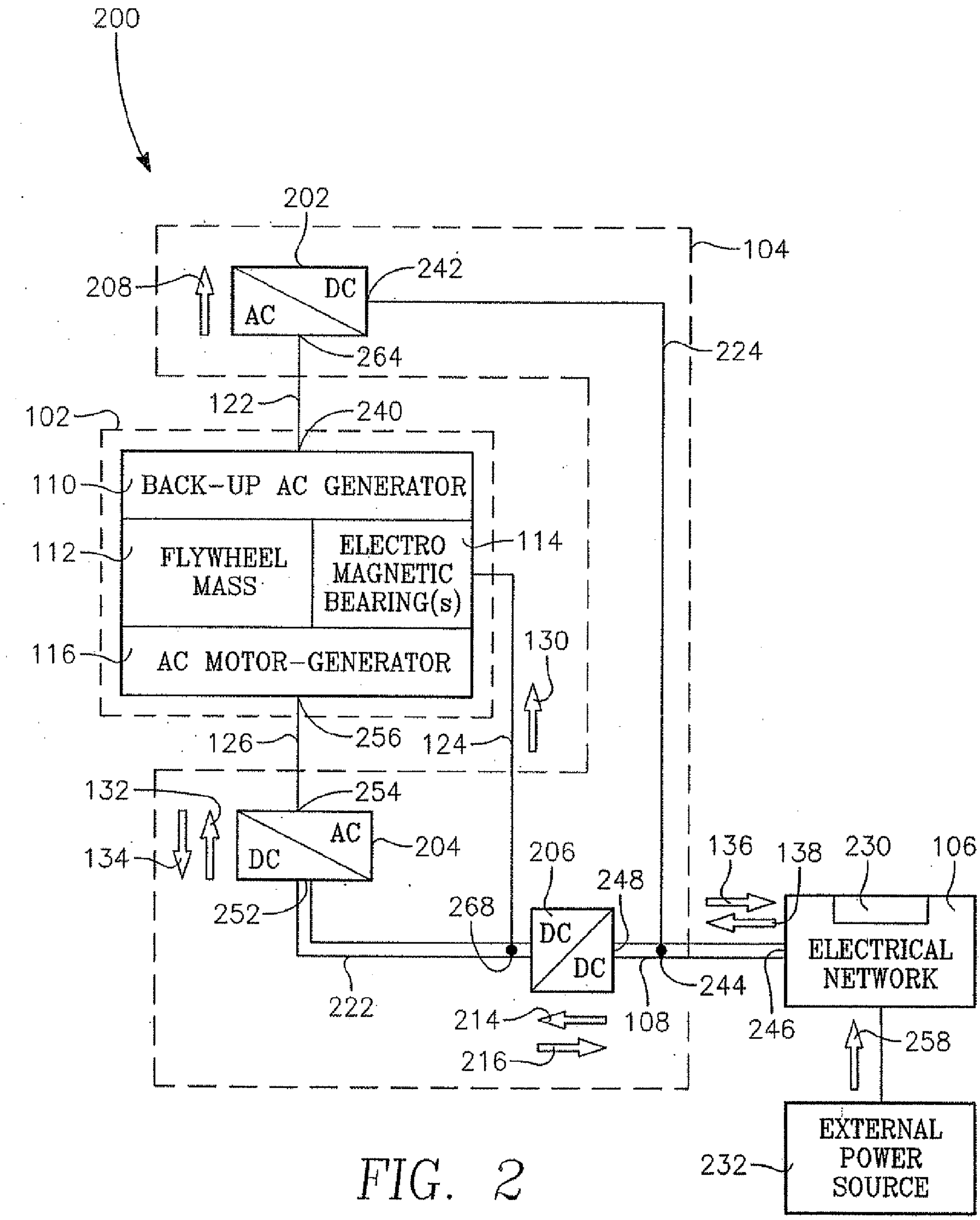

200
202
104
208
DC
AC
242
264
224
122
240
102
110
BACK-UP AC GENERATOR
112
FLYWHEEL MASS
ELECTRO MAGNETIC BEARING(s)
114
130
116
AC MOTOR-GENERATOR
126
256
124
132
254
AC
204
134
DC
206
136
138
230
106
248
252
268
DC
DC
ELECTRICAL NETWORK
244
222
214
108
246
258
216
EXTERNAL POWER SOURCE
232

