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Overvoltage mitigation system

Abstract

An electric motor control system includes an alternating current (AC) electric motor having a first phase input, a second phase input, and a third phase input, and an AC electrical energy source having a first phase output, a second phase output and a third phase output. The system also includes conductors coupled between the phase outputs of the AC electrical energy source and the phase inputs of the AC electric motor. The electric motor control system also has circuitry that further includes a rectifier with phase inputs coupled to the conductors. The rectifier produces a rectified voltage between a positive rectifier output and a negative rectifier output. The system additionally includes an energy storage element coupled across the positive rectifier output and the negative rectifier output and a voltage limiting diode coupled to the positive rectifier output to limit a voltage of the positive rectifier output.

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Background/Summary

INTRODUCTION
(1) This disclosure is in the field of overvoltage mitigation in an alternating current (AC) electrical system.
(2) In an AC electrical system, such as a powertrain of an electric vehicle, overvoltage transients may occur due, for example, by switching that may occur in an inverter that converts stored electrical energy into AC for propelling the electric vehicle. Effective methods of mitigating overvoltage transients in AC electrical systems may be advantageous.
SUMMARY
(3) An electric motor control system includes an alternating current (AC) electric motor having a first phase input, a second phase input, and a third phase input, and an AC electrical energy source having a first phase output, a second phase output and a third phase output. The system also includes a first conductor coupled between the first phase output of the AC electrical energy source and the first phase input of the AC electric motor, a second conductor coupled between the second phase output of the AC electrical energy source and the second phase input of the AC electric motor, and a third conductor coupled between the third phase output of the AC electrical energy source and the third phase input of the AC electric motor. The electric motor control system also has circuitry that further includes a rectifier with a first rectifier phase input coupled to the first conductor, a second rectifier phase input coupled to the second conductor, and a third rectifier phase input coupled to the third conductor, the rectifier producing a rectified voltage between a positive rectifier output and a negative rectifier output. The system additionally includes an energy storage element coupled across the positive rectifier output and the negative rectifier output and at least one voltage limiting diode coupled to the positive rectifier output to limit a voltage of the

positive rectifier output.
(4) In the electric motor control system, the at least one voltage limiting diode may be coupled across the positive rectifier output and the negative rectifier output. Further, the at least one voltage limiting diode may include at least one transient-voltage-suppression (TVS) diode.
(5) Additionally, the circuitry may include a transistor having a control input and configured to conduct current between the positive rectifier output and the negative rectifier output in response to a control voltage at the control input. The voltage limiting diode may be operative to provide control voltage to the control input. The circuitry may include a resistor through which the current is conducted. The control input may be a gate or a base of the transistor.
(6) The AC electrical energy source may include a source of stored electrical energy and an inverter coupled to the source of electrical energy, and the circuitry may further comprise a fourth conductor coupled between a positive rail of the inverter and the positive rectifier output and a fifth conductor coupled between a negative rail of the inverter and the negative rectifier output.
(7) A second motor control system includes an AC electric motor having a first phase input, a second phase input, and a third phase input, an AC electrical energy source having a first phase output, a second phase output and a third phase output, a first conductor coupled between the first phase output and the first phase input, a second conductor coupled between the second phase output and the second phase input, and a third conductor coupled between the third phase output and the third phase input. The system also includes first overvoltage mitigation circuitry coupled across the first conductor and the second conductor, second overvoltage mitigation circuitry coupled across the first conductor and the third conductor, and third overvoltage mitigation circuitry coupled across the second conductor and the third conductor.
(8) In the second motor control system, the AC electrical energy source may further include a source of stored electrical energy and an inverter coupled to the source of stored electrical energy and having the first phase output, the second phase output, and the third phase output. The first overvoltage mitigation circuitry may include a first diode and a second diode, the first diode and the second diode coupled in series with each other and with opposing polarities to one another. The first and second diodes may be TVS diodes.
(9) In the second electric motor control system, the first overvoltage mitigation circuitry may include a parallel connected resistor and inductor interposed in-line in the first conductor; and a capacitor coupled across the first conductor and the second conductor. The resistor, inductor, and capacitor may all be located closer to the inverter than to the AC electric motor.
(10) In the second electric motor control system, the first overvoltage mitigation circuitry may be located closer to the AC electric motor than to the inverter. Further, the source of stored electrical energy may be a battery, and further may be a battery that stores electrical energy at a voltage of greater than or equal to 400 volts.
(11) An electric vehicle includes an AC electric motor to propel the electric vehicle, the AC electric motor having three motor phase inputs, a source of stored electrical energy, and an inverter coupled to the source of stored electrical energy and to the AC electric motor to provide switched electrical energy from the source of stored electrical energy to the AC electric motor for propulsion of the electric vehicle. The electric vehicle also includes a first conductor coupled between a first phase output of the inverter and a first phase input of the AC electric motor, a second conductor coupled between a second phase output of the inverter and a second phase input of the AC electric motor, and a third conductor coupled between a third phase output of the inverter and a third phase input of the AC electric motor. The electric vehicle also includes circuitry that further includes a three-phase rectifier with a first rectifier phase input coupled to the first conductor, a second rectifier phase input coupled to the second conductor, and a third rectifier phase input coupled to the third conductor, the rectifier producing a rectified voltage between a positive rectifier output and a negative rectifier output. The electric vehicle additionally includes an energy storage element coupled across the positive rectifier output and the negative rectifier output, at least one voltage

