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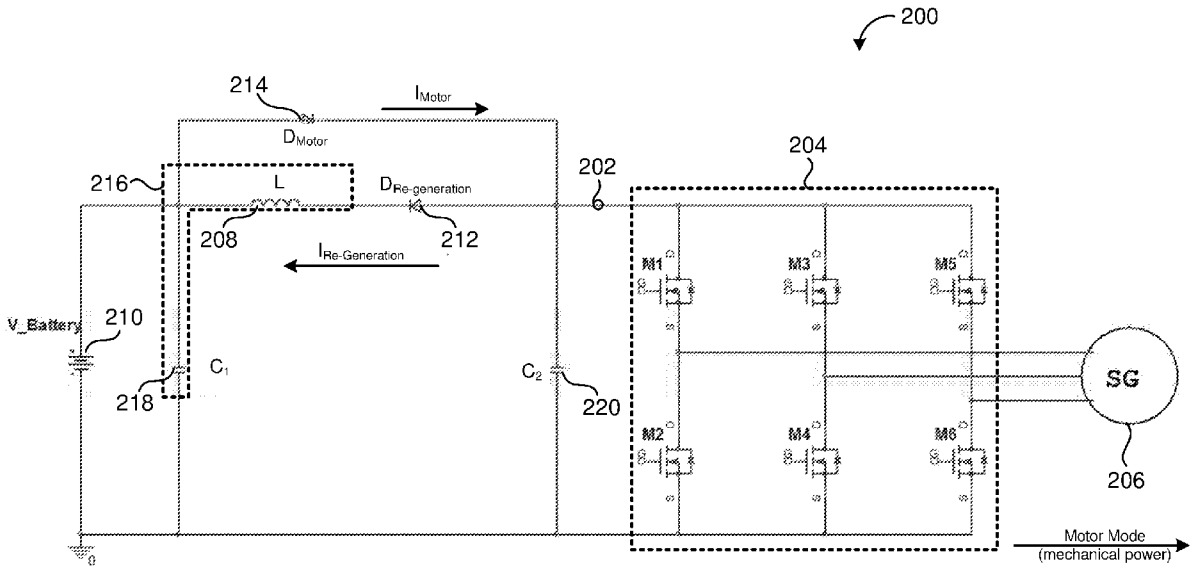


FIG. 2

(57) Abstract: A system for reducing a resonant oscillation on a direct current bus of a power inverter/converter for an electric machine having a variable frequency drive is disclosed. The system includes a battery, a first capacitor connected in parallel with the battery; an inductor connected in series with the first capacitor; a first diode connected in series with the inductor; a second diode connected in parallel with the inductor and the first diode; a second capacitor connected in series with the first diode; and a starter-generator connected to the second capacitor. During a re-generation mode for charging the battery, a re-generation current flows from the starter-generator to the battery, passing through the first diode and the inductor and bypassing the second diode. During a motor mode, a motor current flows from the battery to the starter-generator, passing through the second diode and bypassing the first diode and the inductor.

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[Continued on next page]

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— *as to the identity of the inventor (Rule 4.17(i))*
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

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PI SOURCE INVERTER-CONVERTER FOR HYBRID ELECTRIC VEHICLES

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This U.S. patent application claims priority under 35 U.S.C. §119(e) to U.S. Provisional Application 62/473,012, filed on March 17, 2017, U.S. Provisional Application 62/620,259, filed on January, 1, 2018, and US Non-Provisional Application 15/921,284 filed on March 14, 2018. The disclosures of these prior applications are considered part of the disclosure of this application and are hereby incorporated by reference in their entireties.

TECHNICAL FIELD

[0002] This disclosure relates to Pi Source Inverter-Converter for Hybrid Electric Vehicles (HEVs).

BACKGROUND

[0003] Hybrid electric vehicles (HEVs) are a type of hybrid vehicles and electric vehicles that combine a conventional internal combustion engine (ICE) propulsion system and an electric propulsion system (hybrid vehicle drivetrain). HEVs achieve better fuel economy than conventional vehicles. Several types of HEVs exist, and the degree to which each functions as an electric vehicle varies as well. Hybrid electric cars are the most common of the HEVs; however, there is a recent surge in hybrid electric trucks and buses.

[0004] HEVs may be classified based on how power is supplied to their drivetrain. For example, HEVs may be classified as parallel hybrids, series hybrids, or power-split hybrids. Most hybrid vehicles use regenerative braking to recharge the batteries.

[0005] HEVs may include a variable frequency drive (VFD), which is a type of motor controller that drives an electric motor by varying the frequency and voltage supplied to the electric motor. VFDs may also be known as variable speed drive, adjustable speed drive, adjustable frequency drive, AC drive, microdrive, and inverter. Frequency or hertz is directly related to the speed of the motor, more specifically to its rotations per minute (RPM). In some examples, if the vehicle does not need an

electric motor to run at full speed, the VFD may be used to ramp down the frequency and voltage to meet the requirements of the load of the HEV. Similarly, as the need for speed requirements changes, the VFD can turn up or turn down the motor speed to meet the speed requirements.

[0006] FIG. 1 shows a conventional and common topology of a system 100 of a main power section of a VFD of an HEV. As shown, the VFD includes a three-phase inverter 102 having six MOSFETS M1–M6, each including a diode. The system 100 includes a starter-generator 104 that provides mechanical power to an engine shaft (not shown) during a motor mode and provides electrical power to a battery 106 during a re-generation mode. The system 100 requires bi-directional power flow between the starter-generator 104 and the battery 106. In other words, a current I (e.g., I_{Motor} and $I_{Re\text{-}Generation}$) is able to flow bi-directionally within the DC-Bus 108 based on the operational mode of the vehicle (i.e., motor mode or re-generation mode). The power, i.e., current I_{Motor}, flows from the battery 106 to the starter-generator 104 through the 3-phase inverter 102 during the motor mode, while the power, i.e., current $I_{Re\text{-}Generation}$, flows from the starter-generator 104 (i.e., induction machine) to the battery 106 through the 3-phase inverter 102 during the motor re-generation mode. As can be seen, the 3-phase inverter 102 is configured to operate differently based on the motor mode. For example, during the motor mode, the 3-phase inverter 102 acts as an inverter from DC to 3-phase AC sinusoidal; while the 3-phase inverter 102 acts as a converter from 3-phase AC sinusoidal to DC.

[0007] An inductor 110, positioned in series between the first and second capacitors 118, 120, is used due to EMC regulation constraint by the automotive industry to eliminate the emissions from the converter 102 during the re-generating mode. In fact, the inductor 110 is only used during the Re-Generation mode to filter the battery charging current $I_{Re\text{-}Generation}$ through the inductor 110 and a first capacitor 118 connected in series with the inductor 110, which together are referred to as an L-C filter 116.

[0008] The Energy Stored in the inductor 110 may be calculated as follows:

$$\underline{\text{Motor Mode}}: \quad E_{\text{L}-\text{Motor}} = \frac{\text{L} * {I_{Motor}}^2}{2} \qquad (1)$$

where $E_{L\text{-}Motor}$ is the energy stored in the inductor 110 during motor mode, L is the value of the inductor 110, and I_{Motor} is the current passing through the inductor 110 during motor mode.

$$\underline{\text{Re-Generation Mode}}: \; E_{L-Re-Generation} = \frac{L * I_{Re-Generation}{}^2}{2} \qquad (2)$$

where $E_{L\text{-}Re\text{-}Generation}$ is the energy stored in the inductor 110 during the re-generation mode, and L is the value of the inductor 110, and $I_{Re\text{-}Generation}$ is the current flowing from the starter-generator 104 through the 3-phase converter 102 to the battery 106 during the re-generation mode.

[0009] The Resonant Oscillation on the L-C filter 116: the current flowing in the inductor 110 is 180° lagging the current flowing in the first and second capacitors 118, 120. As such, the energy stored in the first capacitor 118 and the second capacitor 120 may be calculated as follows:

$$E_{C1} = \frac{C_1 * V^2}{2}; \qquad (3)$$

and

$$E_{C2} = \frac{C_2 * V^2}{2}, \qquad (4)$$

where E_{C1} is the energy stored at the first capacitor 118, and E_{C2} is the energy stored at the second capacitor 120, C_1 is the value of the first capacitor 118, and C_2 is the value of the second capacitor 120.

[0010] The energy exchange between the inductor 110 and the first capacitor 118 as well as the second capacitor 120 with 180° phase differences causes a resonant oscillation in the current during the motor mode and re-generation mode and provides ripple current on both of the capacitor 118 and capacitor 120.

[0011] More importantly, the torque of the starter-generator 104 is directly related and proportional to its winding's torque current especially at Field-Oriented-Control scheme of the starter-generator 104, and therefore the Ripple-Current on the DC-Bus 108. In other words, the Resonant-Oscillation current (e.g., $I_{Re\text{-}Generation}$, I_{Motor}) is proportional to the torque applied to the starter-generator 104.

[0012] As described previously, the Ripple-Current (Resonant-Oscillation current) on the DC-Bus 108 is proportional to the torque applied to the starter-generator 104, so the performance and the total output power delivered to the starter-generator 104 are greatly limited by the Resonant-Oscillation of the inductor 110 and the first capacitor 118known together as the L-C filter 116. The Ripple-Current effect may

damage the components of the main power and reduce the overall performance of the main power component significantly. The system 100 as described in FIG. 1, reduces the lifetime of the main power component even with a larger power rating of the main power components. In addition, the Ripple-Current effect may increase the emission to the surrounding area from an EMC perspective. As such, the system 100 may not be stable and prevents the starter-generator 104 from being used at its full designed power. Accordingly, there exists a need for a stable system that utilized the full designed power of the starter-generator 104.

SUMMARY

[0013] One aspect of the disclosure provides a system for reducing a resonant oscillation on a direct current bus of a power inverter/converter for an electric machine having a variable frequency drive. The system includes: a battery; a first capacitor connected in parallel with the battery; an inductor connected in series with the first capacitor; a first diode connected in series with the inductor; a second diode connected in parallel with the inductor and the first diode; a second capacitor connected in series with the first diode; and a starter-generator connected to the second capacitor. During a re-generation mode for charging the battery, a re-generation current flows from the starter-generator to the battery, passing through the first diode and the inductor and bypassing the second diode. In addition, during a motor mode, a motor current flows from the battery to the starter-generator, passing through the second diode and bypassing the first diode and the inductor.

