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(54) VARIABLE MAGNETIZATION MACHINE CONTROLLER

(71) Applicants: **Nissan Motor Co., Ltd.**, Yokohama-shi, Kanagawa (JP); **Wisconsin Alumni Research Foundation**, Madison, WI (US)

(72) Inventors: **Takashi Fukushige**, Kanagawa (JP); **Takashi Kato**, Kanagawa (JP); **Brent S. Gagas**, Madison, WI (US); **Robert D. Lorenz**, Madison, WI (US)

(73) Assignees: **Nissan Motor Co., Ltd.**, Yokohama (JP); **Wisconsin Alumni Research Foundation**, Madison, WI (US)

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PCT Pub. Date: **Mar. 3, 2016**

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H02P 21/00 (2016.01)
H02P 21/04 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H02P 21/0085*** (2013.01); ***H02P 21/04*** (2013.01); ***H02P 25/03*** (2016.02); ***H02P 27/085*** (2013.01); *H02P 2207/05* (2013.01)

(58) **Field of Classification Search**
CPC .. Y02T 10/643; B60L 15/025; B60L 2220/14; H02P 21/06; H02P 21/22
See application file for complete search history.

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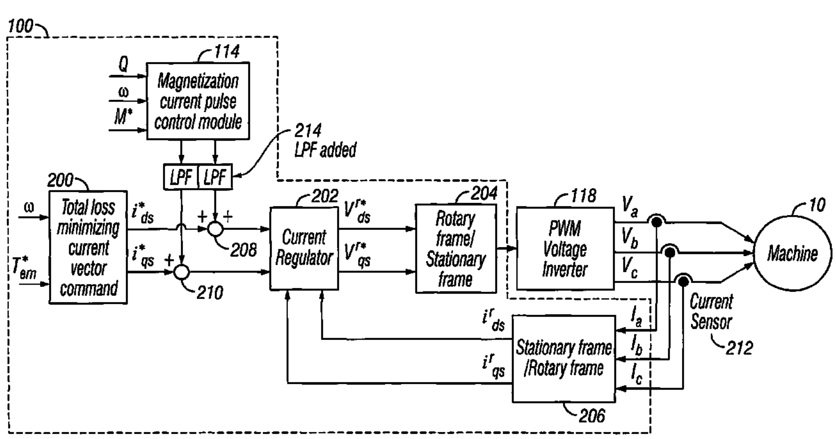
Primary Examiner — Shawki S Ismail
Assistant Examiner — Zoheb S Imtiaz
(74) *Attorney, Agent, or Firm* — Global IP Counselors, LLP

(57) **ABSTRACT**

A variable magnetization machine control system comprising a controller configured to adjust a d-axis current waveform and a q-axis current waveform in accordance with an operating condition of a variable magnetization machine to generate an adjusted d-axis current waveform and an adjusted q-axis current waveform that provide a driving voltage to drive the variable magnetization machine at a predetermined speed while maintaining the driving voltage below a predetermined maximum magnitude.

14 Claims, 17 Drawing Sheets



(51) **Int. Cl.**

H02P 25/03	(2016.01)
H02P 27/08	(2006.01)

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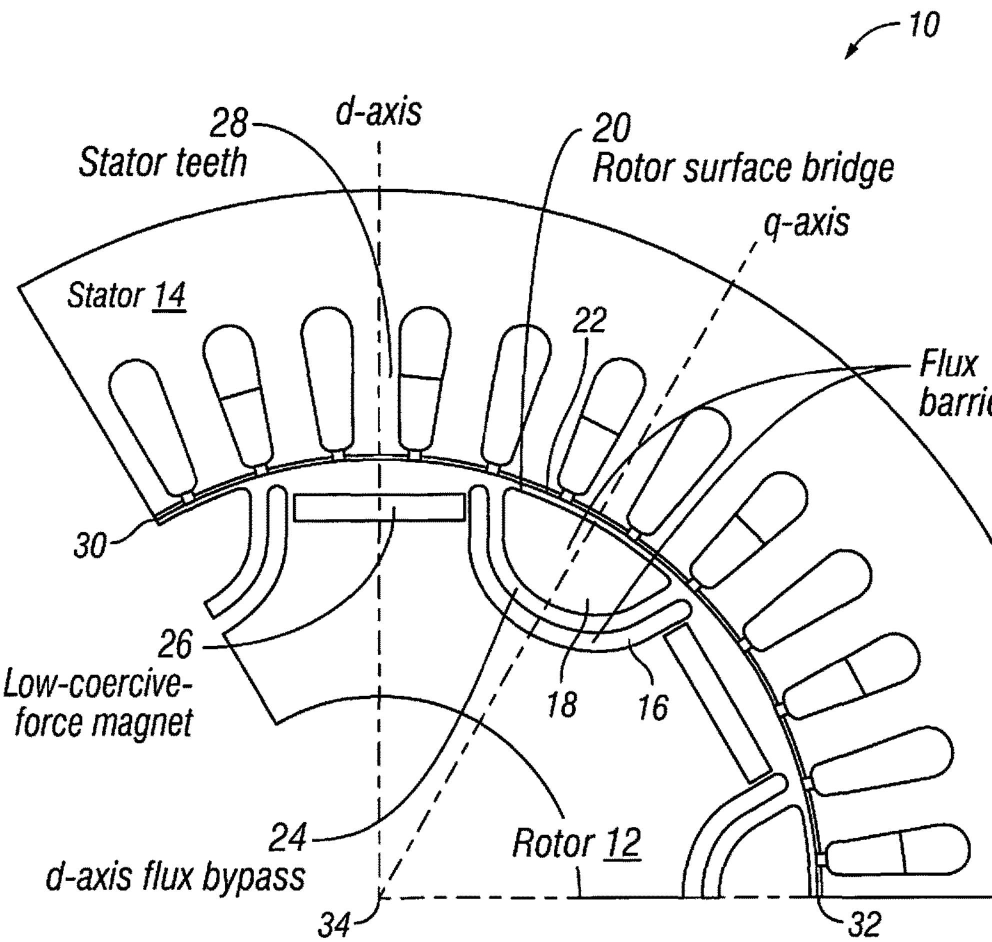

10
28
Stator teeth
d-axis
20
Rotor surface bridge
q-axis
Stator 14
22
Flux
barrier
30
26
Low-coercive-
force magnet
18
16
24
d-axis flux bypass
Rotor 12
34
32

FIG. 1

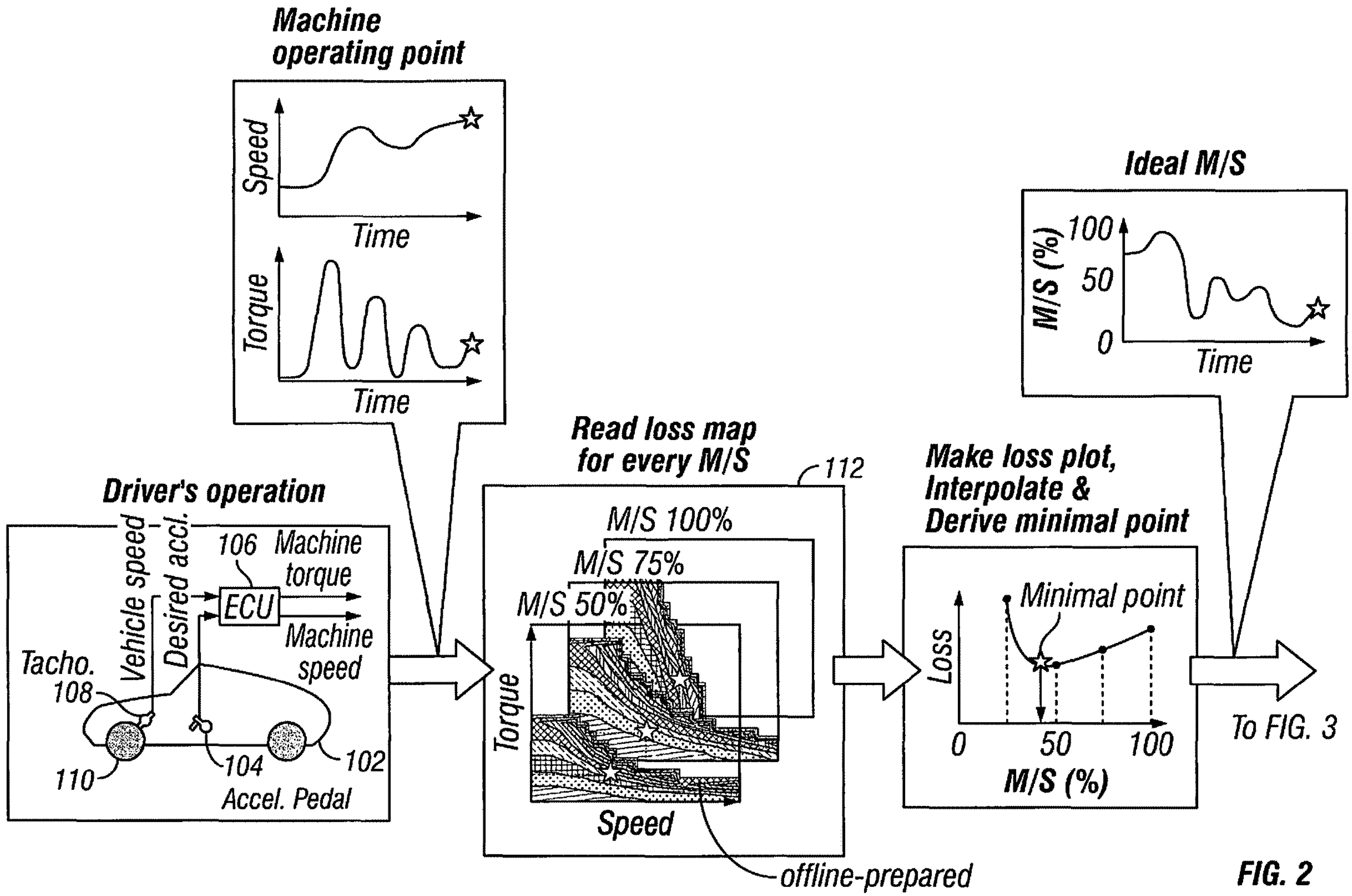

Machine operating point
Speed
Time
Torque
Time
Ideal M/S
M/S (%)
100
50
0
Time
Read loss map for every M/S
112
M/S 100%
M/S 75%
M/S 50%
Torque
Speed
offline-prepared
Make loss plot, Interpolate & Derive minimal point
Minimal point
Loss
0
50
100
M/S (%)
To FIG. 3
Driver's operation
Vehicle speed
Desired accl.
106
Machine torque
ECU
Machine speed
Tacho.
108
110
104
102
Accel. Pedal