limiting diode coupled to the negative rectifier output to limit a voltage between the positive rectifier output and the negative rectifier output, and a transistor having a control input and configured to conduct current between the positive rectifier output and the negative rectifier output in response to a control voltage at the control input. The at least one voltage limiting diode is operative to provide control voltage to the control input.
(12) The transistor may be a p-channel bipolar transistor or a p-channel MOSFET. The at least one voltage limiting diode may include a TVS diode or a Zener diode. Additionally, the circuitry may further include a resistor through which the current is conducted.
(13) The above summary does not represent every embodiment or every aspect of this disclosure. The above-noted features and advantages of the present disclosure, as well as other possible features and advantages, will be readily apparent from the following detailed description of the embodiments and best modes for carrying out the disclosure when taken in connection with the accompanying drawings and appended claims. Moreover, this disclosure expressly includes combinations and sub-combinations of the elements and features presented above and below.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** illustrates an electric vehicle.
(2) FIG. **2** illustrates a powertrain of the electric vehicle.
(3) FIG. **3** is an electrical schematic drawing showing an overvoltage mitigation circuit for the powertrain of the electric vehicle.
(4) FIG. **4** is an electrical schematic drawing showing an alternative overvoltage mitigation circuit for the powertrain of the electric vehicle.
(5) FIG. **5** is an electrical schematic drawing showing another alternative overvoltage mitigation circuit for the powertrain of the electric vehicle.
(6) FIG. **6** is an electrical schematic drawing showing another overvoltage mitigation circuit for the powertrain of the electric vehicle.
(7) FIG. **7** illustrates a variation of the overvoltage mitigation circuitry shown in FIG. **2**.
DETAILED DESCRIPTION
(8) The present disclosure is susceptible of embodiment in many different forms. Representative examples of the disclosure are shown in the drawings and described herein in detail as non-limiting examples of the disclosed principles. To that end, elements and limitations described in the Abstract, Introduction, Summary, and Detailed Description sections, but not explicitly set forth in the claims, should not be incorporated into the claims, singly or collectively, by implication, inference, or otherwise.
(9) For purposes of the present description, unless specifically disclaimed, use of the singular includes the plural and vice versa, the terms “and” and “or” shall be both conjunctive and disjunctive, “any” and “all” shall both mean “any and all”, and the words “including”, “containing”, “comprising”, “having”, and the like shall mean “including without limitation”. Moreover, words of approximation such as “about”, “almost”, “substantially”, “generally”, “approximately”, etc., may be used herein in the sense of “at, near, or nearly at”, or “within 0-5% of”, or “within acceptable manufacturing tolerances”, or logical combinations thereof.
(10) Refer first to FIG. **1**, where an electric vehicle **10** is illustrated. Electric vehicle **10** may be any vehicle that is propelled in whole in part using electrical energy and may include full-electric and hybrid-electric vehicles. Further, electric vehicle **10** may be any style of vehicle, such as a car, truck, van, sport-utility vehicle, motorcycle, bicycle, scooter, boat, aircraft, or the like.
(11) Referring additionally to FIG. **2**, electric vehicle **10** has an electrical powertrain **12**. Electrical powertrain **12** for electric vehicle **10** includes an electric motor **14**. Electric motor **14** may be a