[0014] Implementations of the disclosure may include one or more of the following optional features. In some implementations, the first capacitor and the inductor form an L-C filter. In some examples, during the re-generation mode for charging the battery, the re-generation current flows through the first capacitor and the inductor respectively. In some implementations, during the motor mode, the motor current flows through the second diode.

[0015] In some examples, the system further includes a power inverter/converter connected between the starter-generator and the second capacitor. The power inverter/converter may include six MOSFETS each including a diode. In some implementations, during the motor mode, the power inverter/converter includes an inverter from DC to 3-phase AC sinusoidal. In addition, during the re-generation

mode, the power inverter/converter may include a converter from 3-phase AC sinusoidal to DC.

DESCRIPTION OF DRAWINGS

[0016] FIG. 1. is a schematic view of a prior art topology of a main power section for a starter-generator.

[0017] FIG. 2. is a schematic view of an exemplary topology of a main power section for a starter-generator.

[0018] FIG. 3 is a top Simulink Model view of a main power topology with 100KW interior permanent magnet motor variable frequency drive.

[0019] FIG. 4A is a Simulink Model view of a Sub-Model of a permanent magnet synchronous motor drive that shows the detailed circuit topology of the PI-Source Inverter (C-L-C) of FIG. 3, in accordance with FIG. 1.

[0020] FIG. 4B-1 – 4B-4 is a graph showing the simulation results of FIG. 4A, which shows the resonant oscillation on most of the parameter values.

[0021] FIG. 5A is a Simulink Model view of a sub-model of a permanent magnet synchronous motor drive based on the system of FIG. 3 for eliminating the resonant oscillation, in accordance with FIG. 2.

[0022] FIG. 5B-1 –5B-4 is a graph showing the simulation results of FIG. 5A that show the effect of eliminating the resonant oscillation on all of the parameter values.

[0023] FIG. 6 is a top Simulink Model view of a main power topology with a 3-phase induction machine variable frequency drive using Field-Oriented-Control.

[0024] FIG. 7A is a Simulink Model view of a sub-model of Field-Orient-Control induction motor drive that shows the detailed circuit topology of the PI Source Inverter (C-L-C) based on FIG. 6, in accordance with FIG. 1.

[0025] FIG. 7B-1 – 7B-4 is a graph showing the simulation results of FIG. 7A that show the resonant oscillation on most of the parameter values.

[0026] FIG. 8A is a Simulink Model view of a sub-model of Field-Orient-Control induction motor drive for Eliminating the Resonant Oscillation based on the system as shown in FIG. 6 and in accordance with the system of FIG. 2.

[0027] FIG. 8B-1 – 8B-4 is a graph showing the simulation results of Fig. 8A which shows the effect of elimination of resonant oscillation on all of the parameter values.

[0028] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0029] Referring to FIG. 2, in some implementations, a system 200 significantly reduces a resonant oscillation on a DC (direct current) bus 202 of a power inverter/converter 204 for an electric machine having a variable frequency drive (VFD). The reduction in resonant oscillation on the DC bus 202 leads to a belt starter generator (BSG or SG) 206 operating at its full designed power without any power reduction. Such system 200 may also result in reducing a current rating on an inductor 208 of the system 200 for example, from 260A to 40A, as well as the current rating of a first capacitor 218. In addition, the overall variable frequency drive system 200, including the DC-BUS 202 and inverter/converter 204 as well as the starter-generator 206 (e.g., induction machine), may all operate at a stable condition. As such, the system 200 is a stable system in comparison to previous system (for example, the system 100 shown in FIG. 1).

[0030] FIG. 2 shows the main power system 200 of a VFD of an HEV. As shown, the system 200 includes a 3-phase inverter 204 having six MOSFETS M1–M6, each including a diode. The system 200 includes a starter-generator 206, also referred to as an induction machine, which provides mechanical power to the engine shaft (not shown) during a motor mode, and provides electrical power to the battery 210 during a re-generation mode. Therefore, the system 200 provides bi-directional power flow based on the operational mode of the vehicle (motor mode or re-generation mode). The power flows from the battery 210 to the starter-generator 206 through the 3-phase inverter 204 during the motor mode, while the power flows from starter-generator 206 to the battery through the converter 204 during the re-generation mode.

[0031] The system 200 is designed to manipulate the power that flows through the inductor 208 based on the two different operational modes, such as, the motor mode and the re-generation mode. The system 200 includes two diodes 212, 214, a first diode 212 and a second diode 214, on the DC bus 202 that are passive components, i.e., without a driver or trigger circuit. The first diode 212 is connected in series with the inductor 208, and the second diode 214 is connected in parallel with the inductor

208 and the first diode 212. Therefore, during the motor mode, the current I_{motor} going from the battery 210 to the starter-generator 206 bypassed the inductor 208. While during the re-generation mode, the battery charging current $I_{Re\text{-}Generation}$ going from the starter-generator 206 to the battery 210 passed through the first diode 212 and the inductor 208. During motor mode, the inductor 208 is not allowed to be charged since the current I_{Motor} within the bus 202 bypasses the inductor 208 and flows through the second diode 214. Therefore, during the motor mode, the inductor 208 does not store any energy and thus no resonant oscillation occurs. Since no energy is stored in the inductor 208 and then there will be no resonant oscillation. During the re-generation mode, the battery charging current $I_{Re\text{-}generation}$ flows through the inductor 208 to ensure the battery charging current $I_{Re\text{-}generation}$ is being filtered by the L-C filter 216 that includes the inductor 208 and a first capacitor 218 connected in series with the inductor 208.

[0032] The system 200 ensures that the VFD systems are more stable and reliable in comparison to the prior systems shown in FIG. 1 before including the diodes 212, 214. Therefore, it is possible for the VFD systems to fully function without any power de-rating which significantly contributes to the customer for a better HEV energy saving effect.

[0033] The system 200 as described in the disclosure is a simple and straight forward method that allows for the use of cheap passive components, such as the use of capacitors 218, 220 having a lower capacitance, and the use of the two diodes 212, 214, which results in the use of the full power rating of the starter-generator 206.Therefore, the system as shown in FIG. 2 is configured to eliminate the resonant oscillation with a Pi Source Inverter-Converter with Bi-Directional Power Flow to overcome the setbacks of the previous systems as described in FIG. 1.

[0034] The motoring current I_{Motor} does not flow through the inductor 208. The inductor 208 is only required to be functional as an L-C filter 216 at the Re-Generation mode to keep the battery charging current $I_{Re\text{-}Generation}$ at a highest quality. As such, the system 200 shown is configured to allow the motoring current I_{Motor} to bypassed flow of the inductor 208 through the second diode 214 during the motor mode. This ensures that no excessive energy is stored in the inductor 208 at the motoring mode and thus no energy is exchanged between the inductor 208 and the first and second capacitors 218, 220.

[0035] The inductor 208 is needed due to EMC constraint and therefore the Re-Generative current $I_{Re\text{-}Generation}$ is forced to flow through first diode 212 and the inductor 208 as well as the first capacitor 218, which works as L-C filter 2016. The L-C filter 216 ensures the Re-Generative current $I_{Re\text{-}Generation}$ is filtered to meet the EMC requirements and to eliminate the electrical emissions to the surrounding area of the vehicle, as well as to the battery 210.

[0036] As shown, only the Re-Generative current $I_{Re\text{-}Generation}$ flows through the second diode 212 as well as the inductor 208, therefore the energy $E_{Inductor_Re\text{-}Generation}$ stored in the Inductor 208 may be calculated as follows:

$$E_{\text{Inductor_Re-Generation}} = \frac{V * I_{\text{Re-Generation}}{}^{2}}{2}, \qquad (5)$$

where L is the value of the inductor 208.

[0037] As shown, the bypass second diode 214 ensures that no excessive energy is stored in the inductor 208 during the motor mode and thus ensures that no resonant-oscillation between the inductor 208 and the first and second capacitors 218, 220. During the Re-Generation mode, the battery charging current $I_{Re\text{-}Generation}$ is filtered by the combination of the inductor 208 and first capacitor 218 (together referred to as the L-C filter 216) to ensure that the quality of the battery charging current $I_{Re\text{-}Generation}$ meets the EMC regulatory constraint. In some examples, the battery 210 has a voltage of 48 Volts, the inductor 208 has an inductance of 2.2 micro Henry, the first capacitor 218 has a capacitance of 1200 micro Farad, and the second capacitance 220 has a capacitance of 470 micro Farad. Other values may be possible as well.

[0038] FIGS. 3–10C illustrate simulation models and results in accordance with the description of both FIGS. 1 and 2. Two simulation models are provided using Matlab-Simulink.

[0039] FIGS. 3–5B illustrate a Matlab-Simulink Model using 100KW Interior Permanent Magnet Synchronous Motor Drive. Referring to FIG. 3, a Main Power Topology with 100KW Interior Permanent Magnet Synchronous Motor Drive is illustrated, and generally referred to as 300.

[0040] FIG. 4A illustrates the Sub Model of the Permanent Magnet Synchronous Motor Drive shown in FIG. 3 according to the implementation of FIG. 1 (prior art), which shows the detailed circuit topology of the PI Source Inverter (C-L-C). FIGS.

4B-1 to 4B-4, show the simulation results, which show the resonant oscillation on most of the parameter values. FIG. 4B-1 shows a graph of a motor torque reference 402, a motor torque measurement 404, a rotor speed 406 of the starter generator 104, and the current I_{C1} going through capacitor C1 generally referred to as 408. As can be seen, as the motor torque reference 402 and the motor torque measurement decreases, the rotor speed 406 of the starter generator 104 increases, while the current I_{C1} going through capacitor C1 218 generally referred to as 408 remains constant. FIG. 4B-2 shows a graph of the mechanical power (W) of the starter generator 104 and illustrates a reference mechanical power 410 and the measured mechanical power 412. FIGS. 4B-3 and 4B-4 illustrate currents and voltages respectively. I is the current passing through the DC bus 108 as well as the inductor 110 and V is the phase voltage of the electric machine, i.e., starter generator 104. I_q is the phase current of the starter generator 104 decoupled in quadrature axis and V_q is the associated phase voltage of the starter generator 104 decoupled in quadrature axis. I_d is the phase current of the starter generator 104 decoupled in direct axis and V_d is the associated phase voltage of the starter generator 104 decoupled in direct axis.