FIG. 2

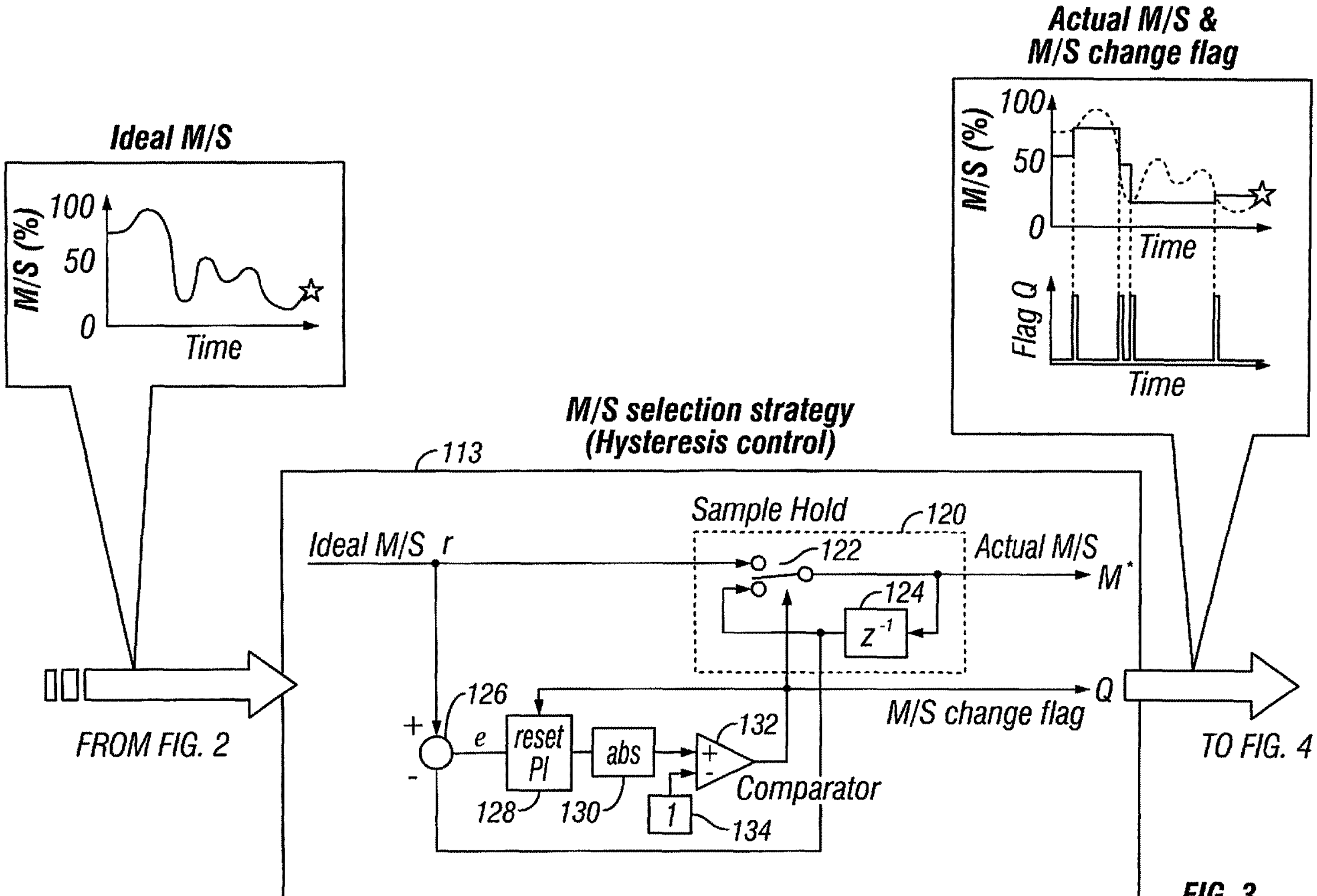

Ideal M/S
M/S (%)
100
50
0
Time
FROM FIG. 2
M/S selection strategy
(Hysteresis control)
113
Sample Hold
120
Ideal M/S r
122
Actual M/S
M*
124
z⁻¹
Q
126
M/S change flag
+
-
e
reset PI
abs
132
Comparator
128
130
1
134
TO FIG. 4
Actual M/S &
M/S change flag
M/S (%)
100
50
0
Time
Flag Q
Time

FIG. 3

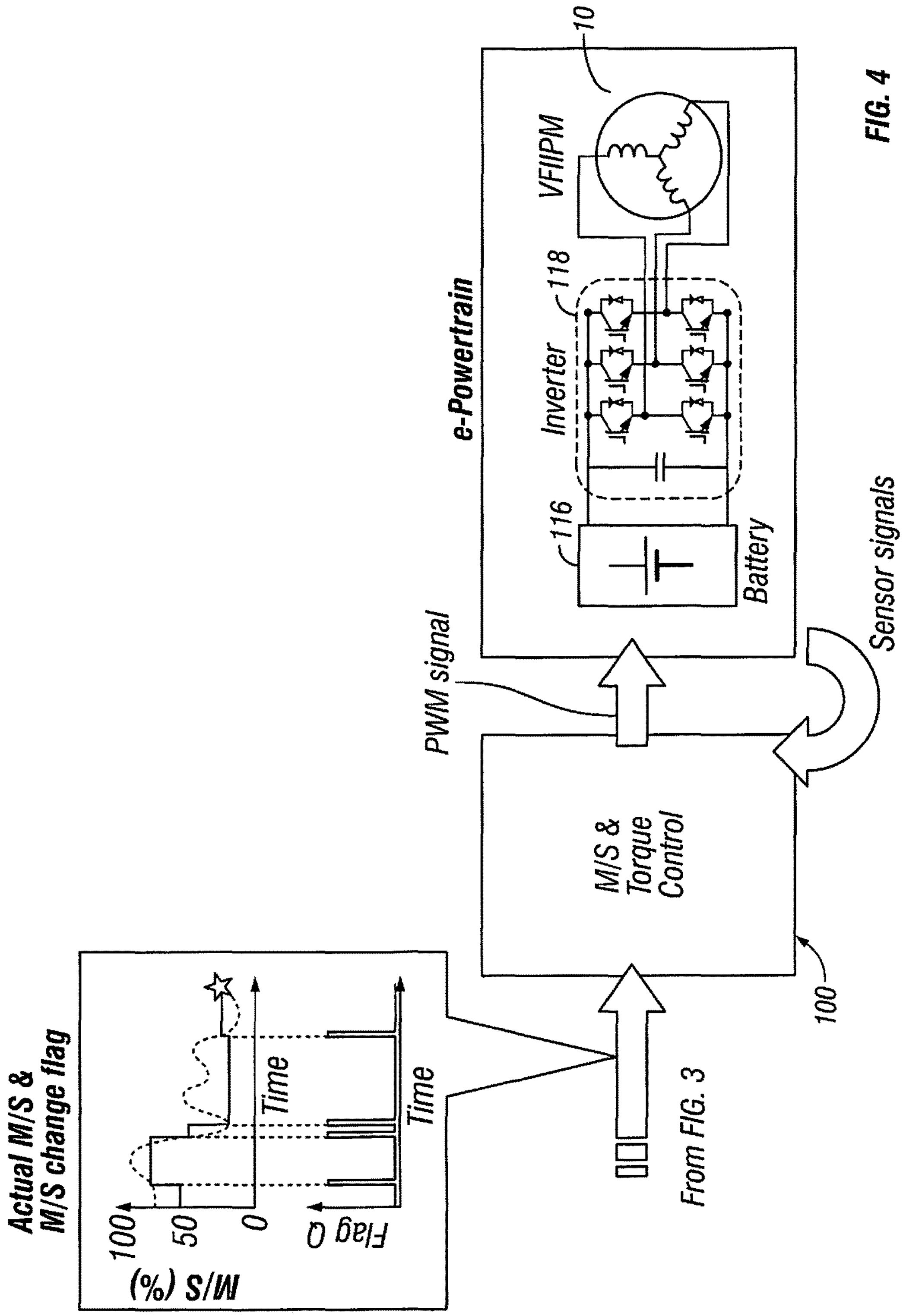
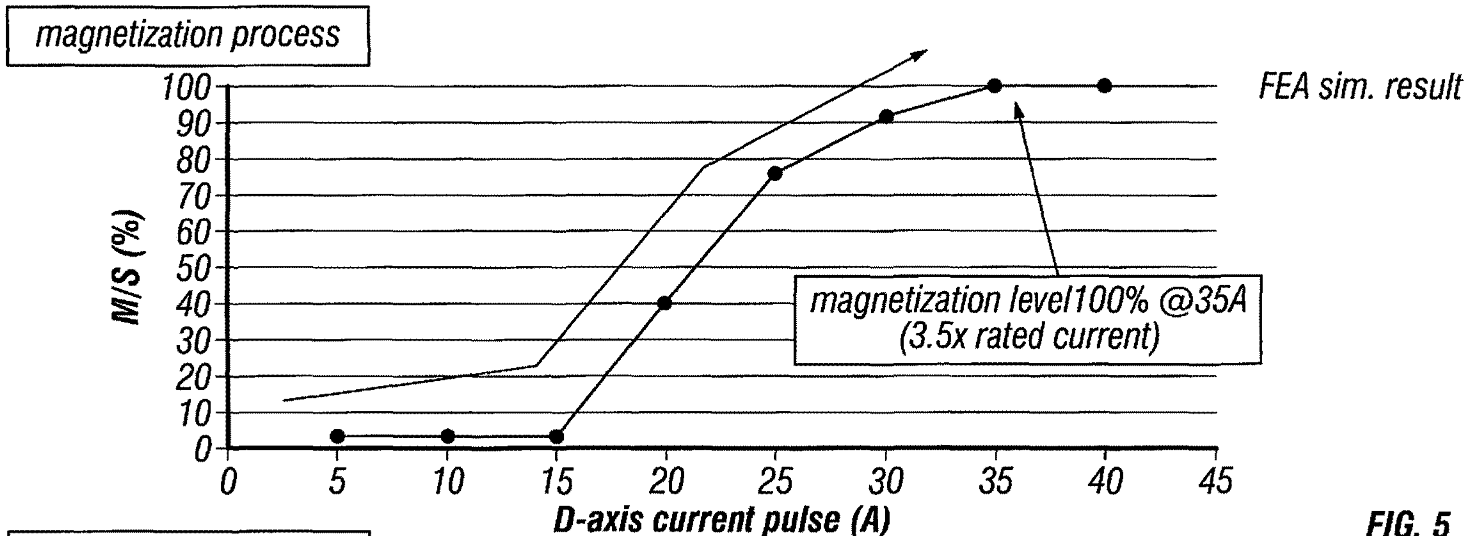
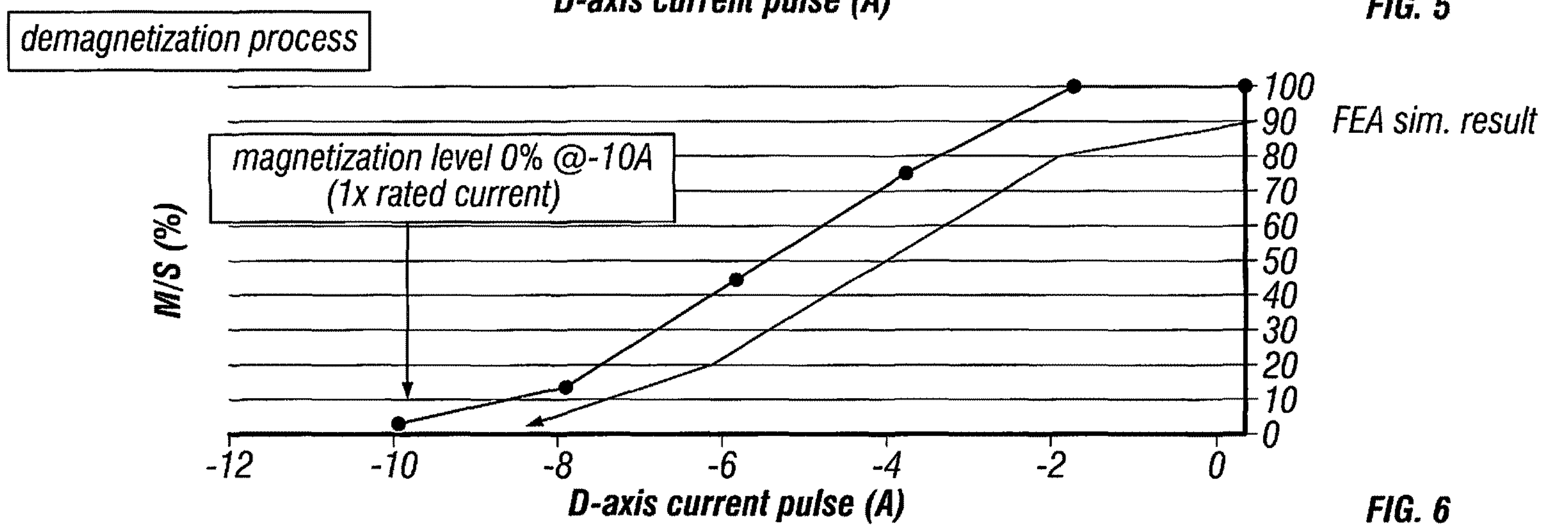