FIG. 2

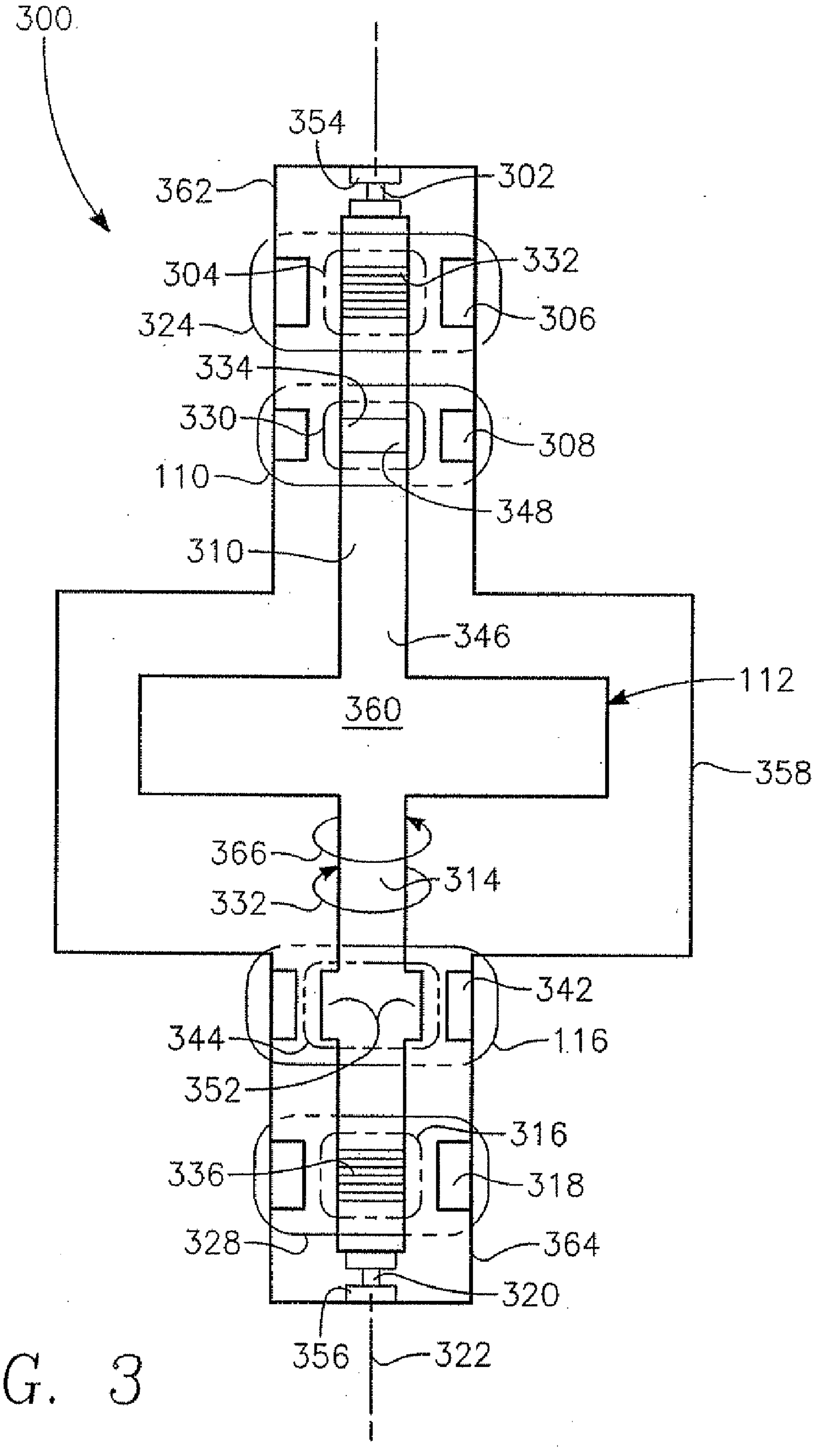

300
354
302
362
332
304
306
324
334
330
308
110
348
310
346
112
360
358
366
314
332
342
344
116
352
316
336
318
328
364
320
356
322