[0041] FIG. 5A shows a Sub Model of the Permanent Magnet Synchronous Motor Drive shown in FIG. 3 based on the system 200 described in FIG. 2 for eliminating the Resonant Oscillation. FIGS. 5B1 – 5B-4 show simulation results that show the effect of the elimination of resonant oscillation on all of the parameter values (as compared to the prior art results shown in FIG. 4B) due to the addition of the two diodes 212 and 214 (FIG. 2, FIG. 5A in comparison with FIG. 1 and FIG. 4A respectively). FIG. 5B-1 shows a graph of a motor torque measurement 504, rotor speed 506 of the starter generator 206, and the current I_{C1} going through capacitor C1, 218 generally referred to as 508. As can be seen, as the motor torque measurement 504 decreases, the rotor speed 506 of the starter generator 206 increases, while the current I_{C1} going through capacitor C1, 218 generally referred to as 508 remains constant. FIG. 5B-2 shows a graph of the mechanical power (W) of the starter generator 206 and illustrates a reference mechanical power 510 and the measured mechanical power 512. FIGS. 5B-3 and 5B-4 illustrate currents and voltages respectively. I is the current passing through the DC bus 202 as well as the inductor 208 and V is the phase voltage of the starter generator 206. I_q is the phase current of the electric machine decoupled in quadrature axis and V_q is the associated phase

voltage of the starter generator 206 decoupled in quadrature axis. I_d is the phase current of the starter generator 206 decoupled in direct axis and V_d is the associated phase voltage of the starter generator 206 decoupled in direct axis. As previously mentioned, the resonant oscillation is significantly reduced on all ~~most~~ of the parameter values in FIGS. 5A–5B-4.

[0042] FIGS. 6–8B illustrate Matlab–Simulink Model using 3 Phase Induction Machine's Variable Frequency Drive with Field-Oriented-Control (FOC). FIG. 6 shows a Simulink top model with the 3 Phase Induction Machine's Variable Frequency Drive using FOC (Field-Orient-Control). FIG. 7A shows a Sub Model of the "Field-Orient-Control Induction Motor Drive" shown in FIG. 6, which shows the Detailed Circuit Topology of the PI Source Inverter (C-L-C) based on the prior art described in FIG. 1. FIGS. 7B-1 to 7B-4 show the simulation results of FIG. 7A that shows the resonant oscillation on most of the parameter values. FIG. 7B-1 shows a graph that includes the stator current, i.e., the current from the starter generator 104. FIG. 7B-2 shows a graph of a reference rotor speed 702 verses a measured rotor speed 704. The rotor speed is the speed of the rotor of the starter-generator 104. FIG. 7B-3 shows a graph of a reference electromagnetic torque 706 and a measured electromagnetic torque 708 on the shaft of the starter generator 206. FIG. 7B-4 shows the DC-Bus voltage V_{108} and the associated current I_{108}.

[0043] FIG. 8A shows the Sub Model of the "Field-Orient-Control Induction Motor Drive" shown in FIG. 6 for eliminating the Resonant Oscillation based on the system as described in FIG. 2. FIG.8B shows the simulation results of FIG. 8A which show the effect of elimination of resonant oscillation on all of the parameter values. FIG. 8A-1 shows a graph that includes the stator current, i.e., the current from the starter generator 206. FIG. 8B-2 shows a graph of a reference rotor speed 802 verses a measured rotor speed 804. The rotor speed is the speed of the rotor of the starter-generator 206. FIG. 8B-3 shows a graph of a reference electromagnetic torque 806 and a measured electromagnetic torque 808 on the shaft of the starter generator 206. FIG. 8B-4 shows the DC-Bus voltage V_{202} and the associated current I_{202}. As previously mentioned, the resonant oscillation is significantly reduced on all of the parameter values in FIGS. 8A–8B-4.

[0044] Therefore, and based on the above simulations, the benefits of the system shown in FIG. 2 include increasing the reliability of the main power section and

stabilizing all the power sections by eliminating the resonant oscillations, reducing the power losses and heat on the main power section and thus extending the lifetime of the main power components, reducing the current rating of the inductor 208 from 260A to 40A, reducing the current rating of the first capacitor 218 capacitor from 9.5A (RMS) to less, and no need to de-rate the BSG inverter 204 and motor/re-generator power rating. As such, the starter-generator 206 including the inverter 204 and motor/re-generator may be used at its full power rating. Current rating, also known as current-carrying capacity or ampacity, is the maximum amount of electric current a conductor or device can carry before sustaining immediate or progressive deteriorations.

[0045] In addition, and based on the results of the simulations discussed, the different types of the simulation results have shown the resonant oscillation as well as the ripple current elimination effect at the same level as a result of the design of FIG. 2 as compared to the prior art shown in FIG. 1.

[0046] As shown and discussed with respect to FIG. 2 and the associated figures discussing the simulations of FIG. 2, the system 200 better controls the current flow on the inductor 208 based on the two different operational modes (Motor Mode and Re-Generation Mode). As such, the disclosed system 200 meets the constraints of the automotive level EMC, and significantly eliminates the resonant oscillation that is caused by the inductor 208. Therefore, the starter-generator 206 can operate at full power without any de-ration, which increases the stability, reliability, and lifetime of the BSG system.

[0047] Since the two diodes 212, 214 are passive components, there is no need for triggering circuits or controls. Therefore, no other additional circuits or components are required.

[0048] The above disclose may be used in all types of HEVs that adopt an electric machine's variable frequency drives, because all types of HEVs require a Re-Generation mode at breaking or down hills mode for catching the vehicle's kinematic energy and convert it to be electrical energy through the converter and charging the battery 210. The described disclosure is not limited to a 48V BSG, but is also applicable to any type of HEV that uses inverter and converter 204.

[0049] A number of implementations have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit

and scope of the disclosure. Accordingly, other implementations are within the scope of the following claims. For example, the actions recited in the claims can be performed in a different order and still achieve desirable results.

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WHAT IS CLAIMED IS:

1. A system for reducing a resonant oscillation on a direct current bus of a power inverter/converter for an electric machine having a variable frequency drive, the system comprising:

a battery;

a first capacitor connected in parallel with the battery;

an inductor connected in series with the first capacitor;

a first diode connected in series with the inductor;

a second diode connected in parallel with the inductor and the first diode;

a second capacitor connected in series with the first diode; and

a starter-generator connected to the second capacitor;

wherein:

during a re-generation mode for charging the battery, a re-generation current flows from the starter-generator to the battery, passing through the first diode and the inductor and bypassing the second diode; and

during a motor mode, a motor current flows from the battery to the starter-generator, passing through the second diode and bypassing the first diode and the inductor.

2. The system of claim 1, wherein the first capacitor and the inductor form an L-C filter.

3. The system of claim 1, wherein during the re-generation mode for charging the battery, the re-generation current flows through the first capacitor and the inductor respectively.

4. The system of claim 1, wherein during the motor mode, the motor current flows through the second diode.

5. The system of claim 1, further comprising a power inverter/converter connected between the starter-generator and the second capacitor.

6. The system of claim 5, wherein the power inverter/converter comprises six MOSFETS each including a diode.

7. The system of claim 5, wherein:

during the motor mode, the power inverter/converter includes an inverter from DC to 3-phase AC sinusoidal; and

during the re-generation mode, the power inverter/converter includes a converter from 3-phase AC sinusoidal to DC.