Actual M/S &
M/S change flag
M/S (%)
100
50
0
Time
Flag Q
Time
From FIG. 3
M/S &
Torque
Control
100
PWM signal
Sensor signals
e-Powertrain
Battery
116
Inverter
118
VFIIPM
10

FIG. 4



magnetization process
100
90
80
70
60
50
40
30
20
10
0
M/S (%)
0
5
10
15
20
25
30
35
40
45
D-axis current pulse (A)
FEA sim. result
magnetization level100% @35A
(3.5x rated current)

FIG. 5



demagnetization process
magnetization level 0% @-10A
(1x rated current)
M/S (%)
100
90
80
70
60
50
40
30
20
10
0
FEA sim. result
-12
-10
-8
-6
-4
-2
0
D-axis current pulse (A)

FIG. 6

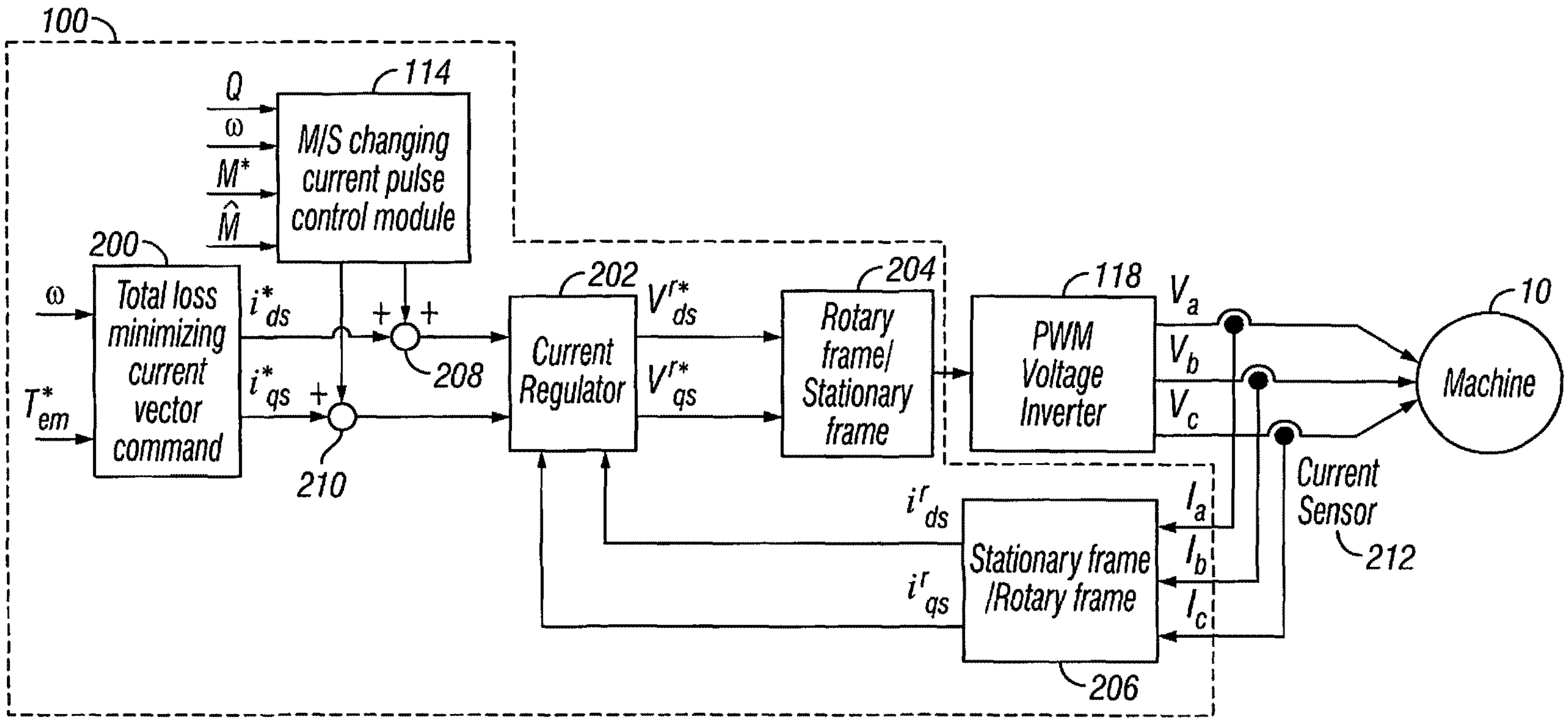

100
114
Q
ω
M*
M̂
M/S changing current pulse control module
200
ω
T^*_{em}
Total loss minimizing current vector command
i^*_{ds}
i^*_{qs}
+
+
+
208
210
202
Current Regulator
V^{r*}_{ds}
V^{r*}_{qs}
204
Rotary frame/ Stationary frame
118
PWM Voltage Inverter
V_a
V_b
V_c
10
Machine
Current Sensor
212
i^r_{ds}
i^r_{qs}
Stationary frame /Rotary frame
I_a
I_b
I_c
206

