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(54) **MOTOR DRIVE ARCHITECTURE WITH ACTIVE SNUBBER**

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See application file for complete search history.

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(57)   **ABSTRACT**

A method and apparatus is disclosed for controlling a system comprising at least one electric motor. The motor drive circuit includes a reconfigurable active snubber. Under given resonance conditions, the active snubber is configured to use a resistive element to dissipate electrical transients across the commutation circuit.

14 Claims, 6 Drawing Sheets
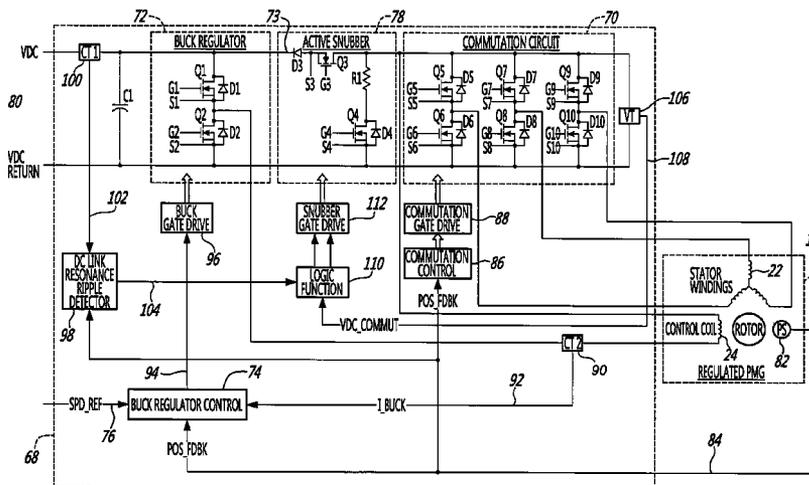
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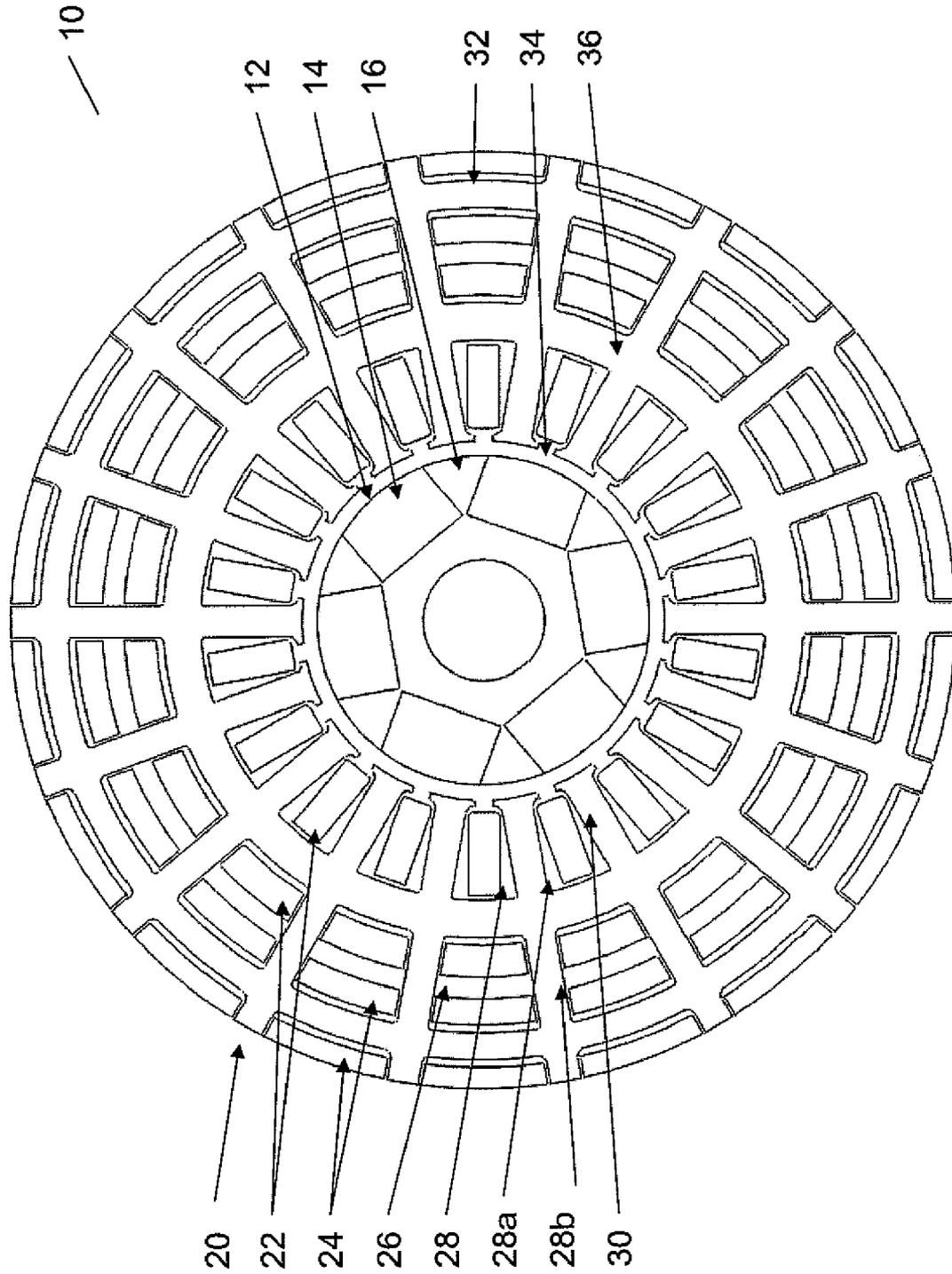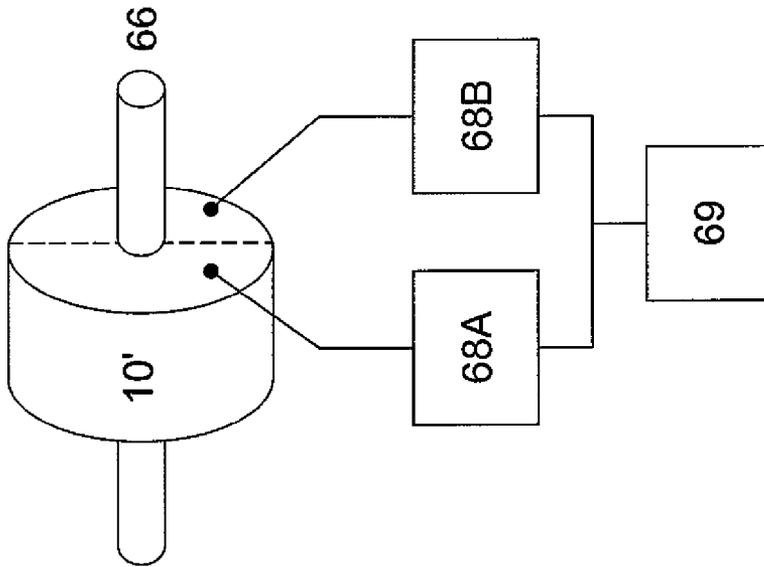European Search Report, EP07253722, Dec. 21, 2007.
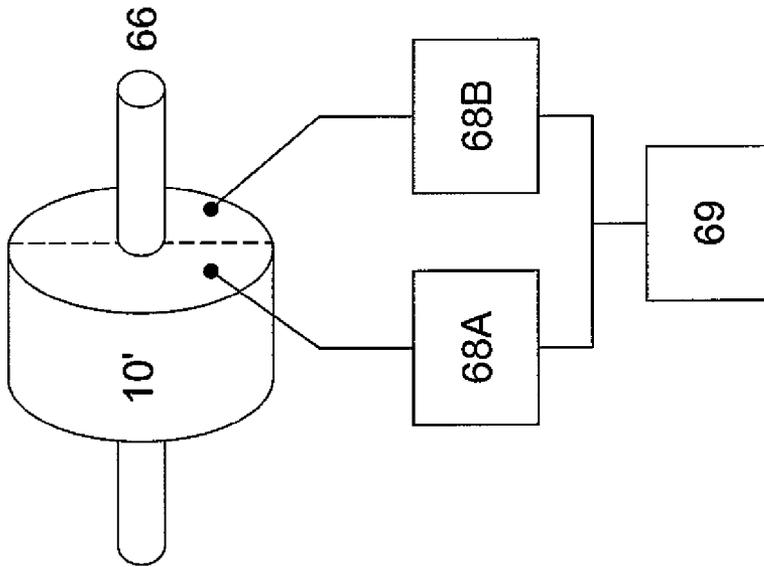
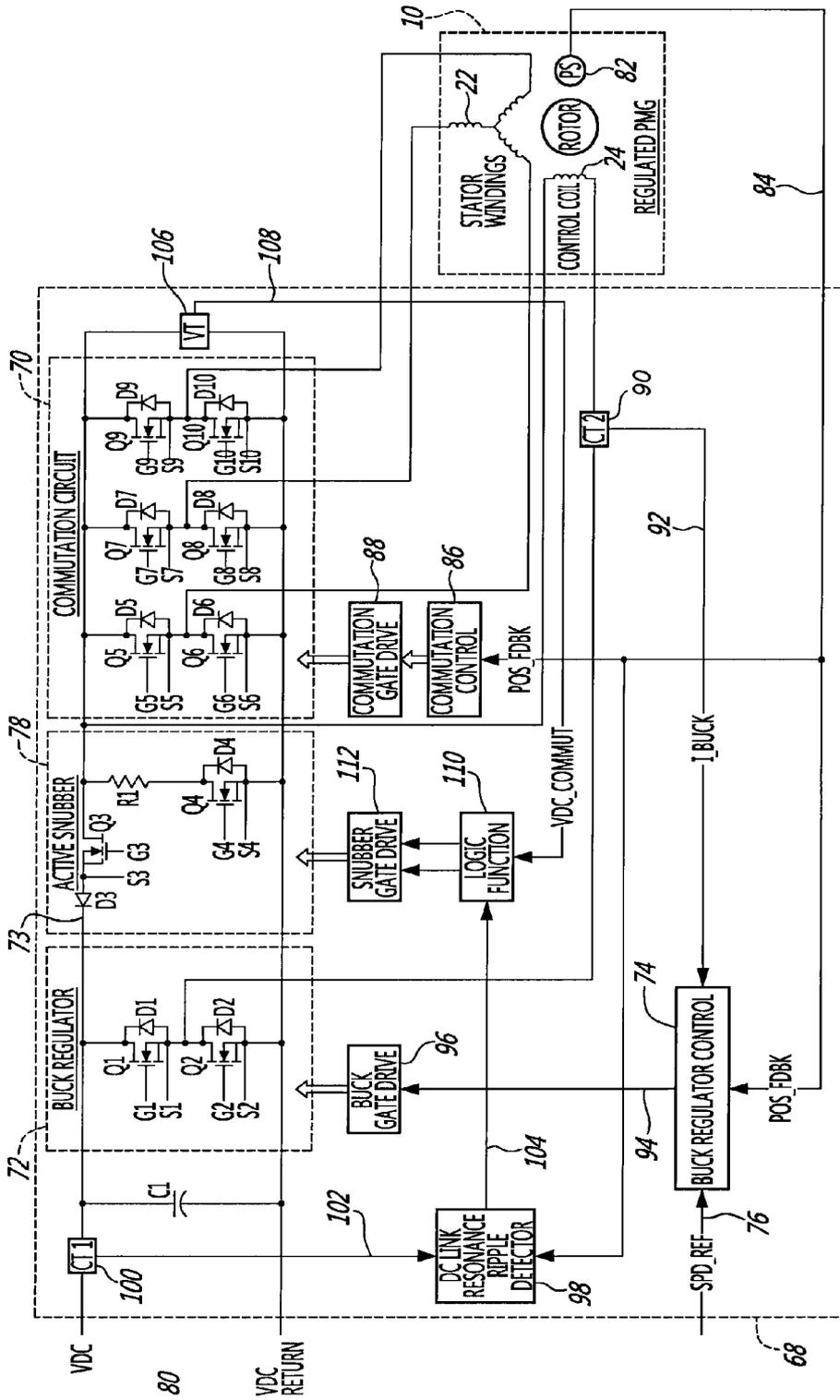* cited by examiner
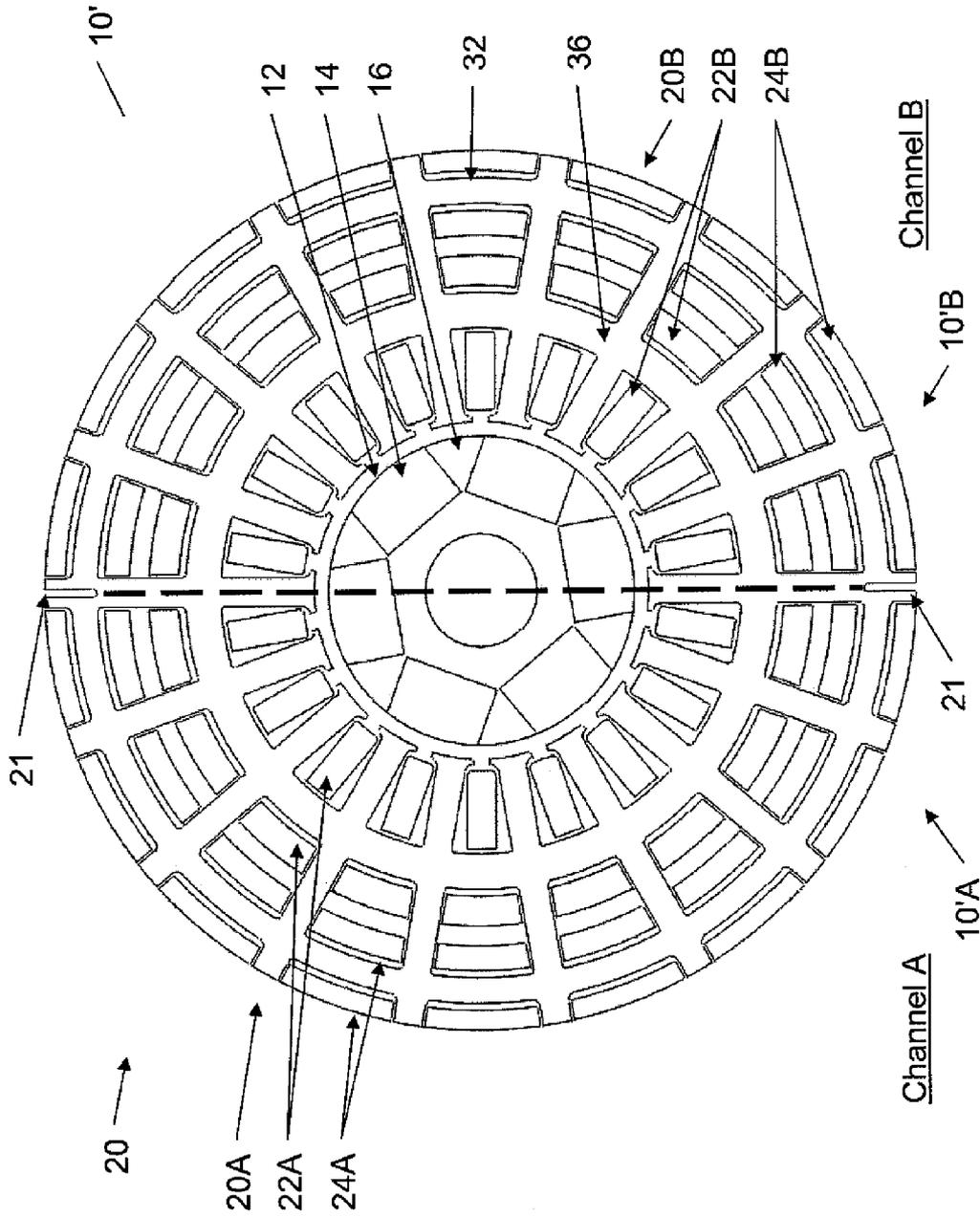
Figure 1