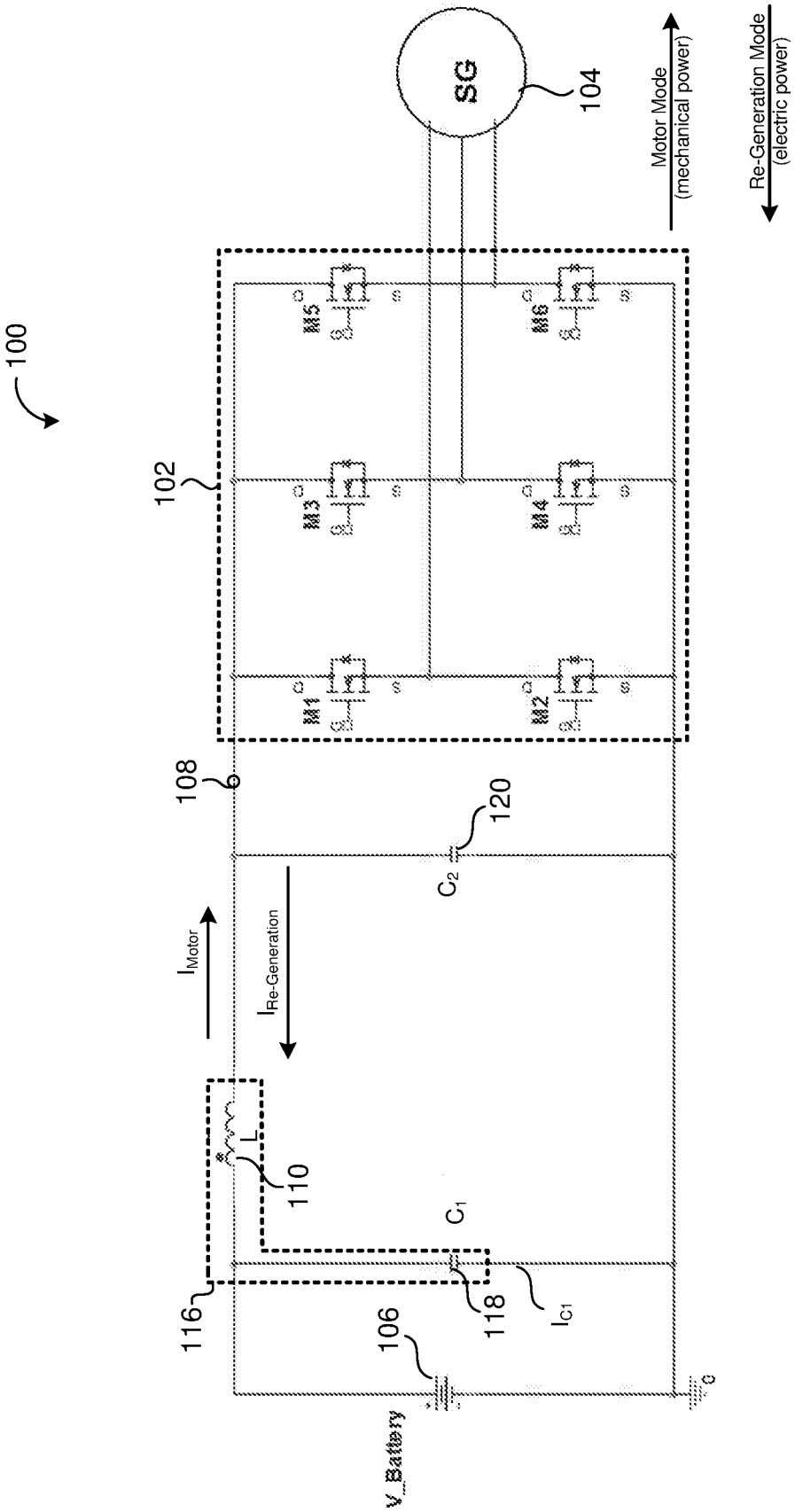


FIG. 1
Prior Art

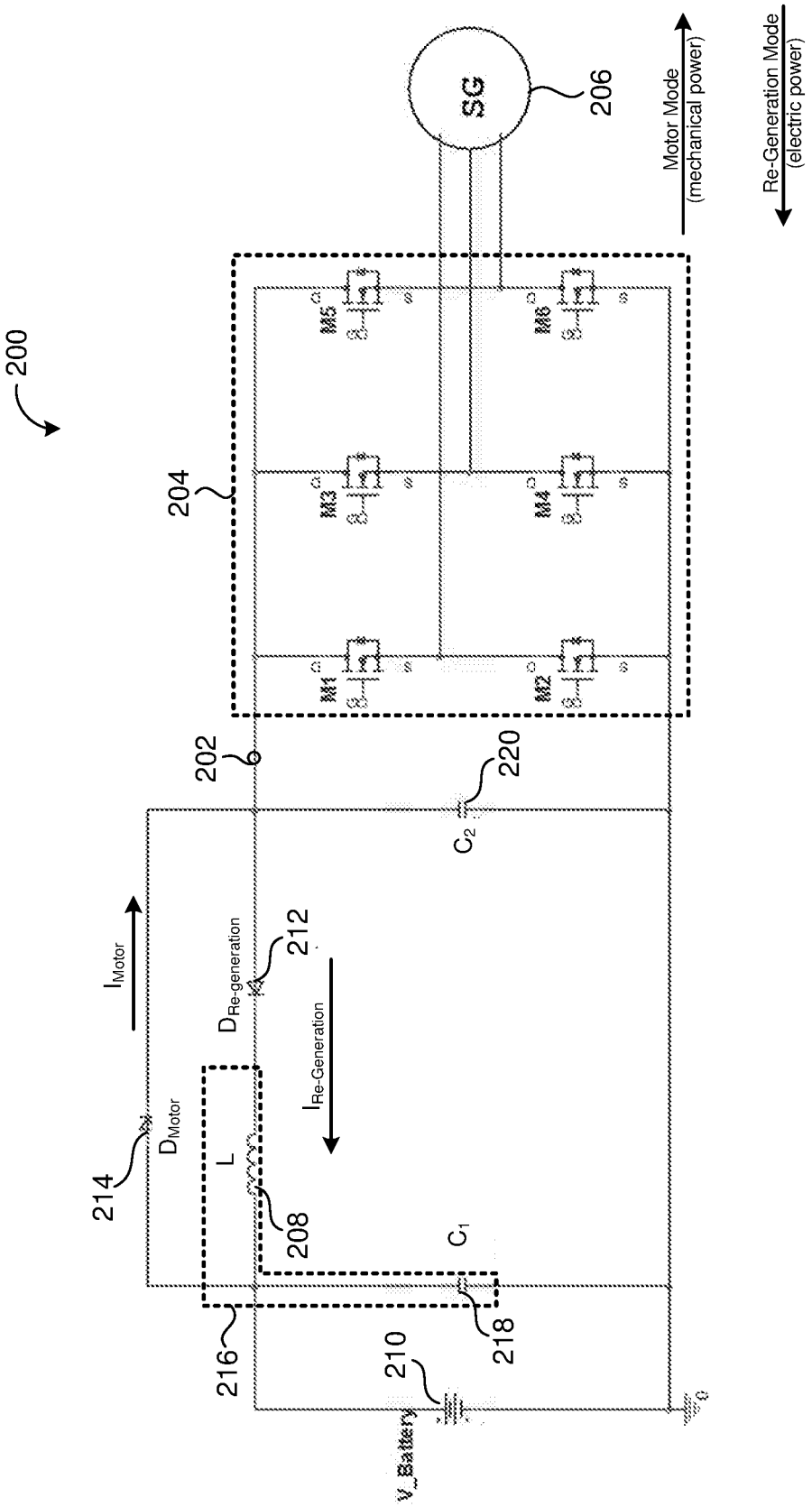

200
204
206
SG
Motor Mode
(mechanical power)
Re-Generation Mode
(electric power)
M1
M2
M3
M4
M5
M6
202
220
C_2
212
$D_{Re\text{-}generation}$
I_{Motor}
$I_{Re\text{-}Generation}$
214
D_{Motor}
L
208
C_1
216
218
210
V_Battery

FIG. 2

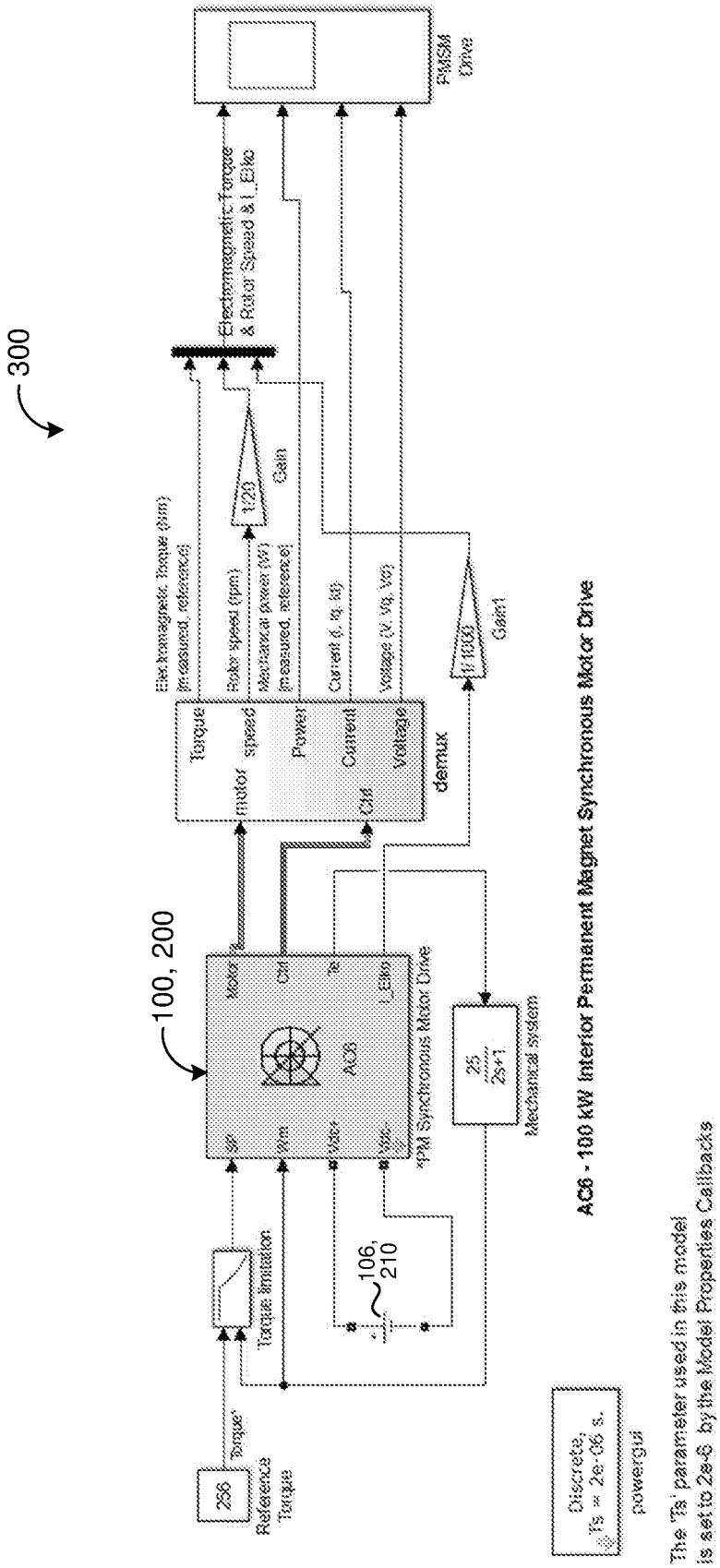

300
100, 200
106, 210
PMSM Drive
Electromagnetic Torque & Rotor Speed & I_Elec
Gain
1/25
Electromagnetic Torque (Nm) measured, reference
Rotor speed (rpm)
Mechanical power (W) measured, reference
Current (i_q, i_d)
Voltage (V_qs, V_ds)
1/1000
Gain1
Torque
motor speed
Power
Current
Voltage
demux
Motor
Ctrl
Elec
AC6
*PM Synchronous Motor Drive
25
25s+1
Mechanical system
Torque limitation
Reference Torque
Discrete, Ts = 2e-06 s.
powergui
AC6 - 100 kW Interior Permanent Magnet Synchronous Motor Drive
The 'Ts' parameter used in this model is set to 2e-6 by the Model Properties Callbacks