three-phase alternating current (AC) electric motor. Electrical powertrain **12** also includes a battery pack **16**, which is a source of stored electrical energy for propulsion of electric vehicle **10** by electric motor **14**. Battery pack **16** is coupled to a power inverter module (PIM) **18**. Battery pack **16** provides propulsive energy to electric motor **14**, via switching performed within PIM **18** controlled by a powertrain control unit (PCU) **20**. As such, battery pack **16** and PIM **18** may be referred to as a source of AC electrical energy. PCU **20** may be a standalone controller, may be integrated with PIM **18**, or may be integrated with other controllers in the electrical system of electric vehicle **10**. Electric vehicle **10** may be propelled by more than one electric motor.

(12) PIM **18** may include six switching elements **30**, **32**, **34**, **36**, **38**, and **40**, the switching of which may be controlled by PCU **20** in the course of control of electric motor **14**. The six switching elements may be insulated gate bipolar transistors (IGBTs), field-effect transistors (FETs) or other suitable transistors. PIM **18** may also have a direct-current (DC) link capacitor **42**. PIM **18** may have three phase outputs, namely first phase output **50**, second phase output **52**, and third phase output **54**.

(13) PCU **20** is understood to be a controller that has sufficient electronic resources (e.g., microprocessor, memory, inputs, outputs, software, access to sensors) to perform control of electric motor **14**.

(14) Electric motor **14** may have a housing **59**. Electric motor **14** may include three phase inputs, a first phase input **60**, a second phase input **62**, and a third phase input **64**, as power inputs for use by electric motor **14** to provide propulsive energy for propelling electric vehicle **10**.

(15) The phase outputs of PIM **18** may be connected to the phase inputs of electric motor **14**. Such connection may be by a first conductor **70** that conductively couples first phase output **50** and first phase input **60**. The connection may also be by a second conductor **72** that conductively couples second phase output **52** and second phase input **62**. The connection may also further be by a third conductor **74** that conductively couples third phase output **54** and third phase input **64**. First conductor **70**, second conductor **72**, and third conductor **74** may be included within a multi-conductor cable that includes an electromagnetic shield **76**. Alternatively or additionally, each of first conductor **70**, second conductor **72** and third conductor **74** may have its own shield.

(16) In referring to “conductors” herein, such reference is also understood to include conductive paths that may include multiple conductors that are themselves electrically coupled together, such as two or more individual conductors that are coupled together by one or more connectors, as may be done for convenience of assembly of electric vehicle **10**.

(17) Electrical powertrain **12** may employ electric motor **14** that operates at high voltages. In non-limiting examples, electric motor **14** may operate at, say, 400 volts or 800 volts. In motors operating at such voltages and where high speed switching by PIM **18** occurs, overvoltage conditions that stress the insulation within electric motor **14** may occur. Overvoltage at the terminals of electric motor **14** may be twice as much or more than the voltage of battery pack **16**, depending in part on the length and electrical characteristics of the cable that contains first conductor **70**, second conductor **72**, and third conductor **76**. That is, if battery pack **16** is charged to 400 volts, the overshoot at the terminals of electric motor **14** may be 800 volts or more; if battery pack **16** is charged to 800 volts, the overshoot at the terminals of electric motor **14** may be 1600 volts or more. High speed switching (that is, high dv/dt) may cause additional effects such as increased common mode currents and increased induced current in the bearings of electric motor **14** that may be detrimental to the durability of the drivetrain system of electric vehicle **10** by causing premature wear of electric motor **14** and the drivetrain components downstream of electric motor **14**.