FIG. 3

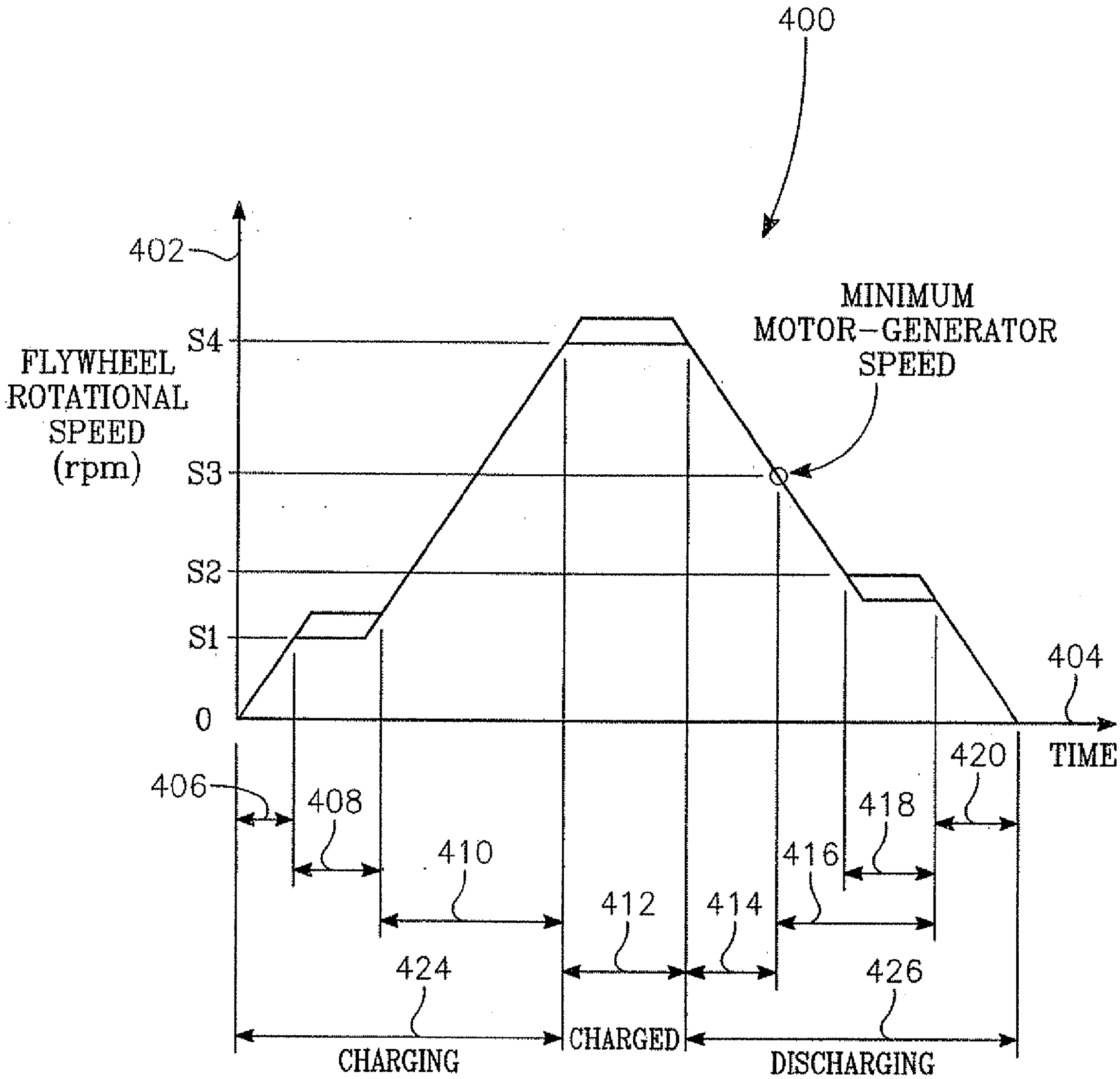

400
402
FLYWHEEL ROTATIONAL SPEED (rpm)
S4
S3
S2
S1
0
MINIMUM MOTOR-GENERATOR SPEED
404
TIME
406
408
410
412
414
416
418
420
424
426
CHARGING
CHARGED
DISCHARGING

FIG. 4

FLYWHEEL SYSTEM WITH SYNCHRONOUS RELUCTANCE AND PERMANENT MAGNET GENERATORS

[0001] This application is a continuation of U.S. application Ser. No. 11/251,394 filed Oct. 14, 2005, which claims priority from U.S. Divisional application Ser. No. 10/863,868 filed Jun. 7, 2004 now U.S. Pat. No. 7,109,622, which claims priority from U.S. Provisional Application 60/476,226 filed Jun. 6, 2003.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates to the electromechanical arts and energy storage systems. In particular, the present invention relates to flywheel systems used for energy storage and conversion.

[0004] 2. Description of Related Art

[0005] Flywheel energy storage systems have provided a mechanical energy storage solution for hundreds of years as evidenced by the potter's wheel. Such systems differ in many respects from modern-day flywheel energy storage solutions. More recent design imperatives including high power density and electric power outputs have led to lightweight, high-speed flywheels operating in evacuated chambers and driving a similarly high-speed electric generator.

[0006] A typical application for today's flywheel is to provide electric power to an electric network for a brief period of time, as might be needed when an electric power outage occurs. Such applications require that the flywheel operate in a stand-by mode, fully charged and ready to convert its mechanical energy into electrical power to support the electrical network when network supply voltage droops.

[0007] To the extent that a protracted power outage occurs and the flywheel's usable electric output is depleted by the external electric network, the flywheel's internal electrical loads may be deprived of the electric power required to complete a normal flywheel shutdown. Critical loads internal to the flywheel system may include electric and electronic controls.