FIG. 3

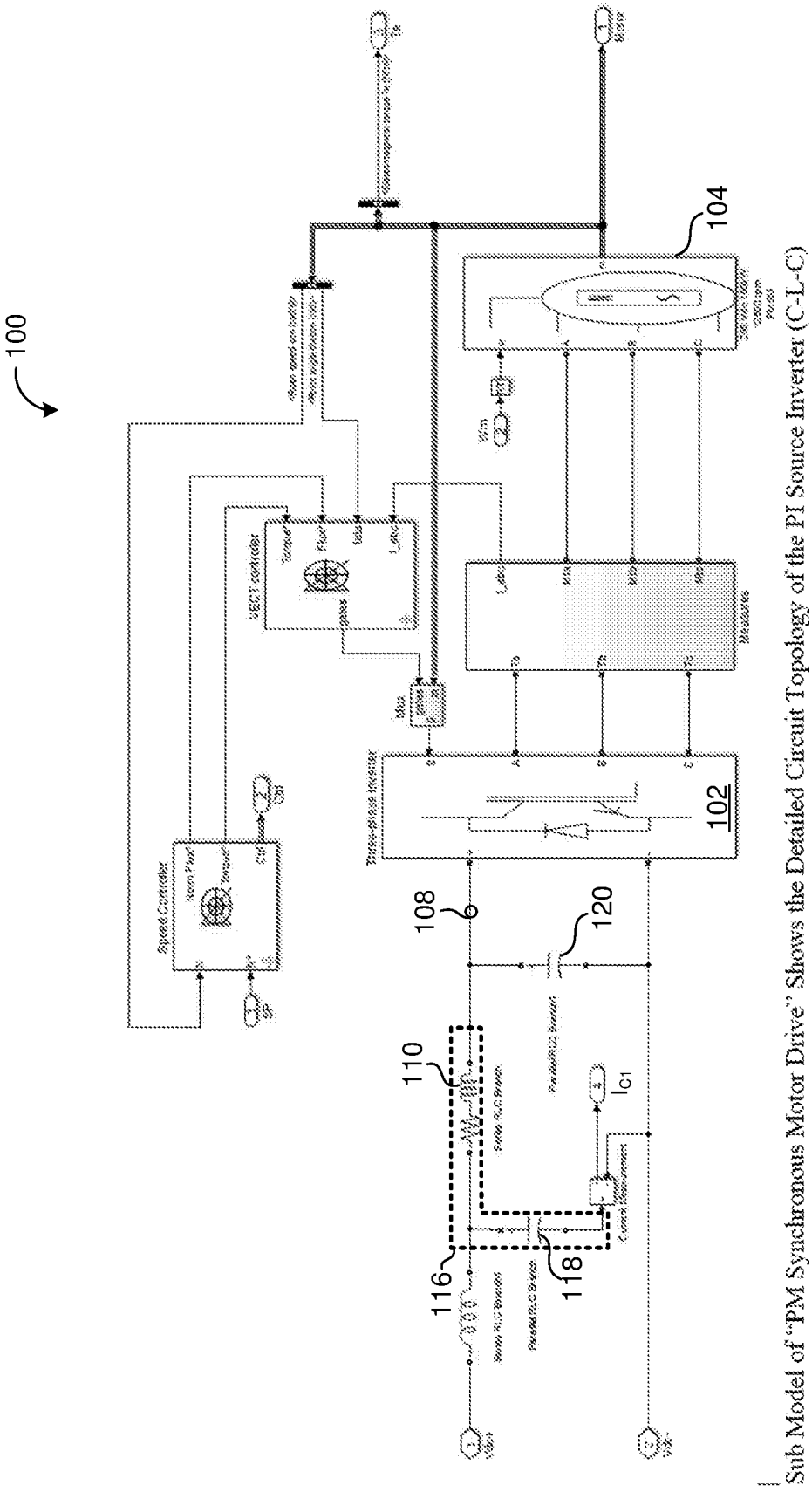


FIG. 4A

Prior Art

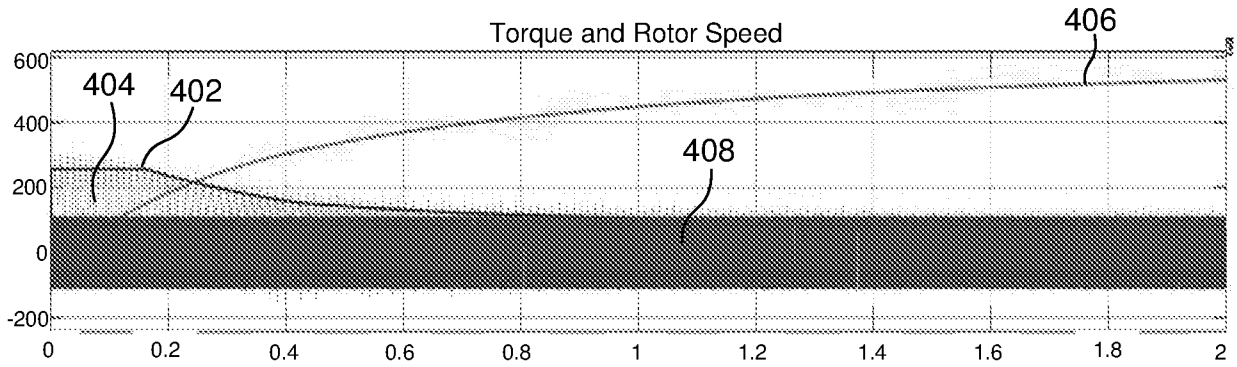


FIG. 4B-1 – Prior Art

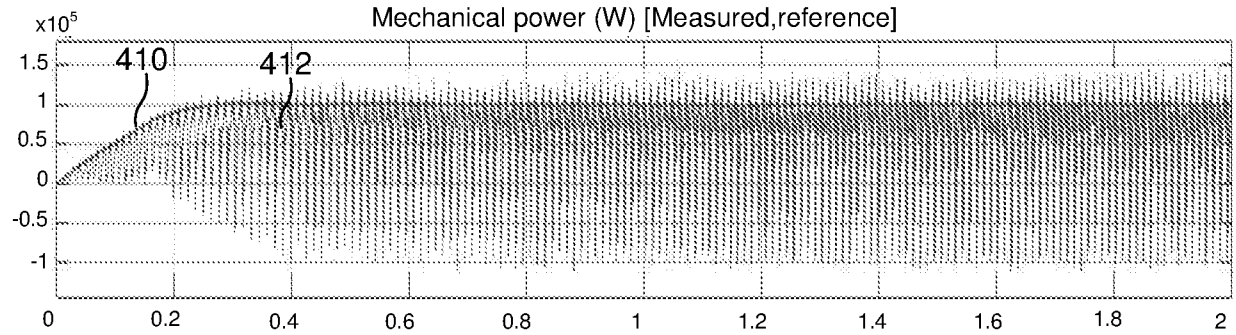


FIG. 4B-2 – Prior Art

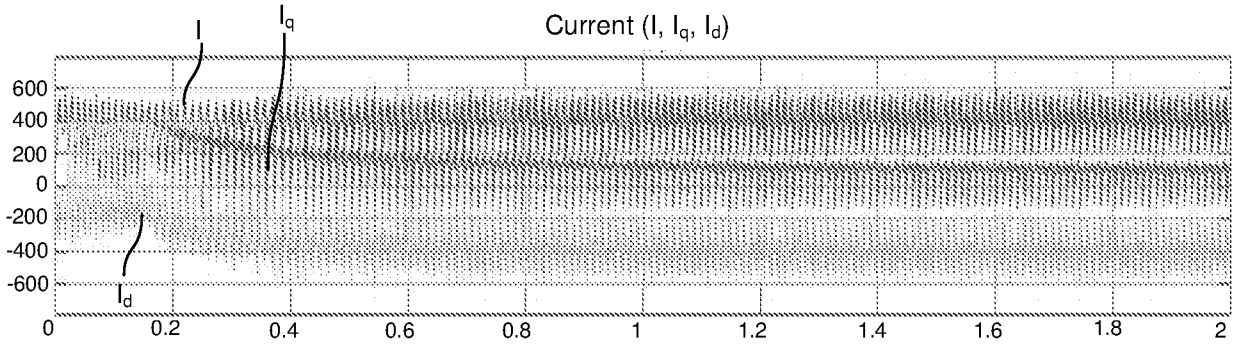


FIG. 4B-3 – Prior Art

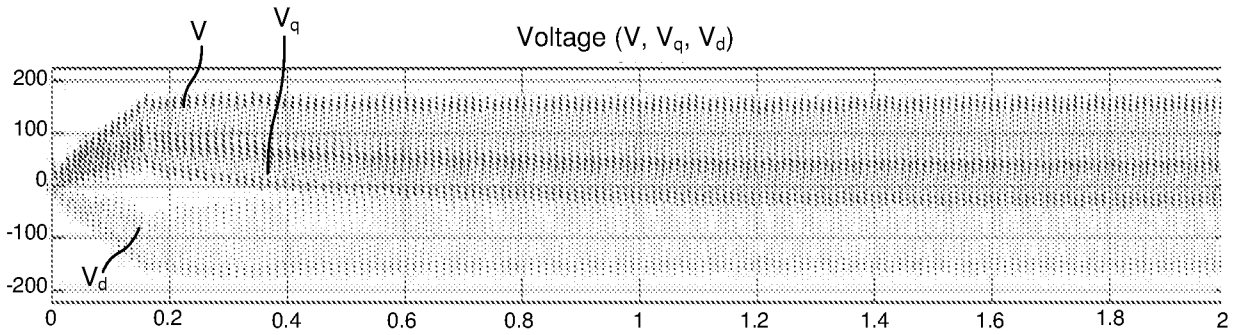


FIG. 4B-4 – Prior Art

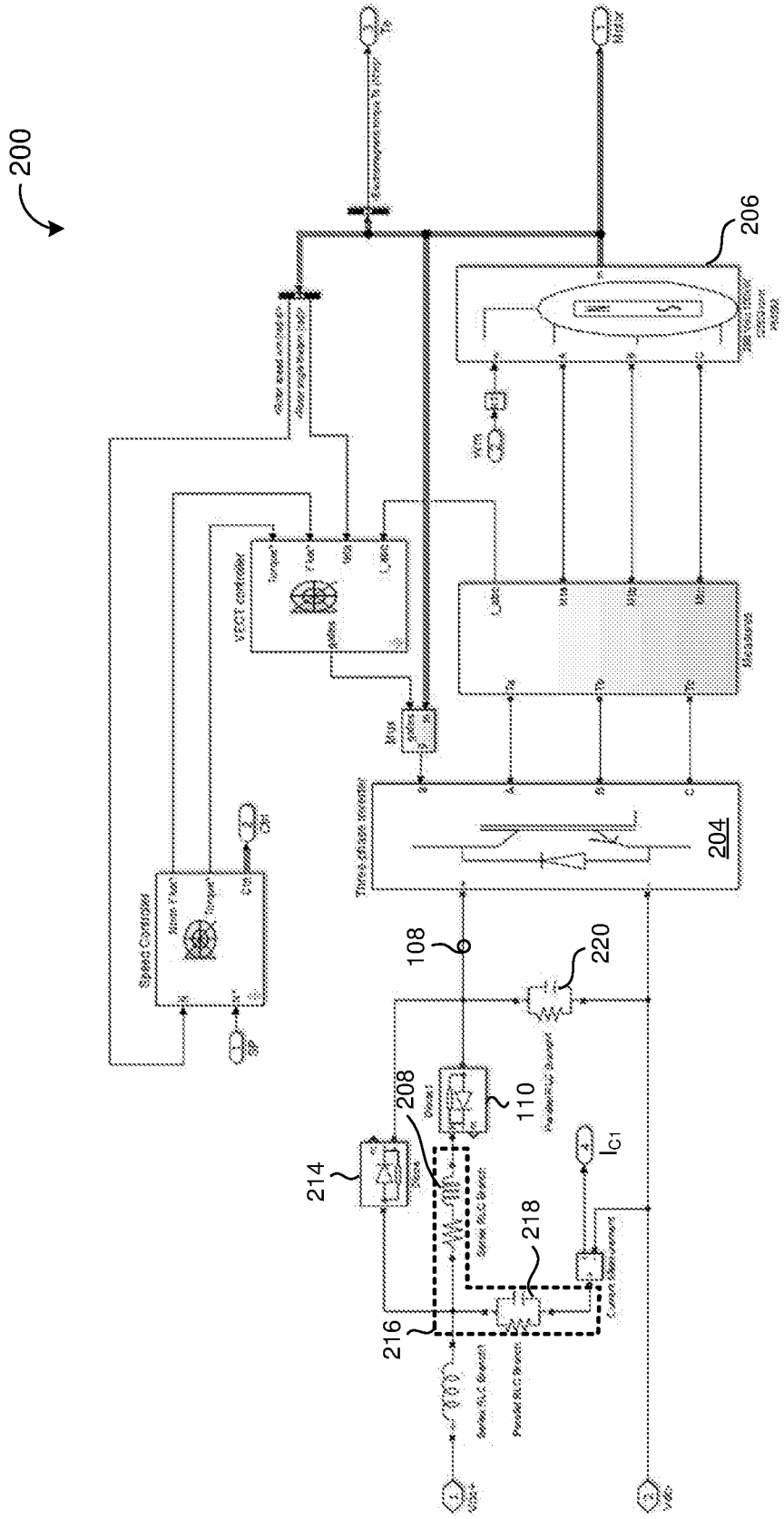


FIG. 5A

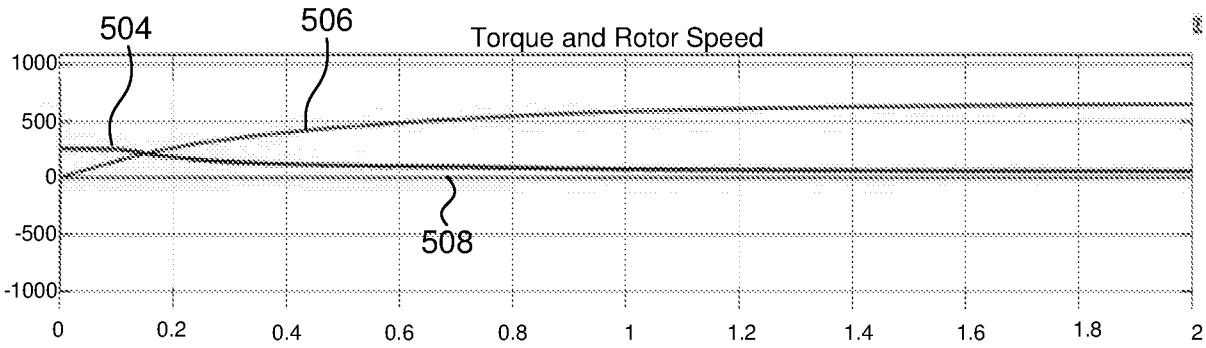


FIG. 5B-1