(18) Electrical powertrain **12** may also include circuitry **100** that may serve as overvoltage suppression or overvoltage mitigation, or overvoltage filtering circuitry for the electrical energy that is conducted on first conductor **70**, second conductor **72**, and third conductor **74**.

(19) Circuitry **100** includes a rectifier **102**, which may be a three-phase diode bridge rectifier. The

diodes of rectifier **102** may be any diodes suitable for the purpose of voltage rectification, such as Schottky diodes. Rectifier **102** has a first rectifier phase input **104**, a second rectifier phase input **106**, and a third rectifier phase input **108**. Rectifier **102** may also have a first rectifier output **110**, which may be a positive rectifier output, and a second rectifier output **112**, which may be a negative rectifier output. The result of rectification by rectifier **102** may be a direct-current (DC) voltage between first rectifier output **110** and second rectifier output **112**. Further included in circuitry **100** is a capacitor **114**, which may serve as an energy storage element.

(20) Additionally included in circuitry **100** is a diode **116** coupled to first rectifier output **110**. Diode **116** is also coupled to second rectifier output **112**, via resistor **118**. Diode **116** may be a voltage limiting or voltage clamping diode such as a transient-voltage-suppression (TVS) or Zener diode (or alternatively, a series connection of two or more voltage limiting or voltage clamping diodes, the series connection coupled to first rectifier output **110** and, via resistor **118**, to second rectifier output **112**). Coupled to the junction between diode **116** and resistor **118** is the base **122** of a transistor **120**.

(21) Transistor **120** may be any type of transistor that is suitable for the purpose described herein, such as a bipolar junction transistor (BJT), an insulated gate bipolar transistor (IGBT), field-effect transistor (FET), or a metal oxide semiconductor field-effect transistor (MOSFET). Base **122** may act as a control input of transistor **120**; based on control voltage applied to base **122**, transistor **120** may cause conduction between collector **124** and emitter **126** of transistor **120**. If transistor **120** is an insulated gate bipolar transistor or a MOSFET, base **122** may instead be a gate of transistor **120**.

(22) Operation of circuitry **100** may be as follows. Rectifier **102** rectifies the three-phase voltages across first conductor **70**, second conductor **72** and third conductor **74**. If the resulting rectified voltage is high enough to represent an overvoltage condition of sufficient magnitude, diode **116** will conduct. This will act to limit, clamp, or suppress the voltage of first rectifier output **110**. At the same time, transistor **120** will conduct, conducting current through resistor **128**. This will act to dissipate electrical energy that has heretofore been stored in capacitor **114**.

(23) It should be noted that resistor **128** may be omitted, particularly in the event that transistor **120** has sufficient capacity to dissipate the electrical energy stored in capacitor **114**. Also, resistor **128** may instead be connected between emitter **126** and second rectifier output **112**, rather than between collector **124** and first rectifier output **110**. In either event, current conducted through transistor **120** would be conducted through resistor **128**.

(24) Transistor **120** may act not solely as an “on-off” switch. Transistor **120**, if a MOSFET for example, may act for substantial periods in its ohmic and/or saturation region and not merely in “on-off” fashion. Or transistor **120**, if a bipolar junction transistor for example, may operate in its “linear” or “active” region, not only in cut-off and saturation.

(25) A significant advantage of circuitry **100** is that, unless the voltage across first rectifier output **110** and second rectifier output **112** is sufficiently high due to an overvoltage condition on first conductor **70**, second conductor **72**, and third conductor **74**, capacitor **114** will simply act as electrical energy storage, without energy dissipation. This is helpful for the efficiency of electric vehicle **10**. However, when the voltage across first rectifier output **110** and second rectifier output **112** is sufficiently high, due to overvoltage among first conductor **70**, second conductor **72**, and third conductor **74**, circuitry **100** will act to dissipate the energy embodied in that overvoltage condition.