[0008] Supplying electric loads internal to the flywheel system during coast down presents a particular problem when the flywheel's electric generator has a minimum operating speed as is typical of inductive generators. Here, another source of electric power will be needed during some portion of the coast down period.

SUMMARY OF THE INVENTION

[0009] Now, in accordance with the invention, there has been found a flywheel system that provides electric power to critical loads during coast down despite the absence of an external power source. A flywheel mass supported by electromagnetic bearings is rotatably coupled to a motor-generator for exchanging mechanical power with the motor generator. Further, the flywheel mass is rotatably coupled to a backup generator for converting mechanical energy from the flywheel mass into electrical power for providing electrical power to the electromagnetic bearings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The present invention is described with reference to the accompanying drawings that illustrate the present invention and, together with the description, explain the principles of the invention enabling a person skilled in the relevant art to make and use the invention.

[0011] FIG. **1** is a diagram showing modules included in the flywheel backup power supply system constructed in accordance with the present invention.

[0012] FIG. **2** is a diagram showing elements included within the power electronics module of the flywheel backup power supply system of FIG. **1**.

[0013] FIG. **3** is a diagram showing elements included in the flywheel module of the flywheel backup power supply system of FIG. **1**.

[0014] FIG. **4** is a diagram showing regimes included in the operation of the flywheel backup power supply system of FIG. **1**.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0015] FIG. **1** shows the flywheel system **100** of the present invention. It includes the flywheel module **102**, power electronics module **104**, and electrical network **106**. In the flywheel module, a first rotatable coupling **120** interconnects the flywheel mass **112** with the motor-generator **116** and a second rotatable coupling **118** interconnects the flywheel mass with the backup generator **110**. At least one electromagnetic bearing **114** provides rotatable support for the flywheel mass.