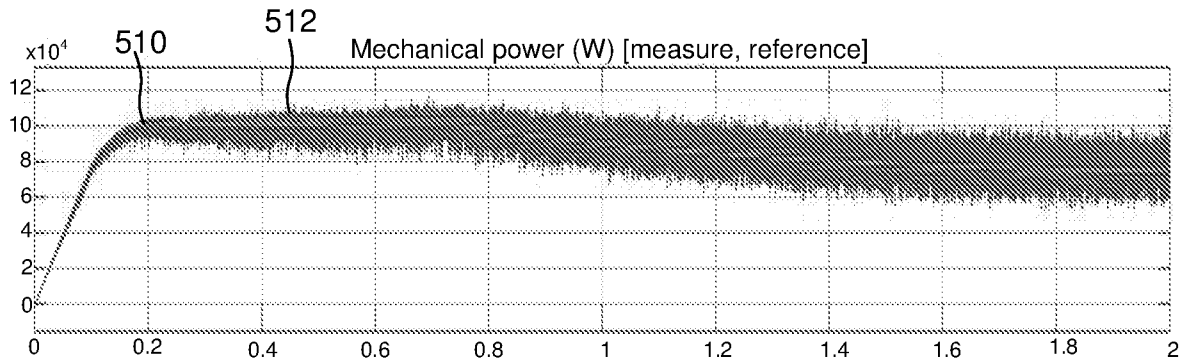


FIG. 5B-2

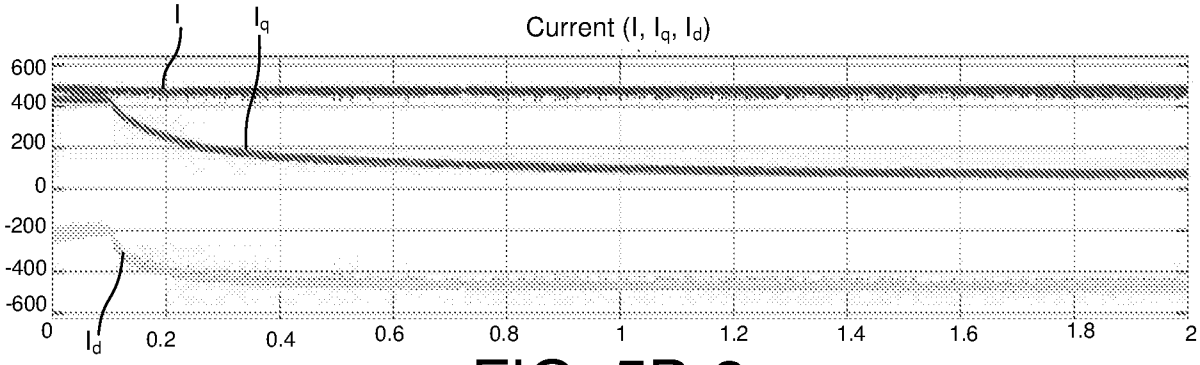


FIG. 5B-3

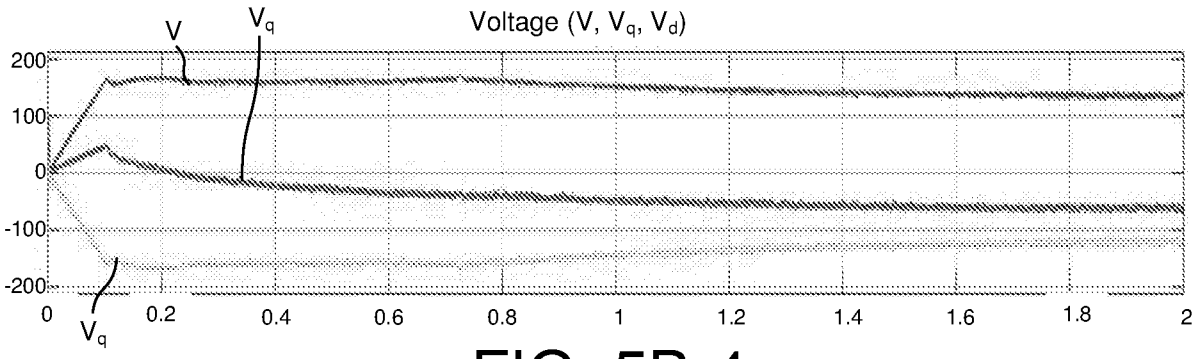


FIG. 5B-4

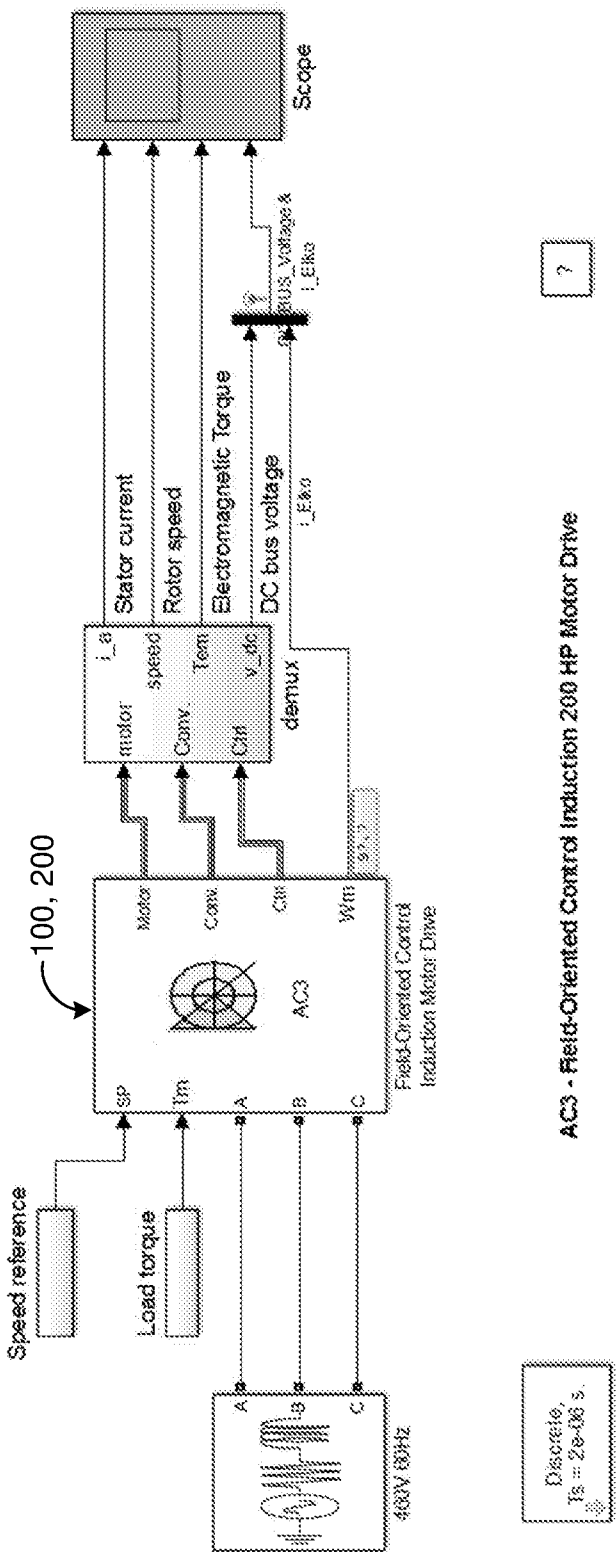

Scope
Stator current
Rotor speed
Electromagnetic Torque
DC bus voltage
demux
100, 200
Field-Oriented Control
Induction Motor Drive
AC3
Speed reference
Load torque
400V 60Hz
Discrete,
Ts = 2e-06 s.
AC3 - Field-Oriented Control Induction 200 HP Motor Drive