(26) A further significant advantage of circuitry **100** is that due to diode **116**, the voltage across positive rectifier first output **110** and second rectifier output **112** will be regulated or clamped at a very consistent voltage, making the overvoltage suppression or mitigation function of circuitry **100** very consistent, predictable, precise and reliable. Diode **116** may be selected to conduct at a voltage value that prevents an overvoltage condition significant enough to damage or degrade electric vehicle **10** or components thereof. At the same time, diode **116** may be selected to conduct at a high enough voltage to tolerate some amount of overvoltage, in order to promote high efficiency by

refraining from dissipating energy in transistor **120** and resistor **128**.
(27) Circuitry **100** may advantageously be located at or near the terminals of electric motor **14**. Circuitry **100** may also advantageously be packaged within housing **59** of electric motor **14**, such as on a circuit board packaged within housing **59** of electric motor **14**.
(28) In the event of very high levels of back emf (electromotive force) that may be generated by electric motor **14** say, in an uncontrolled situation, such back emf may be large enough (above the expected operating voltages within in circuitry **100**) damage various components in circuitry **100**. As such, one or more fuses **111***a*, **111***b*, **111***c*, **111***d*, **111***e* and/or **111***f* may be placed at locations within circuitry **100**, as shown in FIG. **2**.
(29) A variation on circuitry **100** is illustrated in FIG. **7**. Here, a transistor **150** may be provided in place of transistor **120** of FIG. **2**. Transistor **150** may be a p-type bipolar transistor or a p-channel MOSFET. A voltage-limiting or voltage-clamping diode **154** (or alternatively, a series connection of two or more voltage-limiting or voltage-clamping diodes) is provided, coupled to negative output **112** of rectifier **102** and, via resistor **152**, to positive output **110** of rectifier **102**. A resistor **156** dissipates energy stored in capacitor **114** when transistor **150** conducts. Resistor **156** may also be omitted if transistor **150** is capable of dissipating sufficient energy.
(30) As alternative circuitry to circuitry **100**, circuitry **200** for overvoltage mitigation, overvoltage suppression, or overvoltage filtering is illustrated in FIG. **3**. Circuitry **200** may also be coupled to first conductor **70**, second conductor **72**, and third conductor **74** and to first phase input **60**, second phase input **62**, and third phase input **64** of electric motor **14**.
(31) Circuitry **200** may include a rectifier **202**, which may be a three-phase bridge rectifier. The six diodes comprising rectifier **202** may be any suitable diodes for voltage rectification, such as Schottky diodes. Rectifier **202** may have a first rectifier output **210**, which may be a positive rectifier output, and a second rectifier output **212**, which may be a negative rectifier output. The result of rectification by rectifier **202** may be a direct-current (DC) voltage between first rectifier output **210** and second rectifier output **212**. Further included in circuitry **200** is a capacitor **214**, which may serve as an energy storage element.
(32) Circuitry **200** may also include a diode **216** coupled between first rectifier output **210** and second rectifier output **212**. Diode **216** may be a voltage-limiting or voltage-clamping diode, such as a Zener diode or TVS diode. Diode **216** may also be replaced by two or more diodes in series “head-to-tail”, with their clamping or regulation voltages thereby being additive to sum to an overall desired clamping or regulation voltage, without departing from the spirit or scope of this disclosure.
(33) Circuitry **200** will act to store energy via capacitor **214**, thereby not dissipating energy, until the voltage at first rectifier output **210** exceeds the conduction voltage of diode **216**. At that point the excess energy may dissipate via the conduction of diode **216**. This has the considerable advantage of having limited energy dissipation until overvoltage suppression or mitigation is actually needed, and high overall efficiency.
(34) Circuitry **200** may advantageously be located at or near the terminals of electric motor **14**. Circuitry **200** may also advantageously be packaged within housing **59** of electric motor **14**, such as on a circuit board packaged within housing **59** of electric motor **14**.
(35) As an alternative to circuitry **100** and circuitry **200**, circuitry **300** is illustrated in FIG. **4**. As with circuitry **100** and circuitry **200**, circuitry **300** may be coupled to first conductor **70**, second conductor **72** and third conductor **74**, and to first phase input **60**, second phase input **62**, and third phase input **64** of electric motor **14**. Circuitry **300** includes six diodes, diode **302**, diode **304**, diode **306**, diode **308**, diode **310** and diode **312**. The diodes may voltage limiting, voltage clamping, or voltage regulation diodes such as Zener or TVS diodes. Diode **302** and diode **304** may be coupled in series across first conductor **70** and second conductor **72**. Diode **302** and diode **304** may be coupled with opposite polarities to one another (that is, anode to anode or cathode to cathode). As such, diode **302** and diode **304** act to provide bidirectional clamping or bidirectional voltage