[0016] The power electronics module **104** is interconnected to sources and consumers of electric power including the backup generator **110**, the motor-generator **116**, and the electrical network **106**, and at least one electromagnetic bearing **114**.

[0017] A first electrical circuit **122** conducts electric power unidirectionally as shown by flow arrow **128** from the backup generator **110** to the power electronics module **104**. A second electrical circuit **124** conducts electric power unidirectionally as shown by flow arrow **130** from the power electronics module to at least one electromagnetic bearing **114**. A third electrical circuit **126** conducts electric power bi-directionally as shown by the opposed flow arrows **132**, **134** between the motor-generator **116** and the power electronics module. A fourth electrical circuit **108** conducts electric power bi-directionally as shown by the opposed flow arrows **136**, **138** between the power electronics module and the electrical network **106**.

[0018] Flywheel system **100** charging includes absorption and storage of mechanical energy by increasing the rotational speed and hence kinetic energy of rotating elements within the flywheel module **102** including the flywheel mass **112**. Flywheel system charging takes place when the electrical network **106** supplies electric power as shown by flow arrow **138** and the motor-generator **116** consumes electric power as indicated by flow arrow **132** while functioning as an electric motor.

[0019] Flywheel system **100** discharging includes releasing mechanical energy by decreasing the rotational speed and hence kinetic energy of rotating elements within the flywheel module **102** including flywheel mass **112**. Flywheel discharging takes place when the electrical network **106** consumes electrical power as shown by flow arrow **136** that is supplied by the motor-generator **116** as shown by flow arrow **134** while the motor-generator functions as an electric generator.

[0020] FIG. **2** shows a first embodiment of the flywheel system including selected elements of the power electronics module **200**. The power electronics module **104** includes three electric power converters. The first converter **202** is a uni-directional AC-to-DC converter, the second converter is a bi-directional AC-to-DC converter **204**, and the third converter is a bi-directional DC-to-DC converter **206**. The power electronics module also includes an internal DC bus **222**, an external DC bus **108**, and a fifth circuit **224**.

[0021] As mentioned above, the first, second, and third circuits interconnect the power electronics module **104** and the flywheel module **102**. What follows is a description of selected sources and users of electric power flowing in these circuits.

[0022] The first circuit **122** interconnects a backup generator AC output **240** as indicated by flow arrow **208** to a first converter AC input **264**. The fifth circuit **224** connects a first converter DC output **242** to an external DC bus tap **244** on the external DC bus **108**. Electric power users including the electrical network **106** and the third converter **206** thereby receive backup power from their respective interconnections **246**, **248** with the external DC bus.

[0023] The second circuit **124** interconnects an electromagnetic bearing electric power input **266** to an internal DC bus tap **268** on the internal DC bus **222**. Electric power flows from the internal DC bus to the electromagnetic bearing(s) **114** as shown by flow arrow **130**. The internal DC bus may receive electric power from the motor-generator **116**, the electric network **106** or the backup generator **110**. When the motor-generator is providing electric power, the motor-generator electrical connection **256** is an AC output interconnected to a second converter AC connection **254** by the third circuit **126**. Power flows from a second converter DC connection **252** as indicated by flow arrow **134** to the internal DC bus. When the electric network is providing electric power, an electric network connection **246** is a DC output interconnected to a third converter external DC connection **248** by external DC bus **108**. Power flows from a third converter internal DC connection **250** as indicated by flow arrow **214** to the internal DC bus. When the backup generator is providing electric power, power flows as described above from the backup generator to the external DC bus and thereafter to the internal DC bus.

[0024] Turning now to electric power flows associated with charging and discharging the flywheel system **100**, the motor-generator **116** may function either as an electric motor or as an electric generator. During charging the motor-generator functions as an electric motor. During discharging, the motor-generator functions as an electric generator.