FIG. 7

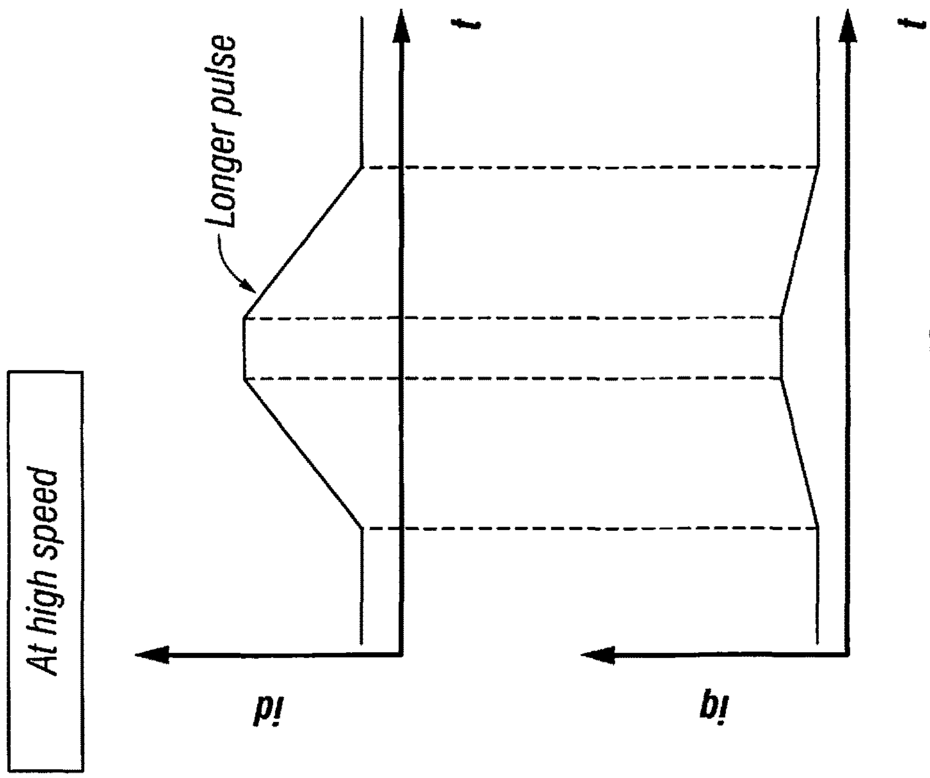

At high speed
Longer pulse
t
id
t
iq

FIG. 9

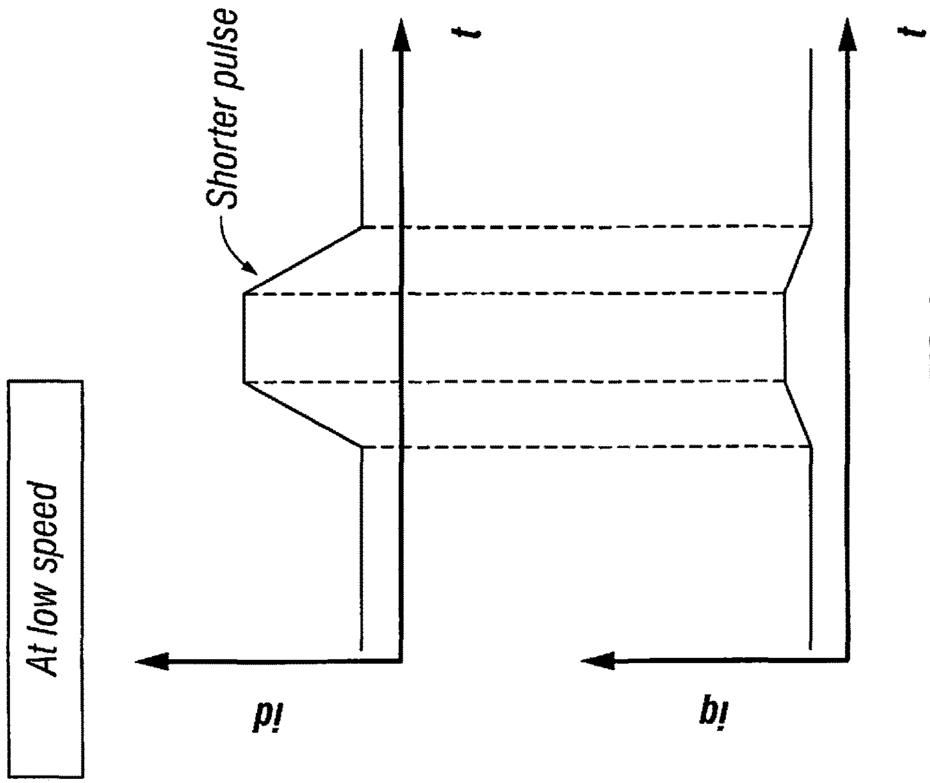

At low speed
Shorter pulse
t
id
t
iq

FIG. 8

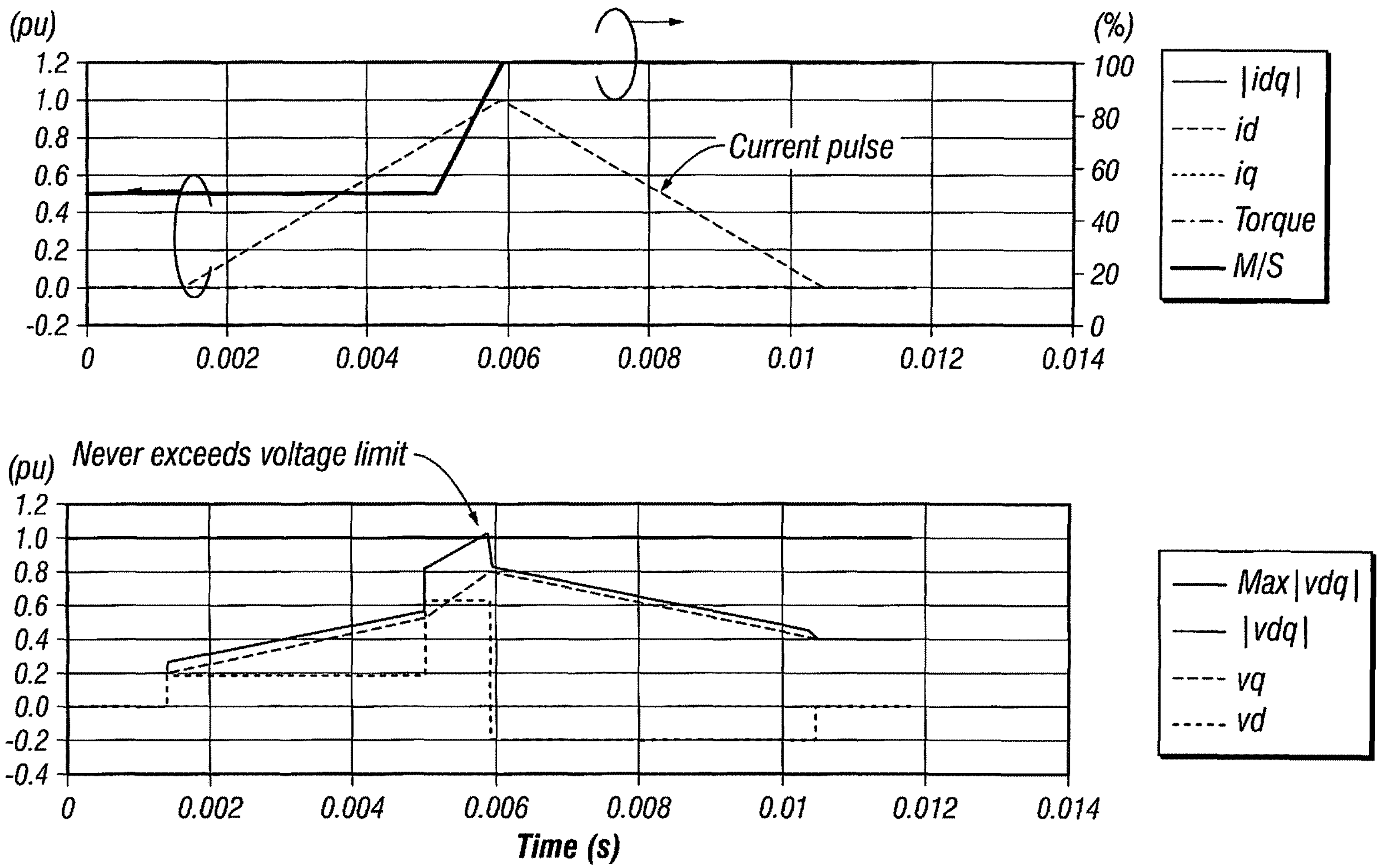

(pu)
(%)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
100
80
60
40
20
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Current pulse
|idq|
id
iq
Torque
M/S
Never exceeds voltage limit
(pu)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
Time (s)
Max|vdq|
|vdq|
vq
vd