limitation to suppress or mitigate overvoltage across first conductor **70** and second conductor **72**.

(36) Diode **306** and diode **308** perform similar bidirectional clamping or bidirectional voltage limitation to suppress overvoltage across first conductor **72** and second conductor **74**. Further, diode **310** and diode **312** perform a similar function in suppressing overvoltage across first conductor **70** and third conductor **74**.

(37) An advantage of circuitry **300** is that it may have a minimum number of discrete electronic components among the overvoltage suppression or mitigation mechanisms disclosed in this disclosure. Circuitry **300** may advantageously be located at or near the terminals of electric motor **14**. Circuitry **300** may also advantageously be packaged within housing **59** of electric motor **14**, such as on a circuit board packaged within housing **59** of electric motor **14**.

(38) Each of diodes **302**, **304**, **306**, **308**, **310**, and **312** may be replaced by two or more diodes in series with their polarities aligned (the diodes configured “head to tail” or anode to cathode) to effectively form one diode in combination, without departing from the spirit of this disclosure.

(39) As an alternative to circuitry **100**, circuitry **200** and circuitry **300**, circuitry **400** is illustrated in FIG. **5**. Circuitry **400** may be coupled to first conductor **70**, second conductor **72** and third conductor **74**, and to first phase input **60**, second phase input **62**, and third phase input **64** of electric motor **14**. Circuitry **400** includes resistor **402**, resistor **404**, resistor **406**, inductor **408**, inductor **410**, inductor **412**, capacitor **414**, capacitor **416**, and capacitor **418**. Circuitry **400** may be located near the phase outputs of PIM **18**.

(40) Resistor **402** and inductor **408** may be coupled in parallel with each other and interposed in-line in first conductor **70**. Capacitor **414** may be disposed across first conductor **70** and second conductor **72**. As such, resistor **402**, inductor **408** and capacitor **414** may form a resistor-inductor-capacitor (RLC) filter. Resistor **404**, inductor **410**, and capacitor **416** may form a second RLC filter. The values of these components may be similar to or the same as the values of resistor **402**, inductor **408**, and capacitor **414**. Resistor **406**, inductor **412**, and capacitor **418** may form a third RLC filter, disposed between first conductor **70** and third conductor **74**. The values of these components may be similar to or the same as the values of resistor **402**, inductor **408**, and capacitor **414**.

(41) These RLC filters may act with respect to voltage transients that appear across first conductor **70**, second conductor **72**, and third conductor **74**. This may both serve to limit voltage overshoot and dv/dt (time rate of change of voltage) in the three-phase system that comprises first conductor **70**, second conductor **72**, and third conductor **74**. The inductance of inductor **408** and the capacitance of capacitor **414** (and that of the other LC pairs) may be selected so that their LC natural frequency is somewhat lower than the natural frequency of the distributed capacitance and inductance of the cable that includes first conductor **70**, second conductor **72** and third conductor **74**. The inductances and capacitances may also be selected to limit the dv/dt to as low a value as desired. Resistors **402**, **404**, and **406** may be selected to critically damp the step response of the RLC circuits. Inductors **408**, **410**, and **412** may be of very small inductance, and having the corresponding resistors **402**, **404**, and **406** in parallel may limit the energy losses involved.