[0025] During charging, the electric network **106** provides DC power to the third converter **206** via external DC bus **108** as indicated by flow arrow **138**. The converter adjusts the voltage to a level suitable for interconnection with the internal DC bus **222** and transfers electric power as indicated by flow arrow **214** to the internal DC bus. The second converter **204** takes power from the internal DC bus, synthesizes an AC output indicated by flow arrow **132**, and transfers power to the motor-generator via third circuit **126**. The AC output is suitable for powering the motor-generator **116** for accelerating the flywheel **360** (see FIG. **3**).

[0026] During discharging, the second converter **204** receives electric power from the motor-generator **116** via third circuit **126** as indicated by flow arrow **134**. The converter adjusts the voltage to a level suitable for interconnection with the internal DC bus **222** and transfers electric power to the internal DC bus. The third converter **206** takes power from the internal DC bus and adjusts the voltage as required for interconnection with the external DC bus **108**. Flow arrows **216** and **136** indicate transfer of electric power from the second converter to the electrical network via the external DC bus.

[0027] It should be noted that although the electrical network **106** is interconnected to the external DC bus **108**, a person of ordinary skill in the art will recognize that the electrical network may include electrical sources and loads having electrical characteristics that differ from those of the external DC bus. Auxiliary electric power converters **230** provide for interconnecting such sources and loads to the extent they are present in the network.

[0028] It should also be noted that while output **242** of first converter **202** may be processed by third converter **206** as shown in FIG. **2**, in a second embodiment, a fourth unidirectional DC-to-DC electric power converter (not shown) might be used to interconnect first converter output **242** with the electromagnetic bearings **114**. In this embodiment, the fourth converter adjusts the voltage level at first converter output **242** to accommodate the requirements of the electromagnetic bearings.

[0029] FIG. **3** shows selected flywheel module elements **300**. Rotating elements include the flywheel shaft **346** and the flywheel mass **112**. Stationery elements include the flywheel housing **358**, first and second electromagnets **306**, **318**, and first and second electric stators **308**, **342**. The flywheel **360** includes the flywheel mass **112** and the flywheel shaft **346**. The flywheel shaft includes first and second sections **310**, **314**. The flywheel shaft shares a common axis of rotation **322** with and is attached to the flywheel mass.

[0030] The flywheel **360** has integrated features including antifriction bearings **354**, **356** and electromagnetic bearings **324**, **328**, a backup AC generator **110**, and a synchronous reluctance AC motor-generator **116**. The sections that follow provide details relating to these features.

[0031] Antifriction bearings **354**, **356** provide rotatable support to the flywheel **360** at low flywheel speeds. The flywheel utilizes first and second touchdown bearing shafts **302**, **320** mated with respective first and second antifriction bearings **354**, **356** for rotatable support. The antifriction bearings support both radial and thrust loads. The touchdown bearing shafts extend outwardly from respective opposing ends of the flywheel shaft and share a common axis of rotation **322** with the flywheel shaft **346**. The first and second antifriction bearings **354**, **356** are fixed to respective first and second flywheel housing parts **362**, **364**.

[0032] Electromagnetic bearing(s) **114** provide rotatable support to the flywheel **360** at higher flywheel speeds when the flywheel is no longer supported by the antifriction bearings **354**, **356**, but now relies on at least one electromagnetic bearing for support. Here, first and second electromagnetic bearings **324**, **328** are shown. The first electromagnetic bearing **324** is proximate to the first shaft section **310** and includes an electromagnet **306** attached to the first flywheel housing part **362** and an adjacent ferromagnetic portion **304** that is integral with the flywheel shaft **346**. The second electromagnetic bearing **328** is proximate to the second shaft section **314** and includes an electromagnet **318** attached to the second flywheel housing part **364** and an adjacent ferromagnetic portion **316** that is integral with the flywheel shaft **346**.