FIG. 6

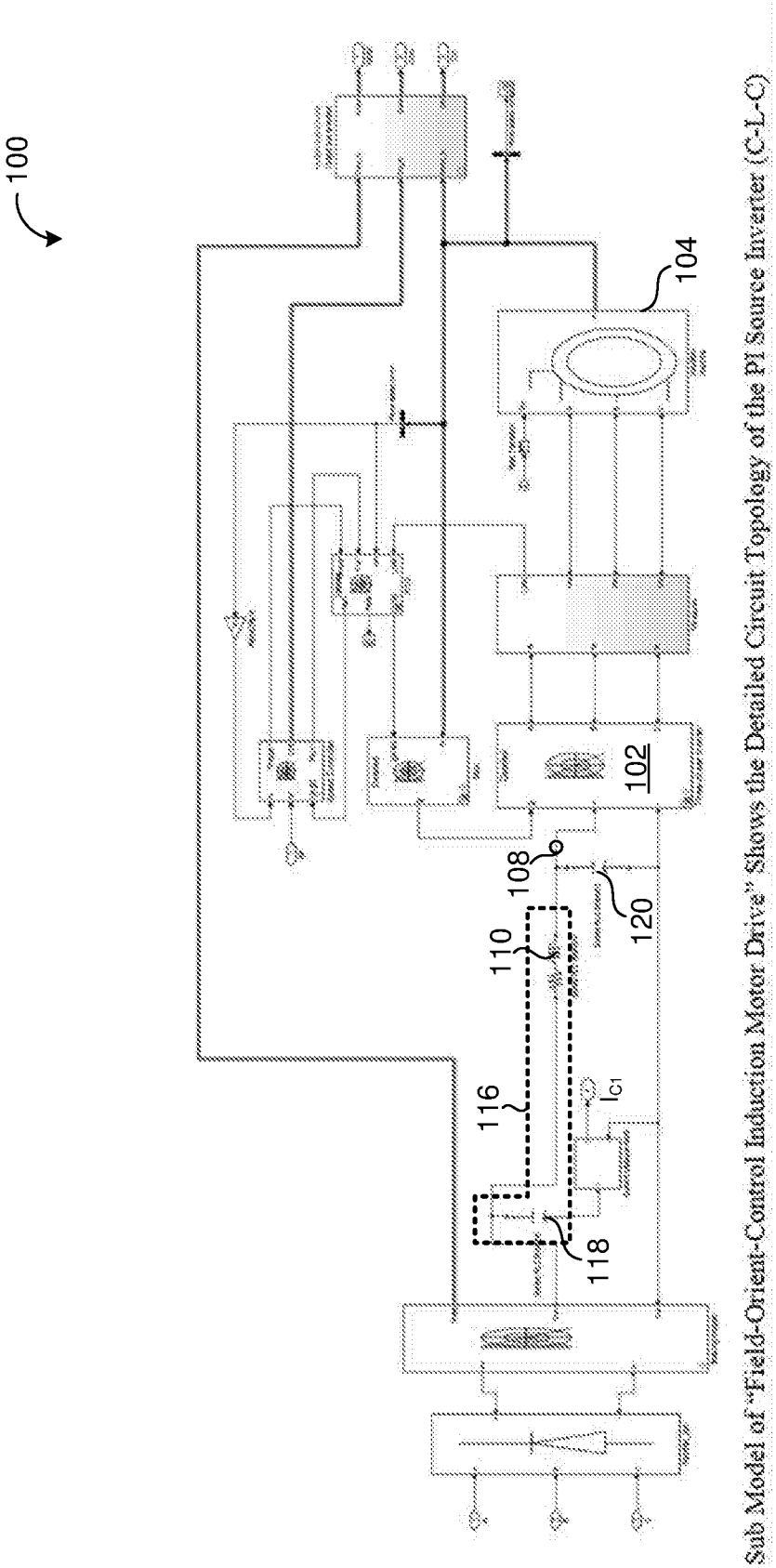


FIG. 7A
Prior Art

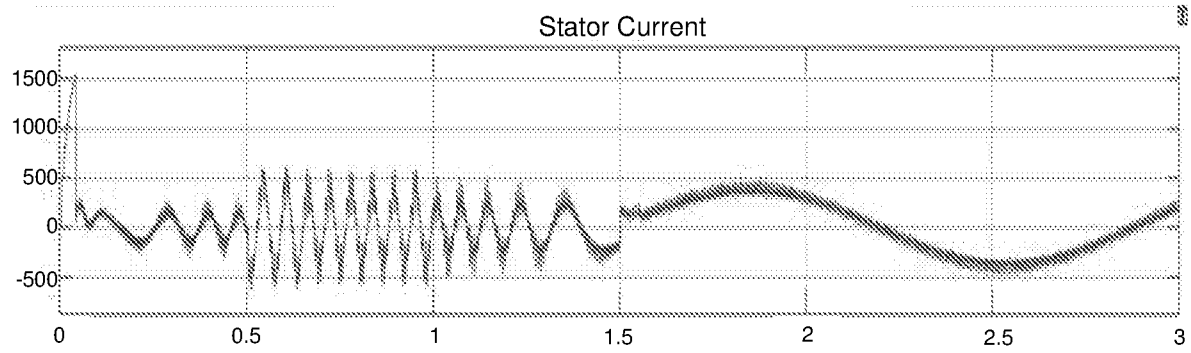


FIG. 7B-1 – Prior Art

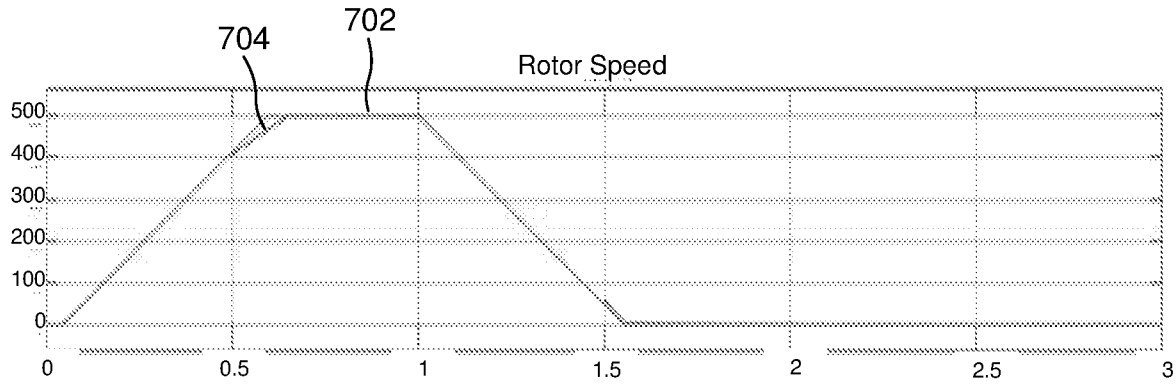


FIG. 7B-2 – Prior Art

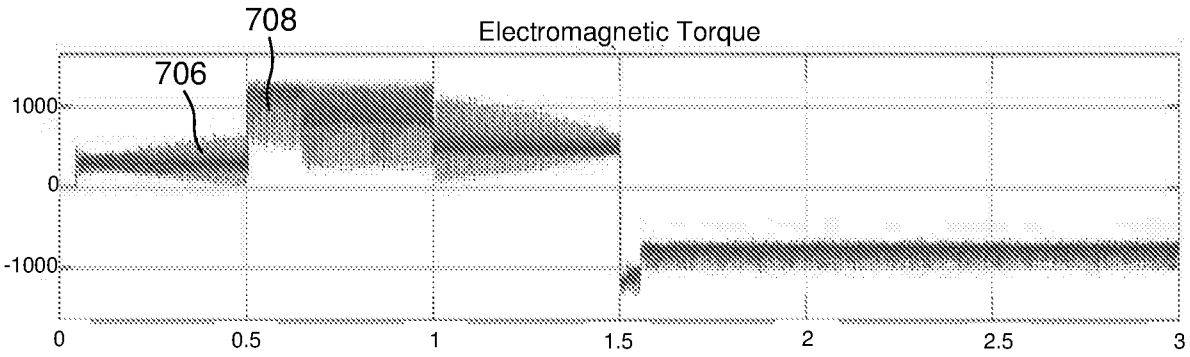


FIG. 7B-3 – Prior Art

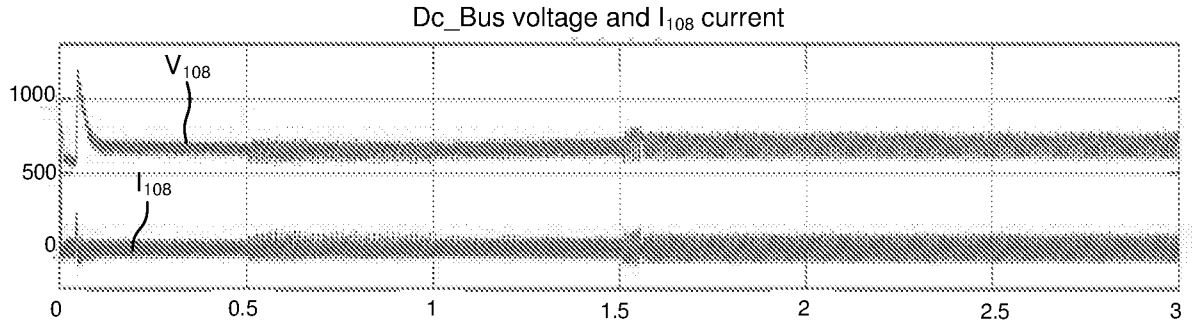


FIG. 7B-4 – Prior Art

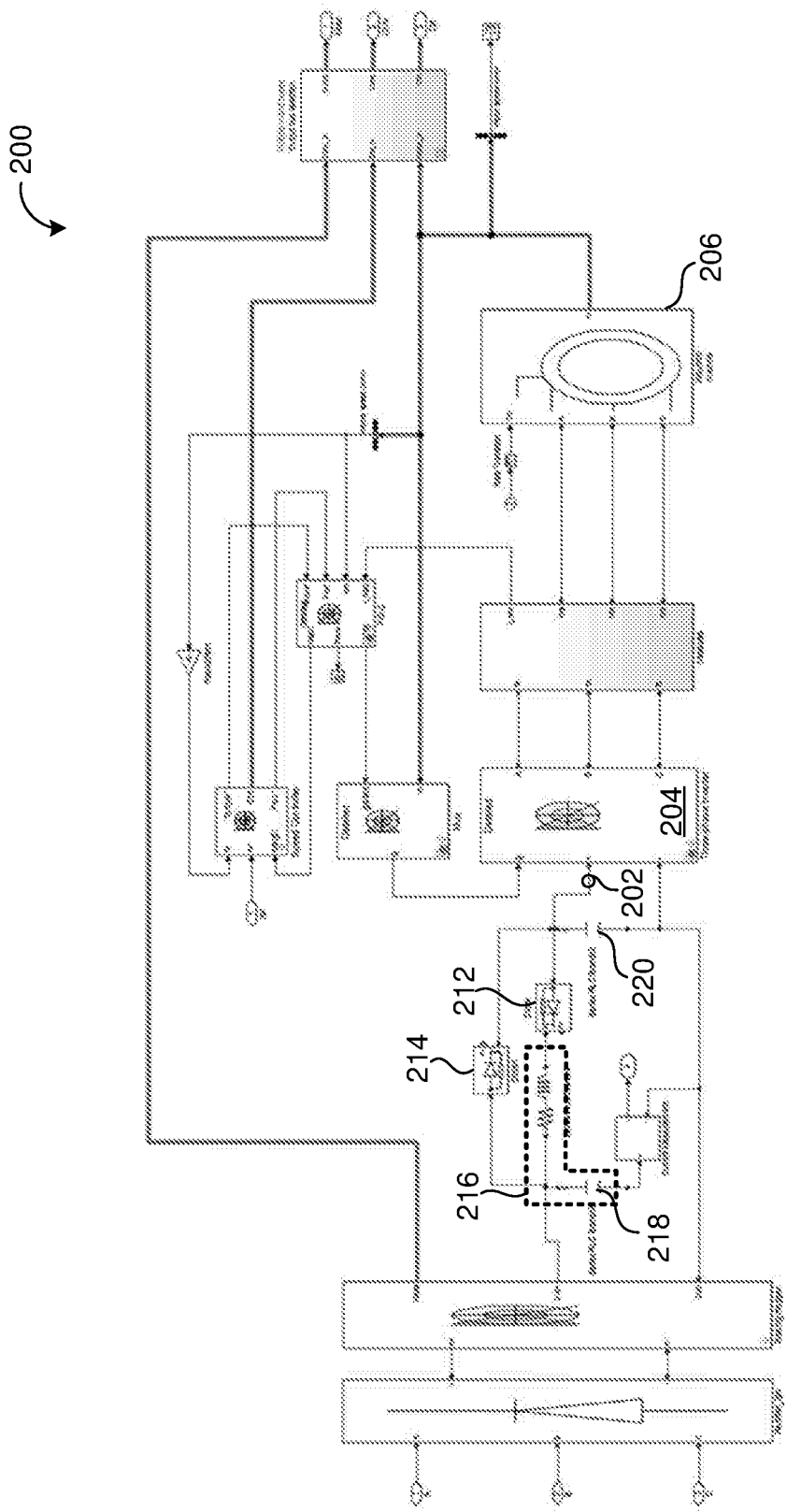


FIG. 8A

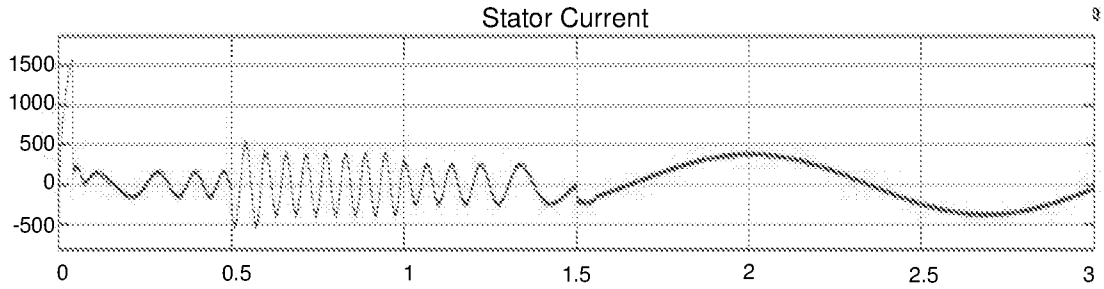


FIG. 8B-1

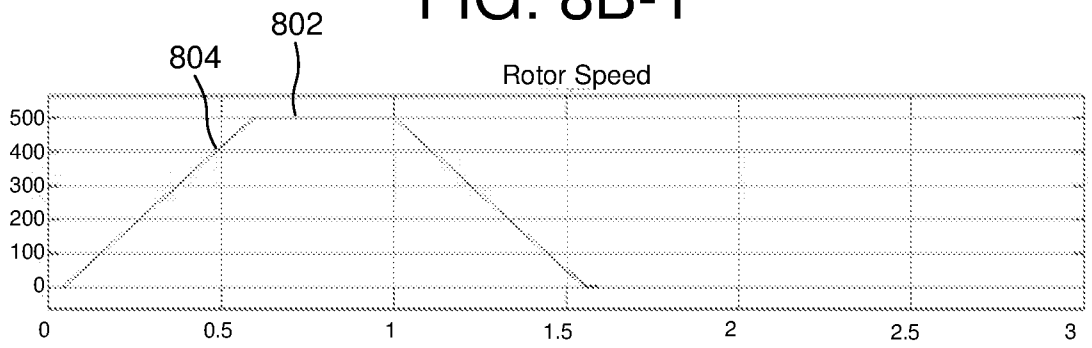


FIG. 8B-2

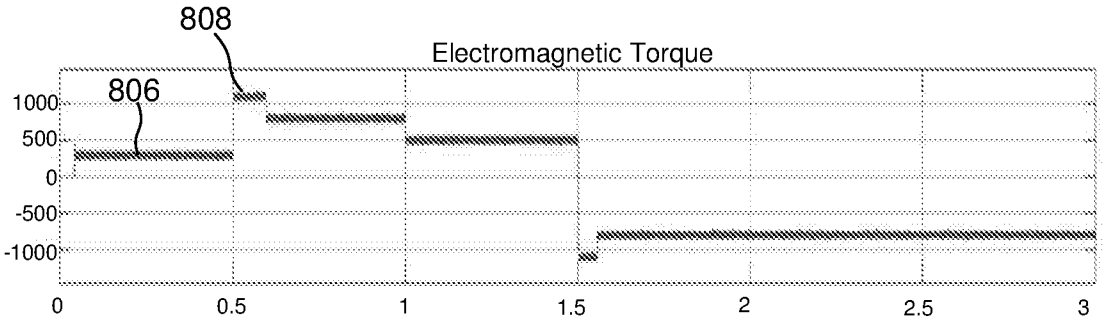


FIG. 8B-3

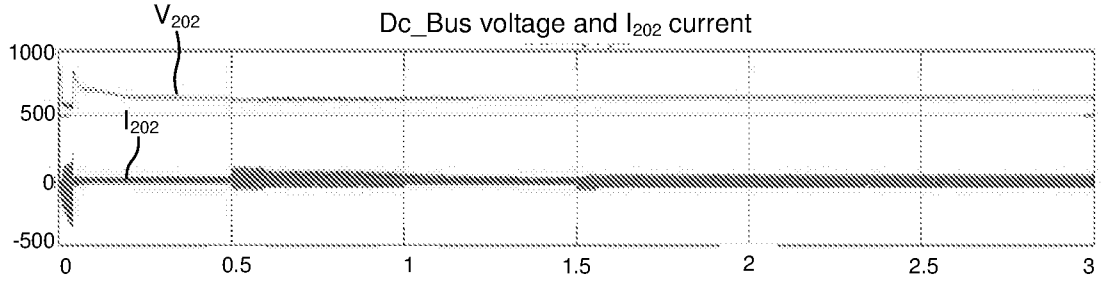


FIG. 8B-4

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/022707

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M1/14 H02P27/06 B60L11/18
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02M H02P B60L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2012/019231 A1 (CHEN LIHUA [US]) 26 January 2012 (2012-01-26) paragraph [0004]; figures 1-3 paragraph [0005] paragraph [0023] paragraph [0030] paragraph [0036] -----	1-7
X	US 2007/236965 A1 (CHEN CHINGCHI [US] ET AL) 11 October 2007 (2007-10-11) paragraph [0027]; figure 4 paragraph [0034] -----	1-7

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 May 2018	06/06/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Gusia, Sorin

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2018/022707

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2012019231 A1	26-01-2012	CN 102347698 A	08-02-2012
		CN 107257204 A	17-10-2017
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		US 2012019231 A1	26-01-2012
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		DE 102007017389 A1	18-10-2007
		GB 2436970 A	10-10-2007
		JP 5060147 B2	31-10-2012
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