(42) As alternative circuitry to circuitry **100**, circuitry **200** and circuitry **300** and circuitry **400**, circuitry **500** is illustrated in FIG. **6**. Here, circuitry **500** includes rectifier **502**, which may be a three-phase diode bridge rectifier. The six diodes comprising rectifier **502** may be any suitable diodes for voltage rectification, such as Schottky diodes. Coupled across first rectifier output **510** and second rectifier output **512** may be a capacitor **514**, which may act as an energy storage element. Further, first rectifier output **510** may be coupled to positive rail **516** of PIM **18** by a conductor **520**. Additionally, second rectifier output **512** may be coupled to negative rail **518** of PIM **18** by a conductor **522**. Conductor **520** and conductor **522** may be small-gauge DC cables. That is, conductor **520** and conductor **522** may not need to be selected for advantageous high-frequency or high-current properties. Conductor **520** and conductor **522**, for instance, may be 12 AWG (American wire gauge) wires. Capacitor **514** may help limit voltage overshoot in first

conductor **70**, second conductor **72** and third conductor **74** while managing energy losses and allowing use of simpler cable containing those conductors (that is, avoiding the need for twisted pair or coaxial cable).
(43) There are numerous advantages of the overvoltage mitigation designs disclosed herein. They comprise passive, low-loss components and may be easy to integrate within the housing of electric motor **14** if so desired. Additionally, in some embodiments, the designs embody simply passive components. Further, the overvoltage mitigation designs do not need to embody control or sensing mechanisms.
(44) It should also be noted that circuitry **100**, **200**, **300**, **400** and/or **500** may be used in combination in an overvoltage mitigation design. They may be located near or within PIM **18** and/or near or within electric motor **14**.
(45) Embodiments of the present disclosure are described herein. It is to be understood, however, that the disclosed embodiments are merely examples and other embodiments can take various and alternative forms. The figures are not necessarily to scale; some features could be exaggerated or minimized to show details of particular components. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the present disclosure.
(46) Furthermore, the embodiments shown in the drawings or the characteristics of various embodiments mentioned in the present description are not necessarily to be understood as embodiments independent of each other. Rather, it is possible that each of the characteristics described in one of the examples of an embodiment can be combined with one or a plurality of other desired characteristics from other embodiments, resulting in other embodiments not described in words or by reference to the drawings. Accordingly, such other embodiments fall within the framework of the scope of the appended claims. Moreover, this disclosure expressly includes combinations and sub-combinations of the elements and features presented above and below.

Claims

1. An electric motor control system comprising: an alternating current (AC) electric motor having a first phase input, a second phase input, and a third phase input; an AC electrical energy source having a first phase output, a second phase output and a third phase output; a first conductor coupled between the first phase output of the AC electrical energy source and the first phase input of the AC electric motor; a second conductor coupled between the second phase output of the AC electrical energy source and the second phase input of the AC electric motor; a third conductor coupled between the third phase output of the AC electrical energy source and the third phase input of the AC electric motor; and circuitry that further includes: a rectifier with a first rectifier phase input coupled to the first conductor, a second rectifier phase input coupled to the second conductor, and a third rectifier phase input coupled to the third conductor, the rectifier producing a rectified voltage between a positive rectifier output and a negative rectifier output; an energy storage element coupled across the positive rectifier output and the negative rectifier output; and at least one voltage limiting diode coupled to the positive rectifier output to limit a voltage of the positive rectifier output.
2. The electric motor control system of claim 1, wherein the at least one voltage limiting diode is coupled across the positive rectifier output and the negative rectifier output.
3. The electric motor control system of claim 2, wherein the at least one voltage limiting diode comprises at least one transient-voltage-suppression (TVS) diode.
4. The electric motor control system of claim 1, wherein: the circuitry further includes a transistor having a control input and configured to conduct current between the positive rectifier output and the negative rectifier output in response to a control voltage at the control input; and the at least one voltage limiting diode is operative to provide control voltage to the control input.