[**0033**] Each of the ferromagnetic portions of the shaft **304**, **316** includes a respective plurality of thin ferromagnetic laminates **332**, **336** having electrical insulation interposed between adjacent laminates. These laminated ferromagnetic structures increase the effectiveness of the electromagnetic bearings by reducing eddy current losses. In particular, eddy currents induced in the ferromagnetic portions by the electromagnets result in I^2 R heating losses. The thin ferromagnetic laminates reduce the magnetic flux in (results in smaller induced voltage) and the conductivity of (smaller conductive cross-section) each ferromagnetic laminate. The result is a reduction in eddy current losses by a factor of approximately $1/n^2$ where n is the number of lamella in a ferromagnetic portion.

[**0034**] The backup generator **110** is a variable speed permanent magnet AC machine. It includes a first electrical stator **308** adjacent to a flywheel shaft permanent magnet portion **330**. The flywheel shaft permanent magnet portion is in the first flywheel shaft section **310** and includes a permanent magnet **348** integral with the flywheel shaft **346**.

[**0035**] Since a permanent magnet generator is self-exciting, the backup generator generates electric power as long as the flywheel **360** is rotating even if no external source of electric power is available. The backup generator therefore provides electric power to the electromagnetic bearings **324**, **328** when operation of the electromagnetic bearing(s) is desirable and when no other electric power source is available to operate the electromagnetic bearing(s). As a person of ordinary skill in the art will recognize, the power produced by the backup generator may be used to power electric loads internal or external to the flywheel system **100**.

[**0036**] The motor-generator **116** is any inductive AC machine known to ordinary persons of skill in the art such as a wound-rotor or a reluctance type machine. The motor-generator includes a second electrical stator **342** and a rotor **344**.

[**0037**] In an embodiment, the motor-generator **116** is a variable speed synchronous reluctance AC machine. Here, the motor-generator includes a second electrical stator **342** adjacent to a flywheel shaft reluctor portion **344**. The reluctor portion is in the second flywheel shaft section **314** and includes a plurality of ferromagnetic reluctor poles **352** integral with the flywheel shaft **346**.

[**0038**] While functioning as an electric motor, the motor-generator **116** transfers torque **332** to the flywheel shaft **346** increasing the rotational speed of the flywheel **360**. While functioning as an electric generator, the motor-generator transfers torque from **366** the flywheel shaft reducing the rotational speed of the flywheel.

[**0039**] Since the motor-generator is not self-exciting, it produces electric power only when induced electric currents magnetize the rotating reluctor poles **352**. An externally excited stator **342** that is magnetically coupled with the reluctor portion induces such currents. Therefore, the motor-generator **116** cannot generate electric power unless there is a source of electric power external to the motor-generator. The power electronics **104** may provide the excitation power; however, when the flywheel **360** speed falls below a minimum value, useful generation of electric power by the motor-generator ends.

[**0040**] FIG. **4** is a graph **400** that illustrates the charging, charged, and discharging cycle of the flywheel system **100**. The vertical axis **402** represents rotational speed of the flywheel mass **112** in revolutions per minute (RPM). The horizontal axis **404** represents time.

[**0041**] Starting from a stand-still and during pre-liftoff **406**, flywheel system charging begins when the motor-generator **116** functions as a motor, applying an accelerating torque **332** to the flywheel shaft **346** as electrical power is converted to mechanical motion. As the flywheel **360** speed increases, the electromagnetic bearing(s) **324**, **328** operate during speed range **S1** to substantially disengage the touch-down bearing shafts **302**, **320** from the antifriction bearings **354**, **356**; this is termed "liftoff"**408**.

[**0042**] During the post-liftoff period **410**, the flywheel **360** is accelerated to the maximum speed range **S4**. Upon reaching speed range **S4**, the flywheel is fully charged **412**. Prior to discharging, the motor-generator cycles on and off as required to maintain flywheel speed within speed range S4. This cycling is required to recover speed decay resulting from friction and other losses in the system.