FIG. 10

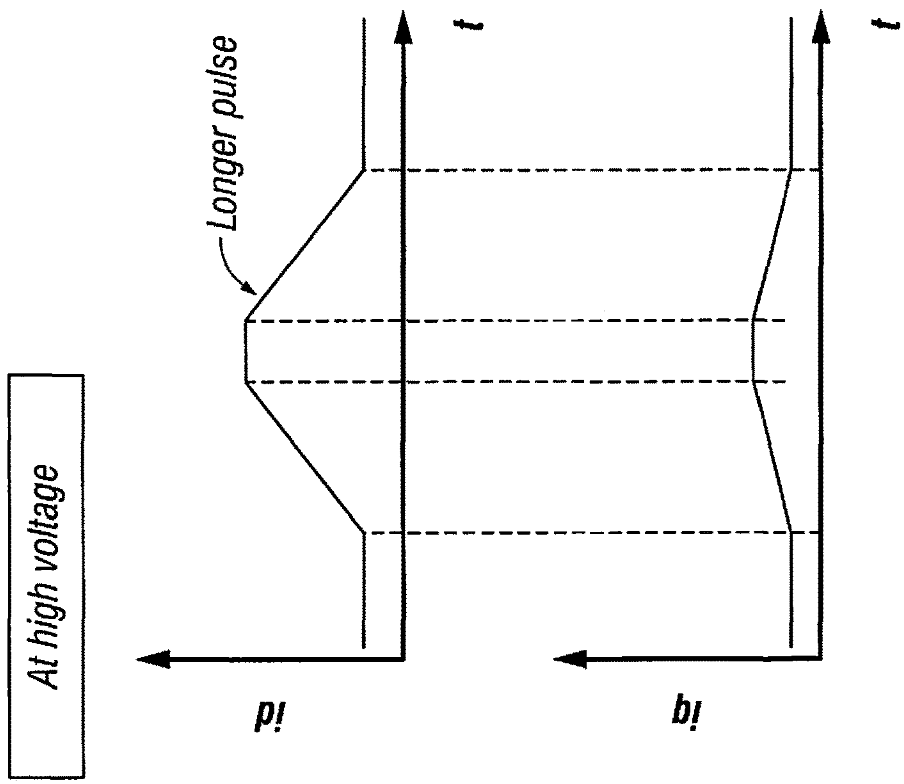

At high voltage
Longer pulse
id
iq
t
t

FIG. 12

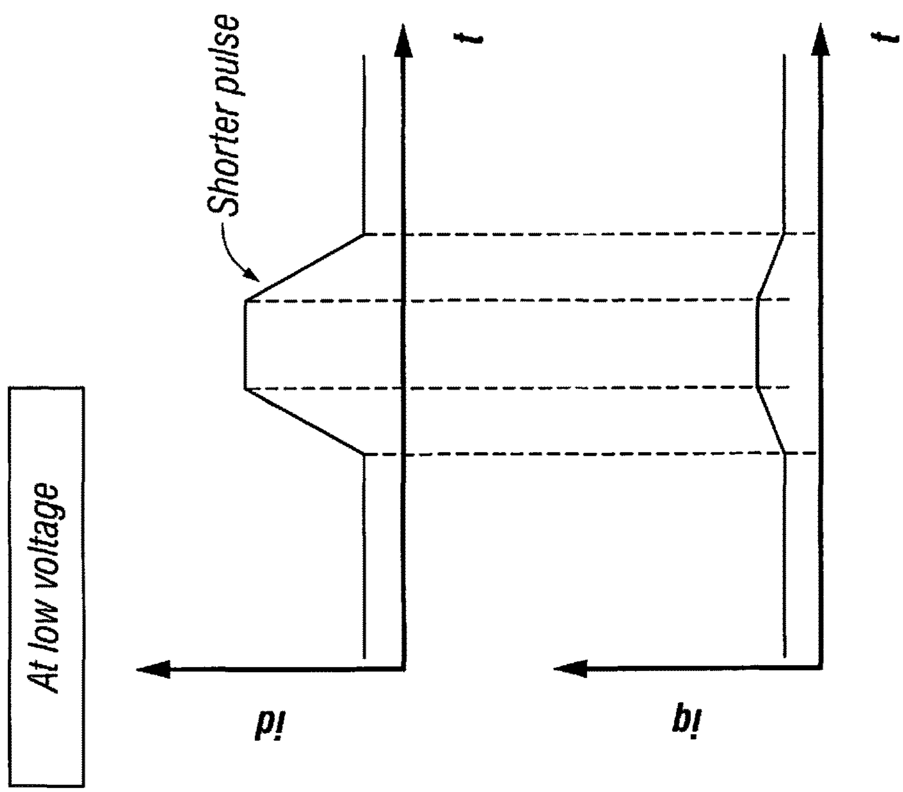

At low voltage
Shorter pulse
id
iq
t
t

FIG. 11

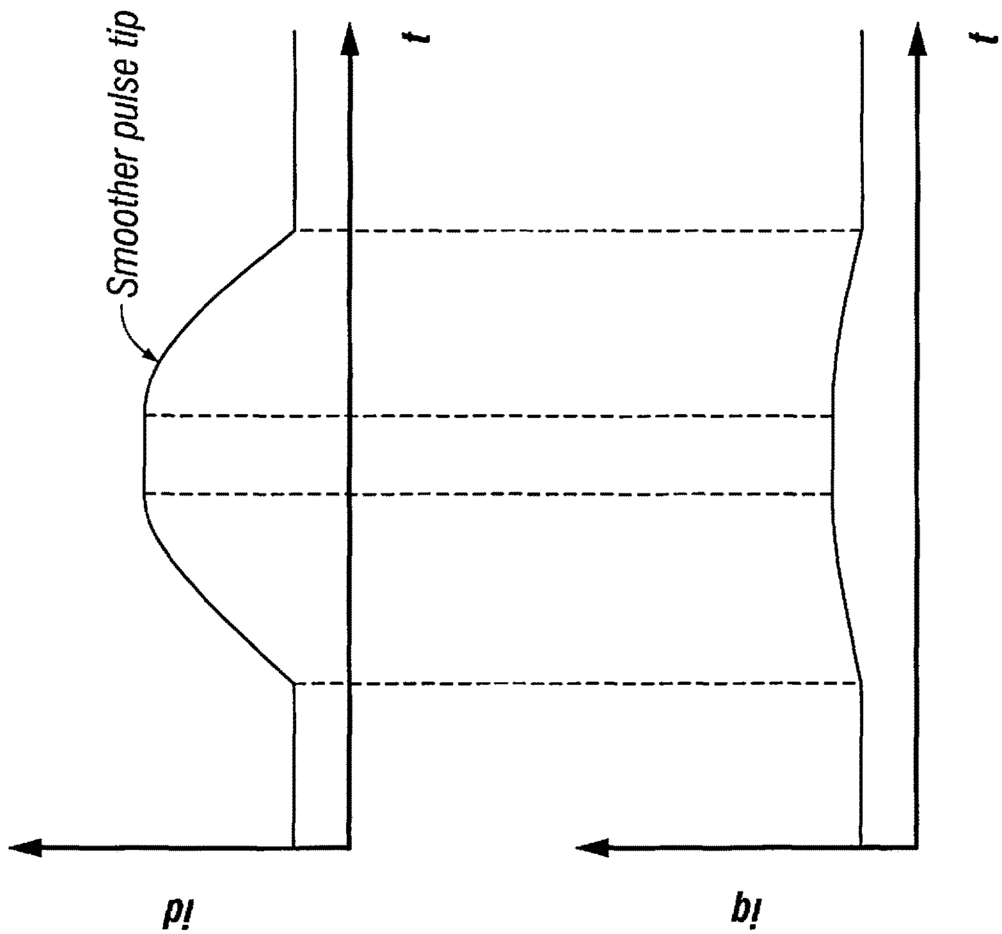


FIG. 13

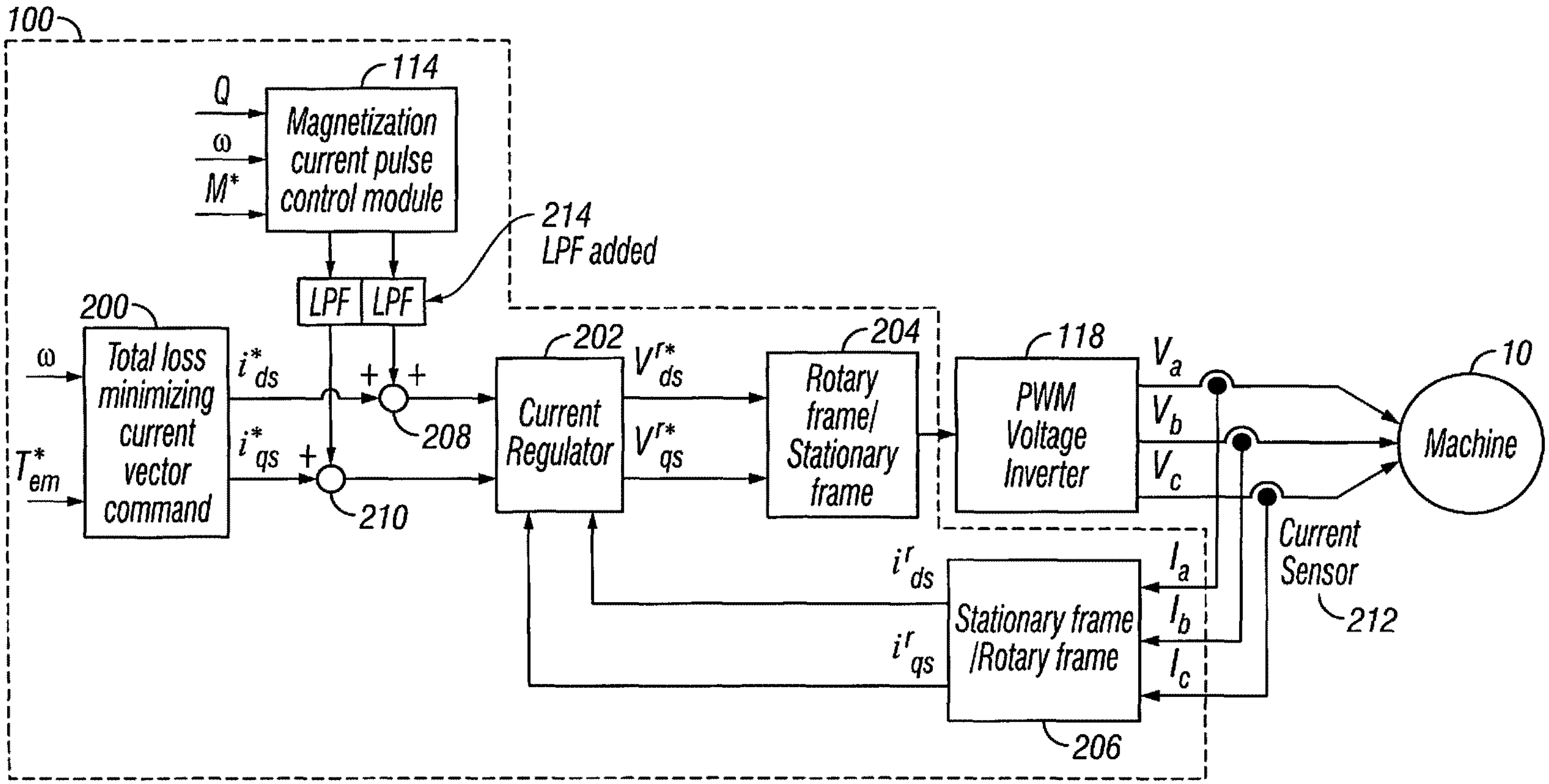

100
114
Q
ω
M*
Magnetization current pulse control module
214
LPF added
LPF
LPF
200
ω
T^*_{em}
Total loss minimizing current vector command
i^*_{ds}
i^*_{qs}
+
+
+
208
210
202
Current Regulator
V^{r*}_{ds}
V^{r*}_{qs}
204
Rotary frame/ Stationary frame
118
PWM Voltage Inverter
V_a
V_b
V_c
10
Machine
Current Sensor
212
i^r_{ds}
i^r_{qs}
Stationary frame /Rotary frame
I_a
I_b
I_c
206