Figure 2

Figure 7

Figure 3

Figure 4

Figure 5

22
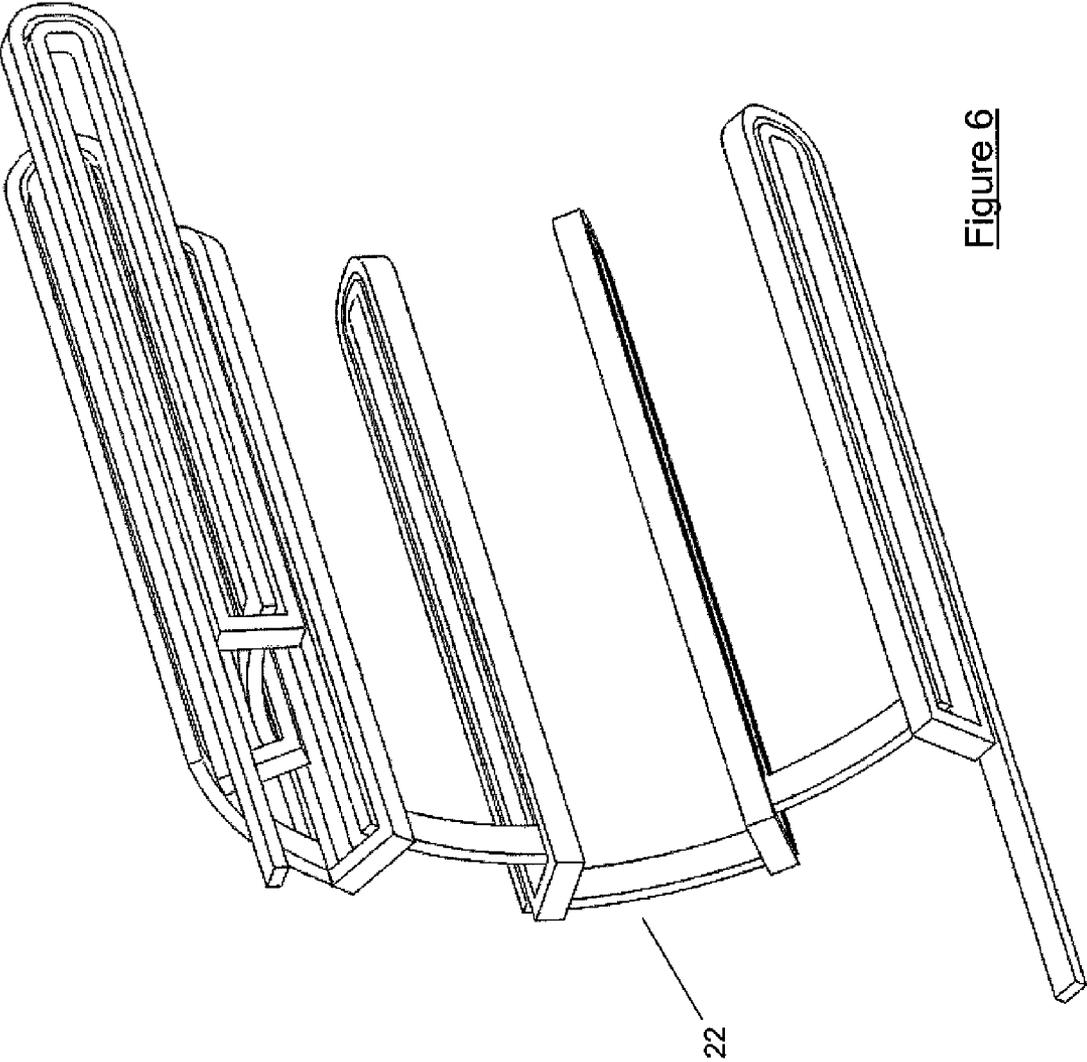
Figure 6

MOTOR DRIVE ARCHITECTURE WITH ACTIVE SNUBBER

TECHNICAL FIELD

The description relates generally to electric motors and, more particularly, to the control of electric motors.

BACKGROUND

In control of electric machines such as permanent magnet motors, current pulses due to electrical transients may be flowed back to the power supply by the use of a transient suppression feedback diode. When the power supply is at some distance away from the motor control circuitry, current pulses flowing back to the power supply may cause resonance or noise issues in the power supply cables at certain motor speeds, or drive current frequencies. Another possible transient damping circuit, or "snubber circuit", uses a resistive element that is switched in to dissipate voltage transients. Such a resistive snubber circuit is less efficient as the electrical transients are dissipated as heat. Accordingly, there is a need to provide improvements which address these and other limitations of prior art motor control systems.

SUMMARY

In one aspect, there is provided an active electrical protection apparatus for damping electrical transients in a control circuit of an electrical machine having phase windings driven using a commutation circuit and powered through a power supply connection. The apparatus comprises a power dissipating circuit arranged in parallel with the commutation circuit, and having a resistive element for dissipating power when electrical transients are damped and a first switch for switchably connecting the resistive element; and a controller for receiving a resonance signal representative of a resonance condition on the power supply connection, and for commanding the first switch at least as a function of the resonance signal.

In another aspect, there is provided an active electrical protection apparatus for damping electrical transients in an electrical machine having phase windings driven using a commutation circuit and powered through a power supply connecting line. The apparatus comprises a power dissipating device arranged in parallel with the commutation circuit, and having a resistive element for dissipating power when electrical transients are damped; a transient suppression device arranged in series with the power dissipating circuit and with the commutation circuit, and having a feedback diode device arranged inversely relative to a drive current of the commutation circuit; a switching device for switchably connecting the power dissipating device and for switchably connecting the transient suppression device; and a switch controller for receiving a resonance signal representative of a resonance condition on the power supply connecting line, and for commanding the switching device at least as a function of the resonance signal.

In another aspect, there is provided a method for damping electrical transients in an electrical machine having phase windings driven using a commutation circuit. The method comprises: providing a resistive element arranged in parallel with the commutation circuit, the resistive element for dissipating power when electrical transients are damped; providing a feedback diode device arranged in series with the power dissipating circuit and with the commutation circuit, and arranged inversely relative to a drive current of the commu-

tation circuit; evaluating a resonance condition based on at least one of a noise level on a power supply line and an operation frequency of the electrical machine; switching the feedback diode device in and out as a function of the resonance condition; measuring a voltage across the commutation circuit; comparing a value of the voltage to a limit voltage value to detect a voltage transient which determines a voltage condition; and switching the resistive element in and out as a function of the resonance condition and the voltage condition.