[**0043**] While charging **424** and cyclically while charged **412**, electrical power from the electrical network **106** is conducted in the direction of flow arrow **214** via external DC bus **108**, the third converter **206**, the internal DC bus **222**, the second converter **204**, and the third circuit **126** to the motor-generator **116**. Electric power supplied to the internal DC bus by the electrical network also powers the electromagnetic bearing(s) **114** via second electrical circuit **124** as indicated by flow arrow **130**.

[**0044**] The discharging period **426** begins when the motor-generator **116** functions as a generator, applying a retarding torque **366** to the flywheel shaft **346** and converting the energy of mechanical motion into electric power. During this process, the rotational speed of the flywheel **360** is reduced. As the speed decreases from speed range S4 to speed S3, the motor-generator generates electric power. Note that similar flywheel discharging occurs when the electrical network's external power source **232** is interrupted: In this case, the power flow to the electrical network **106** indicated by flow arrow **258** stops and the electrical network becomes dependent on the flywheel system for delivery of electric power via external DC bus **108** as indicated by flow arrow **136**.

[**0045**] During the initial discharging period **414**, electrical power from the motor-generator **116** is conducted in the direction of flow arrow **134** via the third circuit **126**, the second converter **204**, the internal DC bus **222**, the third converter **206**, and the external DC bus **108** to the electrical network **106** as indicated by flow arrow **136**. Electrical power supplied to the internal DC bus by the motor-generator also powers the electromagnetic bearings **324**, **328** via the second circuit **124** as indicated by flow arrow **130**.

[0046] When the flywheel **360** reaches the minimum motor-generator speed S**3**, the synchronous reluctance (inductive) motor-generator **116** is no longer able to provide enough electric power to operate the electromagnetic bearing(s) **324**, **328**. During the subsequent backup power speed regime **416**, the backup generator **110** provides sufficient electric power to operate the electromagnetic bearings. The backup generator also provides electric power for other electrical loads that may be necessary to the safe shut-down of the flywheel. As one who is skilled in the art will recognize, backup generator power is available via external DC tap **244** and internal DC tap **268** for powering critical loads whether they be internal or external to the flywheel system **100**.

[0047] When touchdown **418** occurs in speed range S**2**, the electromagnetic bearing(s) are no longer needed and the antifriction bearing shafts **302**, **320** are once again supported by respective antifriction bearings **354**, **356**.

[0048] During the backup power speed regime **416**, electrical power from the backup generator **110** flows as indicated by flow arrow **208** via the first converter, the fifth circuit **224**, the external DC bus **108**, the third converter **206**, the internal DC bus **222**, and the sixth circuit **124** to the electromagnetic bearings **114** as indicated by the flow arrow **130**. Here, the third converter is included in the power flow path to accommodate the backup generator's variable voltage output that rises and falls with the speed of the flywheel **360**.

[0049] Post-touchdown **420** begins when the speed of the flywheel **360** falls below speed range S**2**. This regime is the final portion of the discharging process **426**. If a source of external power is not available, the flywheel will come to rest.

[0050] While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. It will be understood by those skilled in the art that various changes in form and details can be made therein without departing from the spirit and scope of the invention as defined in the appended claims. Thus, the breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

What is claimed is:

1. An flywheel system comprising:

a rotatable assembly;

the rotatable assembly having a single axis of rotation and including a flywheel mass, a motor-generator rotor and a permanent magnet;

a fixed assembly;

the fixed assembly including a first electrical stator adjacent to the permanent magnet;

a containment enveloping the rotating assembly; and,

an electrical load critical to safe flywheel system operation electrically coupled to the first electrical stator for receiving electric power from the first electrical stator.

2. The flywheel system of claim 1 further comprising a second electrical stator adjacent to the motor-generator rotor.

3. The flywheel system of claim 2 wherein the motor-generator rotor includes a plurality of ferromagnetic reluctor poles.

4. The flywheel system of claim 3 wherein a motor-generator incorporating the second electrical stator and the motor-generator rotor is a variable speed synchronous reluctance motor generator.

* * * * *