FIG. 14

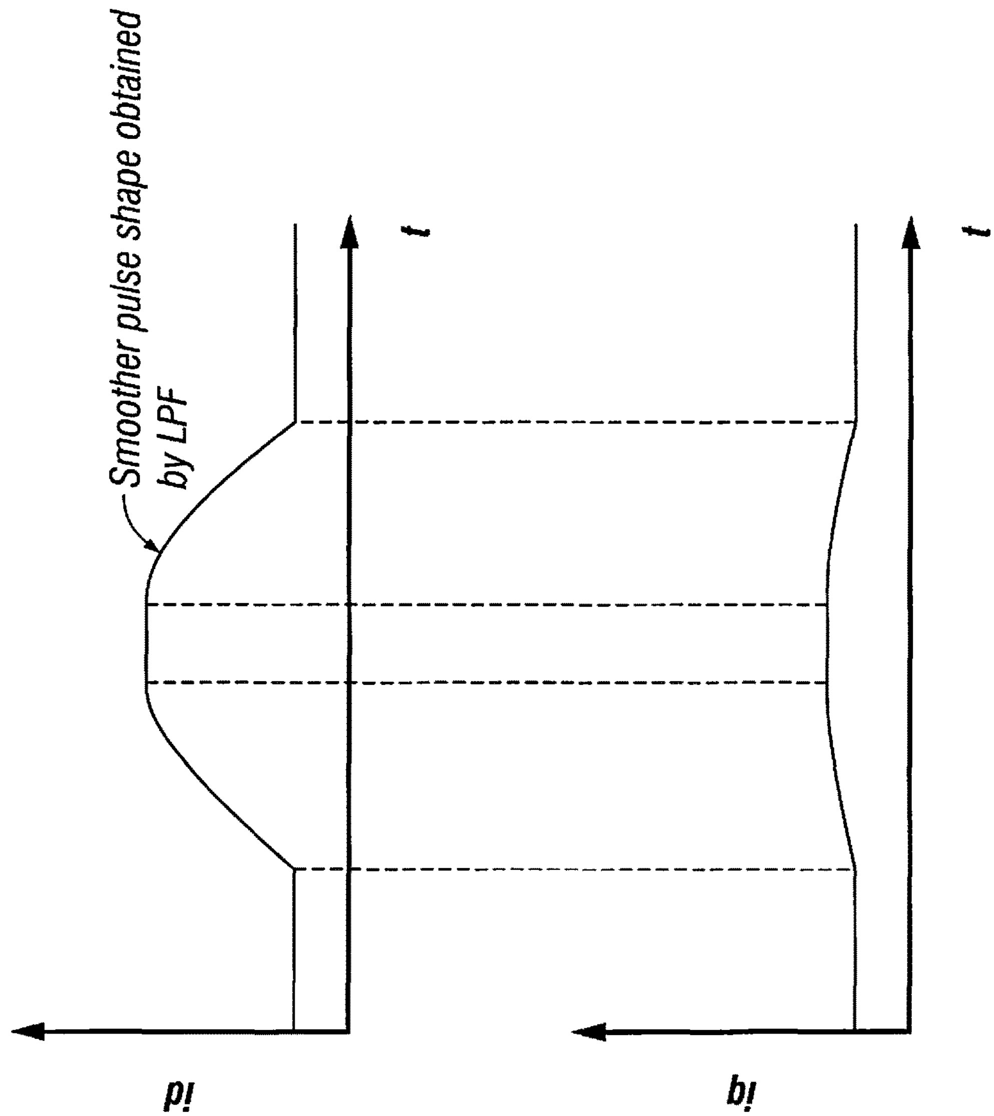


FIG. 15

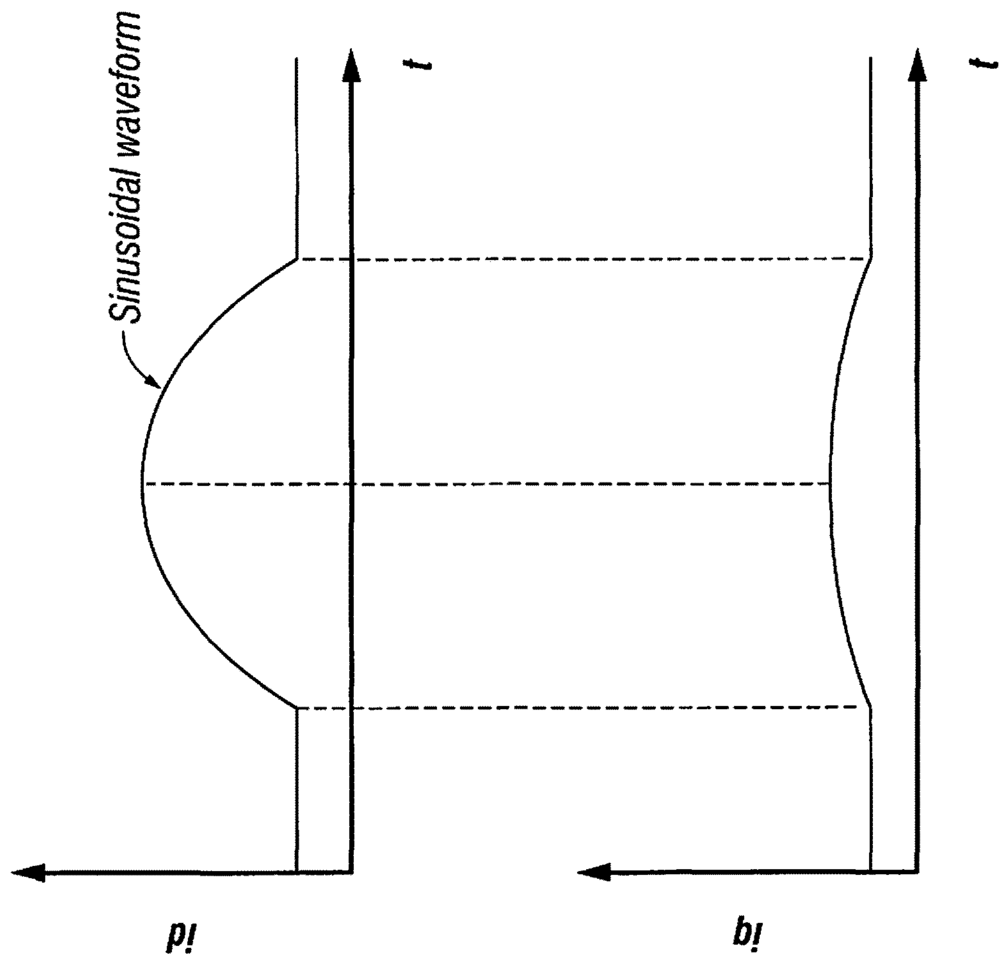


FIG. 16

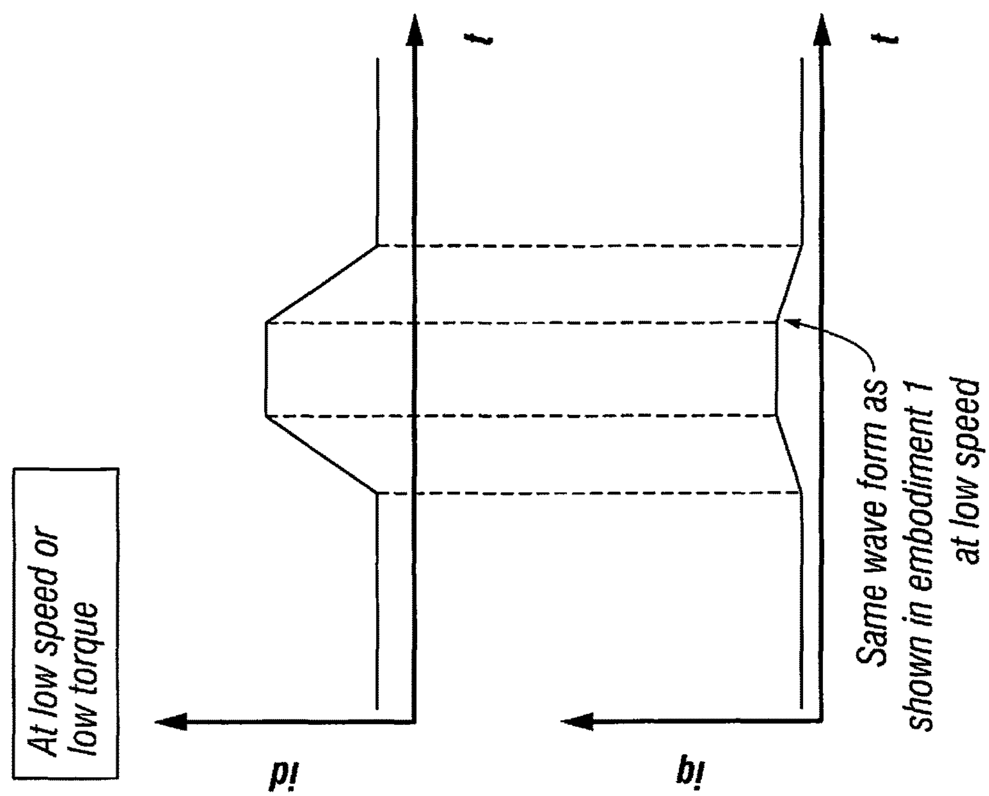

At low speed or low torque
id
t
iq
t
Same wave form as shown in embodiment 1 at low speed