In another aspect, there is provided a method for damping electrical transients in an electrical machine having phase windings driven using a commutation circuit. The method comprises: providing a resistive element arranged in parallel with the commutation circuit, the resistive element for dissipating power when electrical transients are damped; evaluating an electrical resonance condition of a power supply line of the electrical machine; and switching the resistive element in and out as at least as a function of the electrical resonance condition.

Further details of these and other aspects will be apparent from the detailed description and figures included below.

BRIEF DESCRIPTION OF THE DRAWINGS

Reference is now made to the accompanying figures in which:

FIG. **1** is a cross-section of a permanent magnet motor;

FIG. **2** is a partial schematic of the motor of FIG. **1**;

FIG. **3** is a schematic of an arrangement of two of the motor of FIG. **1**;

FIG. **4** is a schematic diagram of one channel of a motor drive circuit for the motors of FIG. **3**;

FIG. **5** is a cross-sectional view, similar to FIG. **1**, of a another arrangement for a motor; and

FIG. **6** is an isometric view of a portion of a phase winding of the motor of FIG. **5**; and

FIG. **7** is a schematic diagram of a control scheme for the motor of FIG. **6**.

DETAILED DESCRIPTION

Referring first to FIGS. **1** and **2**, a permanent magnet (PM) electric machine **10** is depicted. For ease of illustration and description, FIG. **2** shows a linear arrangement of the electric machine **10** of FIG. **1**. However, it is to be understood that the machine **10** may have the circular architecture of FIG. **1**, with an inside or outside rotor. FIG. **1** shows an inside rotor. It will also be understood by the skilled reader that the Figures, as well as the accompanying description, are schematic in nature, and that routine details of machine design have been omitted for clarity, as will be apparent to the skilled reader. The machine **10** may be configured as an alternator to generate electrical power, a motor to convert electrical power into mechanical torque, or both. The motor aspects of such a machine are primarily of interest in the following description, and hence machine **10** will now be referred to as motor **10**.

The motor **10** has a rotor **12** with permanent magnets **14**, interposed by spacers **16**, which rotor **12** is mounted for rotation relative to a stator **20**. A retention sleeve (not shown) is typically provided to hold the permanent magnets **14** and the spacers **16**. Stator **20** has at least one phase winding **22** and at least one control winding **24** (both windings are represented schematically in the Figures as a solid rectangles in cross-section, but the skilled reader will appreciate each may comprise multiple turns of a conductor, as described below). In the illustrated embodiment, the stator **20** has a 3-phase design with three essentially electromagnetically-indepen-

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dent phase windings **22** (the phases are denoted by the circled numerals **1**, **2**, **3**, respectively in FIG. **2**) and, correspondingly, three control windings **24**. The phase windings **22** and control windings **24** are separated in this embodiment by a winding air gap **26** and are disposed in radial slots **28**, divided into slot portions **28a** and **28b**, provided in the stator **20** between adjacent teeth **30**. For ease of description, the adjacent slots **28a**, **28b** are indicated in FIG. **2** as A, B, C, D, etc. The phase windings **22** are electrically insulated from the control windings **24**. A back iron **32**, also referred to as the control flux bus **32** in this application, extends between and at the bottom of the slots **28b**. A rotor air gap **34** separates rotor **12** and stator **20** in a typical fashion. A core or "bridge" portion, also referred to as the "power flux bus" **36** portion of stator **20** extends between adjacent pairs of teeth **30** in slot **28** to form the two distinct slots **28a** and **28b**. The first slots **28a** hold the phase windings **22** only, and the second slots **28b** hold both the phase windings **22** and control windings **24**.

The materials for the PM motor **10** may be any one deemed suitable by the designer. Materials may comprise samarium cobalt permanent magnets, copper phase and control windings, a suitable electromagnetic material(s) for the stator teeth and power and control flux buses, such as electrical silicon steels commonly used in the construction of electromagnetic machines. The stator teeth, power and control flux buses may be integral or non-integral with one another, as desired. Each of the phase windings **22** in this embodiment consists of a conductor with 4 turns per slot, which enters, for instance, the first slot portion **28a** of a selected slot **28** (e.g. at slot "A"), extends through the slot and exits the opposite end of the slot, and then radially crosses the power flux bus **36** to enter the second slot portion **28b** of the same slot **28** (e.g. at slot "A"), after which it extends back through the length of the selected slot, to exit the second slot portion **28b**, and hence exits the slot **28** on the same axial side of the stator as it entered. This path is repeated 4 times to provide the 4 turns of the phase winding in that slot set **28a**, **28b**, before proceeding to the next relevant slot set in the stator. The conductor of phase winding **22** then proceeds to the second slot **28b** of the next selected slot **28** (e.g. slot "D" in FIG. **2**), where the phase winding **22** then enters and passes along the slot **28**, exits and radially crosses the power flux bus **36**, and then enters the adjacent first slot portion **28a** of the selected slot **28**, and then travels through the slot again to exit slot **28a** and the stator adjacent where the winding entered the slot **28b** of the selected slot **28**. This path is also repeated to provide the turns of the phase winding in this slot set **28a**, **28b**, before proceeding to the next relevant slot set in the stator. The phase winding then proceeds to the next selected slot **28** (e.g. slot "G"), and so the pattern repeats. A second phase winding **22** corresponding to phase **2** (not shown), begins in an appropriate selected slot (e.g. slot B of FIG. **2**) and follow an analogous path, and may be wound in an opposite winding direction relative to winding **22** of phase **1**. That is, the phase **2** winding **22** would enter the selected slot (slot B) via slot portion **28b** (since phase **1** winding **22** entered slot A via slot portion **28a**, above), and then follows a similar but opposite path to the conductor of phase **1**, from slot to slot (e.g. slots B, E, etc.). Similarly, the phase **3** winding **22** may be oppositely-wound relative to phase **2**, and thus enters the selected slot (e.g. slot "C") of the stator via slot portion **28a**, and follows the same general pattern as phase **1**, but opposite to the pattern of phase **2**, from slot to slot (e.g. slots C, F, etc.). Thus, as mentioned, the phases of the phase windings **22** are oppositely-wound relative to one another, for reasons described further below.

Meanwhile, a control winding(s) **24** is wrapped around the control flux bus **32**, in a manner as will now be described. In

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this embodiment, control winding **24** may form loops wrapped in a positive turn ratio relative to the phase winding. In this case, a control-to-phase turns ratio of 3:2 is contemplated, such that the control winding is wrapped 6 times around the control flux bus **32** (relative to the phase winding's 4 turns), for reasons described below. The control winding **24** and control flux bus **32** thus provide an integral saturable inductor in stator **20**, as will be discussed below. The direction of winding between adjacent second slots **28b** may be the same from slot to slot, and thus alternatingly opposite relative to the phase winding **22** of a same phase wound as described above, so that a substantially net-zero voltage is induced in each control winding **24**, as will also be described further below. All loops around the control flux bus **32** may be in the same direction. Note that the control winding **24** does not necessarily need to be segregated into phases along with the phase windings, but rather may simply proceed sequentially from slot to slot (e.g. slots A, B, C, D, etc.). Although it is possible to alternate winding direction of the phase windings, and not alternate direction of the control windings, the phase and control windings may be wound in relative opposite directions and in equal slot numbers to ensure a substantially net-zero voltage is induced in each control winding **24** as a result of current flow in the phase windings **22**, so that the function described below is achieved. If the control winding is segregated into phase correspondence with phase windings **22**, for example to reduce its inductance by a series parallel arrangement, there are potentially equal numbers of slots of a given phase in which the phase winding and control winding are wound in opposite directions, to yield the desired induced net-zero voltage.