5. The electric motor control system of claim 4, wherein the circuitry further includes a resistor through which the current is conducted.
6. The electric motor control system of claim 4, wherein the control input is a gate of the transistor.
7. The electric motor control system of claim 4, wherein the transistor is a bipolar junction transistor and the control input is a base of the transistor.
8. The electric motor control system of claim 1, wherein: the AC electrical energy source comprises a source of stored electrical energy and an inverter coupled to the source of electrical energy; and the circuitry further comprises a fourth conductor coupled between a positive rail of the inverter and the positive rectifier output and a fifth conductor coupled between a negative rail of the inverter and the negative rectifier output.
9. An electric motor control system comprising: an AC electric motor having a first phase input, a second phase input, and a third phase input; an AC electrical energy source having a first phase output, a second phase output and a third phase output; a first conductor coupled between the first phase output and the first phase input; a second conductor coupled between the second phase output and the second phase input; a third conductor coupled between the third phase output and the third phase input; first overvoltage mitigation circuitry coupled across the first conductor and the second conductor; second overvoltage mitigation circuitry coupled across the first conductor and the third conductor; and third overvoltage mitigation circuitry coupled across the second conductor and the third conductor.
10. The electric motor control system of claim 9, wherein the AC electrical energy source further comprises: a source of stored electrical energy; and an inverter coupled to the source of stored electrical energy and having the first phase output, the second phase output, and the third phase output.
11. The electric motor control system of claim 10, wherein the first overvoltage mitigation circuitry comprises a first diode and a second diode, the first diode and the second diode coupled in series with each other and with opposing polarities to one another.
12. The electric motor control system of claim 11, wherein the first diode is a TVS diode.
13. The electric motor control system of claim 12, wherein the second diode is a TVS diode.
14. The electric motor control system of claim 10, wherein the first overvoltage mitigation circuitry comprises: a parallel connected resistor and inductor interposed in-line in the first conductor; and a capacitor coupled across the first conductor and the second conductor.
15. The electric motor control system of claim 14, wherein the resistor, inductor, and capacitor are all located closer to the inverter than to the AC electric motor.
16. The electric motor control system of claim 11, wherein the first overvoltage mitigation circuitry is located closer to the AC electric motor than to the inverter.
17. An electric vehicle comprising: an alternating current (AC) electric motor having a first phase input, a second phase input, and a third phase input; an AC electrical energy source having a first phase output, a second phase output and a third phase output; a first conductor coupled between the first phase output of the AC electrical energy source and the first phase input of the AC electric motor; a second conductor coupled between the second phase output of the AC electrical energy source and the second phase input of the AC electric motor; a third conductor coupled between the third phase output of the AC electrical energy source and the third phase input of the AC electric motor; and circuitry that further includes: a rectifier with a first rectifier phase input coupled to the first conductor, a second rectifier phase input coupled to the second conductor, and a third rectifier phase input coupled to the third conductor, the rectifier producing a rectified voltage between a positive rectifier output and a negative rectifier output; an energy storage element coupled across the positive rectifier output and the negative rectifier output; at least one voltage limiting diode coupled to the negative rectifier output to limit a voltage between the positive rectifier output and the negative rectifier output; and a transistor having a control input and configured to conduct current between the positive rectifier output and the negative rectifier output in response to a

control voltage at the control input; wherein the at least one voltage limiting diode is operative to provide control voltage to the control input.

18. The electric vehicle of claim 17, wherein the transistor is a p-channel bipolar transistor or a p-channel MOSFET.

19. The electric vehicle of claim 17, wherein the at least one voltage limiting diode comprises a TVS diode or a Zener diode.

20. The electric vehicle of claim 17, further comprising a resistor through which the current is conducted.