FIG. 17

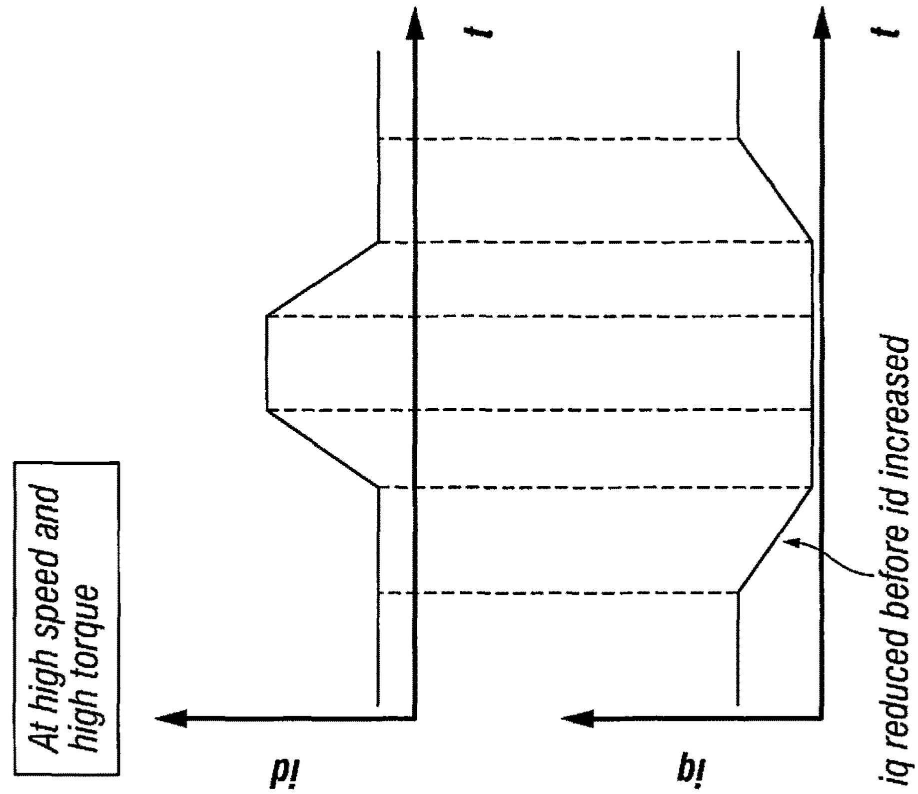

At high speed and high torque
id
t
iq
t
iq reduced before id increased

FIG. 18

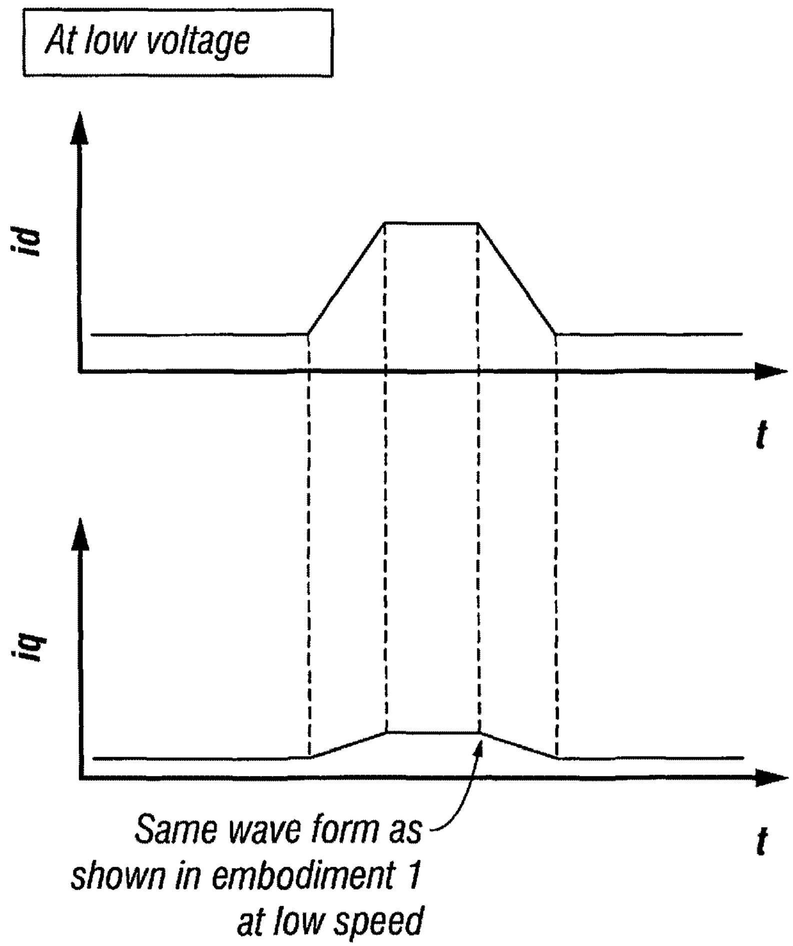

At low voltage
id
t
iq
t
Same wave form as
shown in embodiment 1
at low speed

FIG. 19

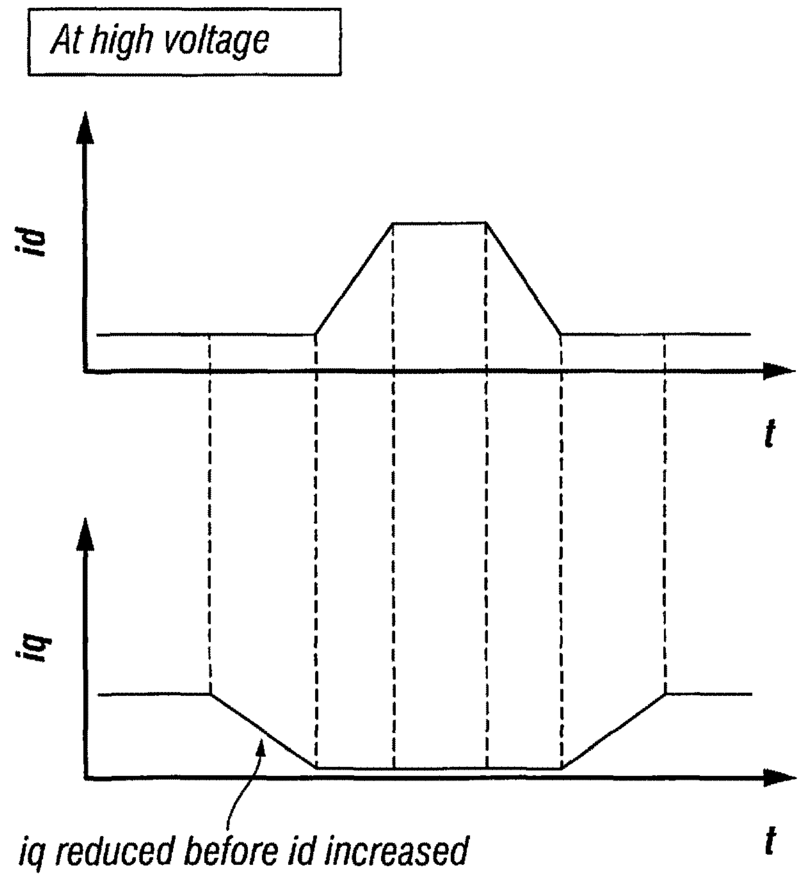

At high voltage
id
t
iq
t
iq reduced before id increased

FIG. 20

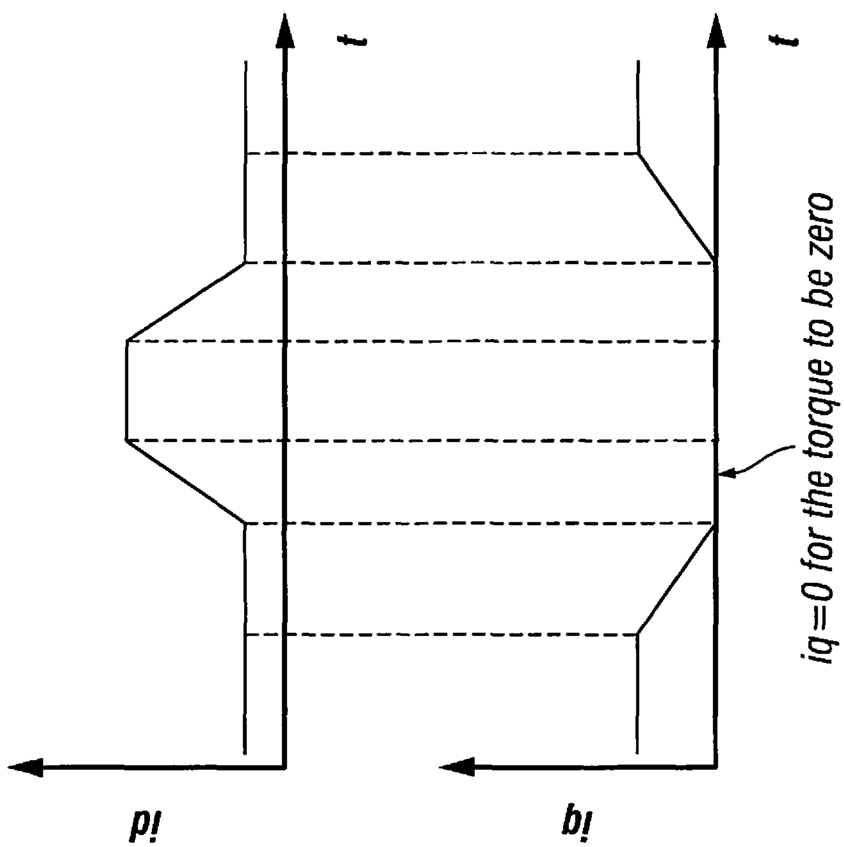


FIG. 21

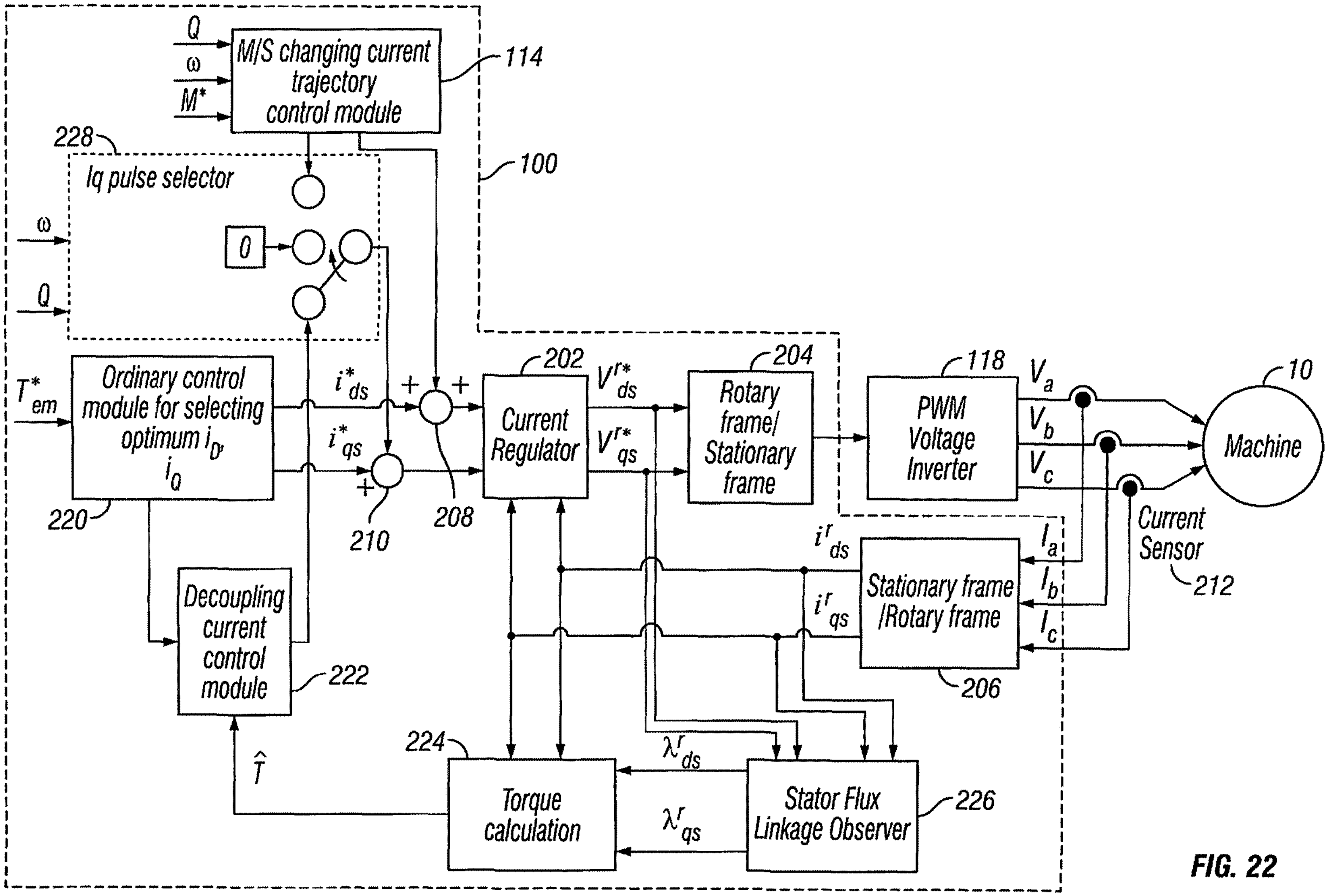

Q
ω
M*
M/S changing current trajectory control module
114
228
Iq pulse selector
100
ω
0
Q
T^*_{em}
Ordinary control module for selecting optimum i_D, i_Q
i^*_{ds}
i^*_{qs}
+ +
+
202
Current Regulator
V^{r*}_{ds}
V^{r*}_{qs}
204
Rotary frame/ Stationary frame
118
PWM Voltage Inverter
V_a
V_b
V_c
10
Machine
Current Sensor
212
220
210
208
i^r_{ds}
i^r_{qs}
I_a
I_b
I_c
Stationary frame /Rotary frame
206
Decoupling current control module
222
224
$\hat{T}$
λ^r_{ds}
λ^r_{qs}
Torque calculation
Stator Flux Linkage Observer
226

FIG. 22

VARIABLE MAGNETIZATION MACHINE CONTROLLER

CROSS-REFERENCE TO RELATED APPLICATION

This application is a U.S. National stage of International Application No. PCT/JP2014/053354, filed Aug. 29, 2014, the entire contents of International Application No. PCT/JP2014/053354 are hereby incorporated herein by reference. Also, related subject matter is disclosed in International Application No. PCT/US2013/048562, filed on Jun. 28, 2013, and in International Application No. PCT/US2014/053350, filed Aug. 29, 2014, the entire contents both of these International Applications being incorporated by reference herein.

BACKGROUND

Field of the Invention

The present invention generally relates to a variable magnetization machine controller. More particularly, the present invention relates to a controller that is able to reduce the voltage induced by a pulse current to control a variable magnetization machine, such as an electric motor or other type of variable flux machine, that is employed in an electric or hybrid electric vehicle, at the reduced voltage.

Background Information

Electric vehicles and hybrid electric vehicles (HEV) include an electric motor that operates as a drive source for the vehicle. In a purely electric vehicle, the electric motor operates as the sole drive source. On the other hand, an HEV includes an electric motor and a conventional combustion engine that operate as the drive sources for the vehicle based on conditions as understood in the art.

Electric vehicles and HEVs can employ an electric motor having variable magnetization characteristics as understood in the art. For example, the magnetization level of the motor can be increased to increase the torque generated by the motor. Accordingly, when the driver attempts to accelerate the vehicle to, for example, pass another vehicle, the motor control system can change the magnetization level to increase the torque output of the motor and thus increase the vehicle speed.

In a typical motor control system, an inverter applies the control voltage to the motor. As understood in the art, as the speed of the motor is increased, the amplitude of the applied voltage will increase given a constant amplitude current pulse, such as the D-axis current pulse. Naturally, this current pulse will affect the voltage induced in the control system.

SUMMARY

However, at a high motor speed, the voltage induced in the control system by the pulse current can increase to a high voltage level. At this high voltage level, the inverter may be no longer capable of providing enough voltage to drive the motor at the desired speed. Accordingly, it is desirable to provide an improved motor control system for a variable magnetization machine, such as a variable magnetization motor or other type of variable flux machine for a vehicle, that is capable of reducing the voltage induced by a pulse current to a low enough level so that the inverter can provide a sufficient voltage to drive the variable magnetization machine even at a high speed.

In view of the state of the known technology, one aspect of a variable magnetization machine control system according to the disclosed embodiments comprises a controller configured to adjust a d-axis current waveform and a q-axis current waveform in accordance with an operating condition of a variable magnetization machine to generate an adjusted d-axis current waveform and an adjusted q-axis current waveform that provide a driving voltage to drive the variable magnetization machine at a predetermined speed while maintaining the driving voltage below a predetermined maximum magnitude.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the attached drawings which form a part of this original disclosure:

FIG. **1** is a partial cross-sectional schematic view of a variable magnetization machine according to a disclosed embodiment;

FIGS. **2** through **4** are diagrammatic views illustrating an example of components, including a controller according to the disclosed embodiments, that are employed in a vehicle to control a variable magnetization machine such as that shown in FIG. **1**;