In use, in a motor mode, a 3-phase power source drives phase windings **22**, which result in current flow in phase windings **22** and a primary magnetic flux along magnetic flux path or magnetic circuit **60**. Interaction of permanent magnets **14** and primary magnetic flux causes rotor **12** to move relative to stator **20**. When the current flow in phase windings **22** is appropriately controlled, the motor **10** rotates with a speed and torque. A current or voltage controller appropriately controls the current flow to the phase windings **22** such that an appropriate speed and torque is obtained. The current in the control windings in normal operation of the motor is substantially the same as the current flow in the phase windings, because they are connected in series, except that in this embodiment current may be DC in the control windings, and AC in the phase windings. The implications for motor control will be discussed further below.

Primary magnetic circuit **60** includes rotor **12**, magnets **14**, rotor air gap **34**, power flux bus **36** and the portion of stator teeth **30** between rotor **12** and power flux bus **36**. Primary magnetic circuit **60** encircles a portion of phase winding **22** and is generated in motor **10** by the combined effect of the rotor magnets and an electrical current in phase windings **22**. Secondary magnetic circuit **62** includes power flux bus **36**, control bus **32** and the portion of stator teeth **30** between control bus **32** and power flux bus **36**. In this embodiment, secondary magnetic circuit **62** encircles the portions of the phase winding **22** and control winding **24** in slot **28b**. Power flux bus **36** divides slot **28** into two slot portions or openings **28a** and **28b**, with one opening **28a** for the phase winding only, and another opening **28b** for the phase and control windings. The primary magnetic circuit **60** encircles an opening **28a** while the secondary magnetic circuit **62** encircles an opening **28b**. Opening **28a** may be radially closer to the rotor than opening **28b**. Power flux bus **36** is common to both the primary and secondary AC magnetic circuit paths in this embodiment. AC current in the phase windings **22** causes a

secondary magnetic flux to circulate in the secondary magnetic circuit **62** when the control bus **64** is not in a saturated state. The primary and secondary magnetic circuits are non-overlapping (i.e. non-intersecting), and remote or isolated from one another. The secondary magnetic circuit is remote from, and does not include, the rotor and may be defined wholly within the stator assembly.

A tertiary magnetic circuit **64** circulates around control bus **32**, as partially indicated in FIG. **2** (i.e. only a portion of the tertiary circuit is shown, as in this embodiment the tertiary circuit circulates around the entire stator **20**). The control flux bus **32** may be common to both the secondary and tertiary magnetic circuit paths and thus the secondary and tertiary magnetic circuits share a common portion, namely the control bus **32**, as will be discussed further below. At least a portion of control flux bus **32** is saturable by the flux density of the tertiary magnetic circuit.

Magnetic flux circulates the tertiary magnetic circuit **64** in the same direction around the control flux bus **32**. As mentioned above, although the control winding **24** is provided in the second slots **28***b* corresponding to a particular phase of the three-phase machine described, the phase windings **22** are wound in the opposite direction in each first slot **28***a* which is due to the opposite polar arrangement of the magnets **14** associated with each adjacent first slot **28***a* of the phase. To ensure that a uniform direction for the tertiary magnetic circuit **64** is provided, as mentioned, the control windings **24** may be wound in the same direction in all second slots **28***b*.

When the control flux bus **32** is magnetically saturated, the inductance (thus impedance) of the phase windings is very low, as if there where no secondary AC magnetic circuit. However, if zero current is applied to the control winding (i.e. the control winding is open circuited, or otherwise switched off), the impedance of the phase windings increases significantly, thus limiting the current that can flow in the phase windings, which may be used to remediate, for example, a faulted condition, such as an internally shorted phase winding or short circuits in the drive electronics. This impedance control has beneficial implications for PM motor control, discussed further below.

It is to be understood that the above description applies only to phase "1" of the described embodiment, and that similar interactions, etc. occur in respect of the other phases. Further details and aspects of the design and operation of motor **10** are found in U.S. Pat. No. 7,262,539.

Thus, in use, in a motoring mode, a power source drives phase windings **22**, and control windings **24**. As will be described hereinbelow in reference to FIG. **4**, in one example arrangement of the motor drive circuit, the two windings **22**, **24** are effectively connected in series and thus the control winding current is equivalent (in magnitude) to the phase winding current. As a result of the 3:2 turns ratio between these two windings **22**, **24**, the slightly higher number of turns in the control winding helps ensure that the control bus is always in a fairly saturated condition during normal motor operation, so as to enable efficient functioning of the motor at any drive current. As discussed above, although the AC flux in the phase windings **22** tends to cancel out the DC flux in the control winding **24** in the control bus sections where the flux directions are in opposition, the 3:2 turn ratio bias in the control winding **24**, prevents the fluxes from actually cancelling. Thus, when the control flux bus **32** is magnetically saturated by the action of current flowing through the control winding **24**, the inductance (thus impedance) of the phase windings **22** is very low, as if there where no secondary AC magnetic circuit, and hence the control windings and second-

ary magnetic circuit would be essentially "invisible" to the motor during normal motor operation.

According to the example arrangement of the motor drive circuit of FIG. **4**, the number of turns on the control winding slots will typically be chosen to be more than the number of turns in the phase winding slots, so as to ensure saturation of the control bus (however possibly not much into saturation, since some inductance in the control winding is a useful inductor for the buck regulator filter function as described below) by having just marginally more ampere turns on the control winding **24** than on the phase windings **22** in the secondary magnetic circuit. The DC flux in the control bus typically dominates relative to the opposing AC flux density in the secondary magnetic circuit, holding the control bus in saturation down to quite low relative values of drive current provided via the control winding **24** to the phase windings **22**, even under the effects of the counter fluxes from the phase windings **22** (i.e. the portion of the phase windings **22** carrying AC in the negative portion of the cycle tends to reduce saturation of the control flux bus, unless the control ampere turns are high enough to maintain saturation).

In use in a fault or shut-down mode, when the drive current to the motor is at or close to zero, i.e. such as when the motor is shut down in response to a fault condition, the control bus de-saturates (as a result of no control current being supplied) and, as a result, the interaction between the primary and secondary magnetic circuits and the inductor-like effect of the control winding **24**, impedes any significant generated currents from flowing in the phase windings due to continued rotation of the shut-down motor and any short circuit failure in the main phase circuits. Further discussion is found in U.S. Pat. No. 7,262,539.

FIG. **3** shows a redundancy arrangement in which two motors **10** are co-mounted on the same output shaft **66**, and driven by suitable motor drives **68**, each in communication with a system controller **69**, and operated as described above. If one motor **10** should fail in a short circuit, open circuit or ground (whether in the motor itself or the drive electronics or lead wires), the drive(s) **68** may adjust control of the remaining motor **10** (or motors **10**, if there are more than two provided in total, and two or more are to remain operational in the event of the shutdown of one) to compensate for the resulting loss in torque, and the failed motor is no longer driven. The controller **69** provides the appropriate control to motor drives **68**. As described above, the failed motor is also in effect disconnected, by bringing current flow in its control windings to zero, resulting in the impedance of the phase windings of the failed motor increasing to a high value, as previously described, such that the drag torque due to a short circuit type failure is minimized. Motor failure detection **84** may be achieved using any suitable approach, such as identifying/measuring/detecting incorrect speed or torque as a function of current, voltage, high temperature, machine impedance, etc. Failure detection results in a signal provided to an appropriate controller for interrupting the current supply to the motor system (i.e. bringing current flow to zero, as mentioned above).

FIG. **4** shows a simplified example scheme of a motor drive **68** for driving a motor **10**. It should be noted that the motor **10** schematically depicted in FIG. **4** depicts only a single control winding **24** for the three phases of its associated phase winding set, the control winding **24** proceeding slot-to-slot in the stator irrespective of the phase arrangements of the phase windings **22**. As discussed generally above, this is just one of many control winding arrangements possible, and the skilled reader will be able to apply the present teachings to such arrangements in light of the teachings herein.

The motor **10** is driven by the motor drive **68**, comprising a three-phase H-bridge commutation circuit **70** driving the phase windings **22** of the motor **10**. A commutation control **86** controls the commutation gate drive **88** of the commutation circuit **70** with feedback on the position of the motor **10**, as read by a position sensor **82**. The commutation scheme may be a six-step 120-degree overlapping scheme in a "make before break" sequence. This sequence in conjunction with an active snubber **78** reduces high amplitude voltage spikes occurring at the input of the inverter (commutation circuit) **70** due to the inductive effect of the stator windings **22** of motor **10** during motor commutation.

Current flow to the motor **10**, and thus the motor's torque and speed, is adjusted using a suitable pulse width modulated supply system or "buck regulator" circuit **72** making use of the control winding **24** of the motor **10** as described below. The buck regulator **72** may be any suitable circuit. The skilled reader will appreciate that buck regulators typically require a filter inductor as an energy storage device for stepping down the voltage level. In this configuration, the buck regulator **72** uses the control winding **24** as its inductor, thus eliminating the need for an additional inductor, and consequently reducing the weight of the buck regulator **72**. This filter inductor replacement role of the control winding **24** may dictate design features of the control winding **24**, as the designer will consider the buck regulator requirements as well as the motor requirements in providing a suitable control winding configuration. The output of the control winding **24** is connected to the inverter (commutation circuits) **70**, that operates in a six-step mode and provides AC current to the phase windings **22** of the motor **10**.

In use, the buck regulator **72** varies the current flow to the phase windings **22** of the motor **10**, and thus controls the torque and speed of the motor **10**, based on an input speed request **76** received from system controller **69** (not shown). Current is provided from a DC source **80** to the phase windings **22**, via the control winding **24**, as already described.

The buck regulator **72** is controlled by a buck regulator controller **74** which adjusts the duty cycle of the buck regulator **72** to control the torque and speed of the motor **10**. The regulator controller **74** receives the speed request **76**, a position feedback signal **84** from the position sensor **82** and a current feedback signal **92** from a current transducer **90** measuring the drive current level at the control windings **24**. The position feedback signal **84** is used to determine a speed error relative to the speed request **76**, and the duty cycle of the buck regulator **72** is adjusted to vary the level of the drive current. A duty cycle signal **94** is provided to the buck gate drive **96** that controls switch Q1 and Q2 of the buck regulator **72**.

The buck regulator **72**, buck regulator controller **74** and buck gate drive **96** are of any suitable type, which includes suitable types well-known to the skilled reader, and thus need not be discussed further here.

An active snubber **78** is used to damp electrical transients occurring at the input of the inverter (commutation circuit) **70** due to the inductive effect of the stator windings **22** of motor **10** during motor commutation. The active snubber **78** uses a transient suppression feedback diode **73** for most of the operation frequencies of the motor **10**. The power supply may be at some distance away from the motor control circuitry and current pulses flowing back to the power supply may cause resonance or noise issues in the power supply cables at certain motor speeds (or drive current frequencies). Accordingly, to avoid line impedance issues, the active snubber **78** is reconfigurable into a power dissipating circuit at resonance frequencies of the power supply network.

Accordingly, the active snubber **78** has a transient suppression circuit in series with the commutation circuit **70** and the power supply cables. The transient suppression circuit comprises a feedback diode **73** in series with switch Q3 (i.e., a MOSFET transistor) to switch in and out the feedback diode **73**. The feedback diode **73** is connected inversely relative to the drive current so that voltage pulses at the inductors of the motor **10** are passed on to the power supply on electrical transients, and the commutation circuit **70** is thereby protected. The feedback diode **73** is used (i.e. "in") during most of the operation of the motor **10** and ensures an efficient operation of the motor system at most drive frequencies.

However, at resonant frequencies of the power supply network, voltage pulses due to electrical transients are damped in a power dissipating circuit, to eliminate the generation of high voltages and currents that would otherwise result when the line inductance/impedance resonates with power supply capacitance at specific frequencies of motor or buck regulator operation. The power dissipating circuit is arranged in parallel with the commutation circuit **70** and comprises a resistive element, i.e. resistor R1, in series with switch Q4 (i.e. a MOSFET transistor). The power dissipating circuit is only used when the drive current corresponds to resonant frequencies. The feedback diode **73** is then switched "out" and switch Q4 switches R1 "in" in order to damp high-level voltage pulses at the commutation circuit **70**. Accordingly, no more than one of the resistor R1 and feedback diode **73** is switched "in" at a time. R1 will depend on the voltage range of the drive, for low (**28**) voltage drives this value may be from 0.1 ohm to 2 or 3 ohms, for higher voltage systems the resistor value will be proportionally higher. It is noted that the MOSFET switches may be replaces by other types of devices for high voltage type applications.

In order to define the switch condition of switch Q3 and switch Q4, a resonance detector **98** detects an electrical resonance on the power supply lines using a current measurement **102** provided by a current transducer **100** installed at the power supply cables, and the position feedback signal **84** provided by the position sensor **82**. The resonance detector **98** evaluates the frequency of the drive current using the variation of the position feedback signal **84** in time and also evaluates the amplitude of ripple component on the nominally direct current of the power supply cables using line current measurement **102**. The resonance condition is determined as a combination of the two inputs. It is noted that in this embodiment the frequency of the induced noise ripple on the power supply lines is six times the motor operation electrical frequency. Resonance is detected by monitoring the magnitude of dc link current using current sensor **100**. The motor position feedback signal **82** provides motor rotor position data that is used to identify ripple on the dc bus that caused by the motor commutation. A resonance signal **104** representative of a resonance condition on the power supply line is provided to a switch controller **110**.

The switch controller **110** along with snubber gate drive **112** controls switch Q3 and switch Q4 of the active snubber **78**. When the noise ripple level on the DC bus is below a predetermined value, Q3 is closed to switch "in" the feedback diode **73** and allow transient suppression.

When a resonance condition is detected by the resonance detector **98**, the feedback diode **73** is switched "out" and the power dissipating circuit is used to dissipate high-level voltage pulses typically on a cycle by cycle basis. Switch Q4 is then controlled as a function a voltage measurement across the commutation circuit **70** on a cycle by cycle basis. Accordingly, a voltage signal **108** is provided by a voltage transducer **106**. Switch Q4 is switched on to switch the resistor R1 "in"

and dissipate the electrical transient when the voltage measurement reaches a limit instantaneous voltage value, in order to limit voltage transient across the commutation circuit **70** from rising above a predetermined limit. Damages to the commutation circuit **70** are thereby prevented. Voltage transients are dissipated in resistor R1 instead of being fed back to the power supply circuit as current pulses, which limits the noise due to resonance on the power supply lines and thereby avoids high AC voltages and currents from occurring in the power supply system. Furthermore, the dissipating function of the snubber **78** is only used in case of high voltage transients across the commutation circuit **70**. A more efficient dissipative snubber is thereby provided.

The active snubber **78** advantageously provides an efficient operation of the motor system at most operation frequencies except the resonant frequencies of the power supply network, where the electrical transients are dissipated in a resistive element as heat.

Referring again to FIG. **3**, both motors **10** and their associated controllers **68** are arranged as described with reference to FIG. **4**, to provide a dual redundant motor system. To enhance redundancy protection, separate DC sources **80** are provided for each motor system. The operation of such a dual redundant system according to FIGS. **1-5** will now be described.

Referring again to FIG. **3** and to FIG. **4**, in a normal operation mode of the motors **10**, the drive **68** to each motor **10** is adjusted so that the motors contribute in desired proportions to the torque delivered to shaft **66**, and the shaft rotates at a desired speed, as requested by system controller **69**. Both motors **10** may be driven concurrently to provide torque and, when a higher efficiency operation or higher power operation is desired, the respective drives **68** can be adjusted accordingly to adjust the contribution proportion of each motor **10**. The control winding **24** of each motor **10** functions as the filter inductor for its respective buck regulation circuit **72**, as described above. Also as described above, the control winding **24** of each motor may also keep its respective control bus saturated (by virtue of the relative turns ratio between phase and control winding) to keep the control winding otherwise virtually "invisible" to the motor **10**. Should one motor **10** fail, such as in a short circuit, open circuit or ground, the drive **68** to the other motor **10** can be adjusted using its buck regulator **72** to increase the AC input to the phase windings **22** of the operational motor **10** to compensate for the loss in torque caused by loss of the other motor **10**. As the skilled reader will appreciate, the failed PM motor **10** can tend to add drag and heat to the system, however with the present arrangement the failed motor **10**, can be "turned off" by no longer energising the windings (i.e. and thus the current in the control winding is reduced to zero), which thus adjusts the failed motor **10** to a high impedance condition for the phase windings, as already described, thereby minimizing drag and heat generation. The current to the respective control windings and inverters is controlled by external control signals provided to the buck regulator circuits. If the system controller **69** requests zero current, then the relevant buck regulator stops providing current accordingly. This control command may be based on the system controller **69** detecting a fault or other command to set the current to zero. The resulting adjustment of the impedance characteristics of the phase windings of the affected motor **10**, from low impedance during proper motor function to a high impedance in the failed condition, results in much improved operation and controllability, particularly in PM motors where rotor excitation cannot be independently controlled.

FIG. **5** illustrates a 3-phase, "dual channel" PM motor **10'** according to the general "multi-channel" principles described in applicant's U.S. Pat. No. 6,965,183, but modified in accordance with the above teachings, as will now be discussed further. The same reference numerals are used to denote the analogous elements described with reference to the embodiments above, and thus all elements will not be redundantly described here. Stator **20** of dual channel PM machine **10'** is conceptually divided into an "A" half and a "B" half, thus providing a distinct stator sector for each channel, each channel provided with its own independent winding sets. Thus windings **22** and **24** will be described in terms of phase winding sets **22A** and **22B** and control winding sets **24A** and **24B**, as discussed further below. Other features associated with channels A and B are also described as "A" or "B", specifically, to indicate their respective channels.

Motor **10'** has a multi-channel architecture (in this case, dual channel), in that a plurality of circumferentially distributed distinct and fully independent (i.e. electromagnetically separate) "sets" of phase and control windings are provided in each stator sector corresponding to the multiple channels. In this case, two such sets of 3-phase phase and control windings are provided, namely a 3-phase set of phase windings **22A** and **22B** and respective control windings **24A** and **24B** (which happen to be single phase in this embodiment). This multi-channel architecture provides a plurality of functional "motor elements" within the same machine structure, which may either be operated in conjunction, or independently, as desired. The construction of motor **10'** is otherwise generally as described above with respect to the single channel embodiment of motor **10**.

The dual channel PM motor **10'** provides a single rotor rotating relative to two effectively independent stators, or stator sections. Thus, rotor **12** rotates relative to a stator sector **20A** (i.e. the portion of stator **20** with phase windings **22A**) and also relative to a stator sector **20B** (i.e. the portion of stator **20** with phase windings **22B**). When operated as a motor, the two "motors" (i.e., in effect, motors **10'A** and **10'B**) are driven independently, as described generally above with respect to motor **10**, but are synchronized such that they co-operate, as if only one "motor" is present. In normal motoring mode, the two "motors" (**10'A** and **10'B**) of motor **10'** are operated as described above with respect to motors **10** in FIG. **3**. Likewise, if one channel of the machine **10'** should fail in a short circuit, open circuit or ground (whether in the motor **10'** itself, or in the drive electronics or lead wires), the drive to the remaining channel is adjusted to compensate for the loss in torque, and the failed channel is no longer driven. The drive of the failed channel is effectively disconnected by bringing current flow in the control windings **22A** or **22B** to zero, resulting in the impedance of the phase windings **24A** or **24B** of the channel increasing to a high value, as previously described, such that the drag torque due to a short circuit type failure in the channel is minimized. This multi-channel configuration offers two fully redundant systems (i.e. channel A and channel B) with a minimum of hardware, thereby minimizing weight and space and increasing reliability. Channel failure detection may be achieved using any suitable approach, such as incorrect speed or torque as a function of current, voltage, high temperature, machine impedance, etc.

Referring again to FIG. **5**, the stator of the multi-channel motor **10'** includes means for impeding cross-talk between the tertiary magnetic circuits of channels A and B, such as is described in applicant's co-pending U.S. patent application Ser. No. 11/419,238 filed May 19, 2006. As described in that application, the presence of a cross-talk reduction feature, such a stator slit **21** acts to substantially contain the tertiary

magnetic flux within the channel. As such, the tertiary magnetic flux travels along the entire length of the control flux bus **32** to the channel boundary, where the presence of the cross-talk reduction slit **21** redirects the flux up to power flux bus **36**, where it then travels back along entire length of the power flux bus **36** (this flux is not present, and therefore not depicted, in the single channel embodiment of FIG. **2**), until the path joins up again with the beginning of the tertiary path, in the vicinity of another cross-talk reduction slit **21**.

FIG. **6** shows an isometric free-space view of a portion of a phase winding **22**A of the motor of FIG. **4**, but for the fact that only two turns are shown for reasons of drawing clarity.

Referring to FIG. **7**, a control system for dual-channel motor **10'** is shown. FIG. **7** is similar to FIG. **3**, but for the configuration of motor **10'** in FIG. **7** relative to two motors **10** of FIG. **3**. Motor drives **68**A and **68**B are each as described above with respect to FIG. **4**, and these two independent motor drives are provided, one for each channel of motor **10'**. In use, a similar operation is obtained when the control scheme of FIG. **4** is applied to the dual channel motor **10'** of FIG. **7**. Accordingly, in normal operation, channels A and B may be operated separately, or conjunctively, and motor drives **68**A and **68**B are controlled accordingly by controller **69**. When a failure is detected on one motor channel, the current flow in its respective control windings **24**A or **24**B is set to zero in order to increase impedance of the phase windings **22**A or **22**B and thereby minimize a drag torque and other undesirable effects otherwise brought on by the failed channel.

The dual-channel design of FIGS. **6** and **7** offers obvious size and weight savings over the two motors system as shown in FIGS. **4** and **5**. The two-motor design of FIGS. **3** and **5**, however, has its own advantages over the dual-channel arrangement of FIGS. **6** and **7**, such as simplicity of individual components.

It is contemplated that, although the active snubber **78** is described herein in conjunction with an embodiment wherein the motor **10** has control windings **24** and is used in a dual fail-safe motor configuration, the active snubber circuit **78** can also be advantageously used in the motor drive circuit of any single motor and of motors without control windings **24**. In any case, the buck regulator can use an independent inductor winding. Accordingly, the active snubber **78** described herein is not limited to this particular application but can be extended to any other motor drive application.

The skilled reader will appreciated that the resonance condition which determines the switch condition of the active snubber **78** can be determined using variable inputs. For example, the resonance condition may be determined according to only the operation frequency of the motor. If the operation frequency to which resonance noise appears on the power supply line is predetermined, switch Q3 and switch Q4 may be controlled as a function of the operation frequency instead of being a function of the noise level, the operation frequency being representative of a resonance condition on the power supply line. The operation frequency may be determined using the position sensor **82** or, alternatively, the speed request signal **76** could be used as an input of the resonance detector **98**.

While a combination of the current ripple amplitude on the power supply lines and of the frequency of the position feedback signal is used in the illustrated embodiment to determine the resonance condition, one will understand that a single one of the current ripple amplitude and the frequency of the motor could alternatively be used.

Furthermore, other parameters can alternatively be used to evaluate the resonance condition. For example, a temperature

measurement on the power supply lines or elsewhere could be used to evaluate the resonance condition.

The skilled reader will appreciate that a failure is not required to turn a channel or motor "off" as described above, but rather the approach may be used in any suitable situation where it is desired to shut a channel "off", including as part of a normal operation scheme.

In another control scheme, the dual motor arrangement of FIG. **3**, or as the case may be, the dual channel motor of FIG. **7**, is controlled using a modified motor drive in which buck regulator **72** has a dedicated filter inductor independent from the control windings **24**. Separate DC current sources respectively drive the phase and control windings independently from one another. Phase windings may be driven as described above so that torque is split as desired among the motors or channels in normal operation, during which time the DC source provides control current at a sufficient level to keep the control flux bus fully saturated at all times, for reasons already described. In the event of a channel failure, phase winding current in the other motor/channel is adjusted to compensate for the loss of torque due to the failed channel, while the current from source **81** to the control winding(s) for the failed channel is brought to zero to minimize the drag torque due to the failed channel.

In this embodiment, the control winding has different design constraints than those of the above embodiments, and thus the control winding may have a higher number of turns relative to the phase windings, to minimise the amount of control current required to saturate and maintain saturation in under the influence of desaturating fluxes from the main phases.

In the arrangement of FIG. **7**, where the control current is supplied from a source separate from the phase windings, and is independently variable relative to the phase windings, if the phase winding current in the motor/channel exceeds a specific value, such as a desired maximum limit, the inductance of the phase winding will abruptly increase, tending to limit the current in the phase winding to that specific value or limit. This can be used to simplify the drive system of very low impedance (i.e. high speed) PM motors. For example, the motor can be designed using this feature to intrinsically limit inrush current on start-up by appropriately designing this feature into the motor, such that other typical inrush limiting techniques, such as duty cycle control, may be omitted or operated at lower frequencies.

The above description is meant to be exemplary only, and one skilled in the art will recognize that changes may be made to the embodiments described without departing from the scope of the embodiments disclosed. Such modifications are intended to fall within the scope of appended claims.

What is claimed is:

1. An active electrical protection apparatus for damping electrical transients in a control circuit of an electrical machine having phase windings driven using a commutation circuit and powered through a power supply line, the apparatus comprising:

    a power dissipating circuit arranged in parallel with said commutation circuit and configured to dissipate power on the power supply line, the power dissipating circuit having a resistive element and a first switch configured to switchably connect said resistive element to the power supply line;

    a resonance detector configured to evaluate a frequency of a current on the power supply line, detect a resonance condition on said power supply line based on the evaluated frequency and provide a resonance signal representative of the resonance condition; and

a controller configured to receive the resonance signal and command said first switch at least as a function of said resonance signal.

2. The active electrical protection apparatus as claimed in claim 1, further comprising a transient suppression circuit arranged in series with said power dissipating circuit and with said commutation circuit, said transient suppression circuit having a feedback diode device arranged inversely relative to a drive current of said commutation circuit and a second switch for switchably connecting said feedback diode device, said controller being further for commanding said second switch as a function of said resonance signal, no more than one of said resistive element and said feedback diode device being switched in at a time.

3. The active electrical protection apparatus as claimed in claim 2, wherein said first switch and said second switch each comprises a Metal Oxide Semiconductor Field Effect Transistor (MOSFET).

4. The active electrical protection apparatus as claimed in claim 1, further comprising a current transducer for measuring the current at said power supply line and for providing a current signal, said current signal to be provided to said resonance detector for detecting said resonance condition.

5. The active electrical protection apparatus as claimed in claim 4, further comprising a position sensor for sensing a position of said electrical machine and for providing a position signal, said resonance detector receiving said position signal in time for evaluating an operation frequency of said machine for use in detecting said resonance condition.

6. The active electrical protection apparatus as claimed in claim 1, further comprising a voltage transducer for measuring a voltage at said commutation circuit and for providing a voltage signal, said voltage signal to be provided to said controller for commanding said first switch as a function of said voltage signal and said resonance signal.

7. An active electrical protection apparatus for damping electrical transients in an electrical machine having phase windings driven using a commutation circuit and powered through a power supply connecting line, the apparatus comprising:

a power dissipating device arranged in parallel with said commutation circuit, and having a resistive element configured to dissipate power on the power supply connecting line when the electrical transients on the power supply connecting line are damped;

a transient suppression device arranged in series with said power dissipating circuit and with said commutation circuit, and having a feedback diode device arranged inversely relative to a drive current of said commutation circuit;

a switching device configured to switchably connect said power dissipating device to the power supply connecting line and to switchably connect said transient suppression device;

a resonance detector configured to evaluate a frequency of a current on the power supply line, detect a resonance condition on said power supply line based on the evaluated frequency and provide a resonance signal representative of the resonance condition; and

a switch controller configured to receive the resonance signal and command said switching device at least as a function of said resonance signal.

8. The active electrical protection apparatus as claimed in claim 7, wherein said switching device comprises a first switch connected in series with said power dissipating device for switching it in and out, and a second switch connected in series with said transient suppression device for switching it in and out.

9. The active electrical protection apparatus as claimed in claim 7, further comprising a voltage transducer for measuring a voltage at said commutation circuit and for providing a voltage signal, said voltage signal to be provided to said switch controller for commanding said switching device as a function of said voltage signal and said resonance signal.

10. A method for damping electrical transients in an electrical machine having phase windings driven using a commutation circuit, the machine further having a resistive element arranged in parallel with said commutation circuit wherein the resistive element is configured to dissipate power when electrical transients are damped and a feedback diode device arranged in series with said power dissipating circuit and with said commutation circuit, and arranged inversely relative to a drive current of said commutation circuit, the method comprising:

evaluating a resonance condition based on at least one of a frequency of a current on a power supply line and an operation frequency of said electrical machine;

switching said feedback diode device in and out as a function of said resonance condition;

measuring a voltage across said commutation circuit;

comparing a value of said voltage to a limit voltage value to detect a voltage transient which determines a voltage condition; and

switching said resistive element in and out as a function of said resonance condition and said voltage condition.

11. The method as claimed in claim 10, wherein said feedback diode device is switched in when a value of said current on the power supply line is below a predetermined value.

12. The method as claimed in claim 11, wherein said resistive element is switched in when a value of said current on the power supply line is above said predetermined value and said value of said voltage signal is above said limit voltage value.

13. A method for damping electrical transients in an electrical machine having phase windings driven using a commutation circuit, the electrical machine further having a resistive element arranged in parallel with said commutation circuit, the resistive element for dissipating power when electrical transients on a power supply line are damped, the method comprising:

evaluating a frequency of a current on the power supply line of said electrical machine;

detecting a resonance condition on said power supply line based on the evaluated frequency; and

switching said resistive element in to damp electrical transients on the power supply line and out at least as a function of said electrical resonance condition.

14. The method as claimed in claim 13, wherein said resonance condition is also based on an operation frequency of said electrical machine.

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