FIGS. **5** and **6** are graphs which illustrate an example of the relationship between the magnetization state (M/S) of the variable magnetization machine and the d-axis current pulse that are applied to the variable magnetization machine by the configuration shown in FIGS. **2** through **4** during a magnetization process and a demagnetization process;

FIG. **7** is a block diagram illustrating an example of components of a controller employed in the configuration shown in FIGS. **2** through **4** according to a disclosed embodiment;

FIG. **8** is a graph illustrating an example of d-axis and q-axis currents provided by the controller to operate the variable magnetization machine at a low speed according to a disclosed embodiment;

FIG. **9** is a graph illustrating an example of d-axis and q-axis currents provided by the controller to operate the variable magnetization machine at a high speed according to a disclosed embodiment;

FIG. **10** is a graph illustrating an example of the d-axis and q-axis currents, and d-axis and q-axis voltages, provided by the controller to operate the variable magnetization machine, in relation to the magnetization state and torque of the variable magnetization machine, a combination of the d-axis and q-axis voltages, and a maximum voltage according to a disclosed embodiment;

FIG. **11** is a graph illustrating an example of d-axis and q-axis currents provided by the controller to operate the variable magnetization machine at a low voltage according to a disclosed embodiment;

FIG. **12** is a graph illustrating an example of d-axis and q-axis currents provided by the controller to operate the variable magnetization machine at a high voltage according to a disclosed embodiment;

FIG. **13** is a graph illustrating an example of d-axis and q-axis currents having a smoother pulse tip as provided by the controller to operate the variable magnetization machine according to a disclosed embodiment;

FIG. **14** is a block diagram illustrating an example of components of a controller employed in the configuration shown in FIGS. **2** through **4** including a low pass filter arrangement according to another disclosed embodiment;

FIG. **15** is a graph illustrating an example of d-axis and q-axis currents having a smoother pulse shape as provided by the controller shown in FIG. **14** to operate the variable magnetization machine according to a disclosed embodiment;

FIG. **16** is a graph illustrating an example of d-axis and q-axis currents having a sinusoidal waveform as provided by the controller as discussed herein to operate the variable magnetization machine according to a disclosed embodiment;

FIG. **17** is a graph illustrating an example of d-axis and q-axis currents provided by the controller to operate the variable magnetization machine at a low speed according to another disclosed embodiment;

FIG. **18** is a graph illustrating an example of d-axis and q-axis currents provided by the controller to operate the variable magnetization machine at a high speed according to another disclosed embodiment;

FIG. **19** is a graph illustrating an example of d-axis and q-axis currents provided by the controller to operate the variable magnetization machine at a low voltage according to another disclosed embodiment;

FIG. **20** is a graph illustrating an example of d-axis and q-axis currents provided by the controller to operate the variable magnetization machine at a high voltage according to another disclosed embodiment;

FIG. **21** is a graph illustrating an example of d-axis and q-axis currents provided by the controller to operate the variable magnetization machine according to a further disclosed embodiment; and

FIG. **22** is a block diagram illustrating an example of components of a controller employed in the configuration shown in FIGS. **2** through **4** arrangement according to a further disclosed embodiment.

DETAILED DESCRIPTION OF EMBODIMENTS

Selected embodiments will now be explained with reference to the drawings. It will be apparent to those skilled in the art from this disclosure that the following descriptions of the embodiments are provided for illustration only and not for the purpose of limiting the invention as defined by the appended claims and their equivalents.

As shown in FIG. **1**, a variable magnetization machine **10**, which can also be referred to as a variable magnetization motor or other type of variable flux machine, includes a rotor **12** and a stator **14**. As discussed herein, the terms variable magnetization machine and variable flux machine can be used synonymously to refer to the same type of machine. The variable magnetization machine **10** can be employed in any type of electric vehicle or HEV such as an automobile, truck, SUV and so on, and in any other type of apparatus as understood in the art. The rotor **12** and the stator **14** can be made of metal or any other suitable material as understood in the art.

In this example, the rotor **12** is configured to include a plurality of pairs of flux barriers **16** and **18**, which can be configured as air gaps or can include any suitable type of insulating material as is conventional in the art. Although only one full pair and two partial pairs of the flux barriers **16** and **18** are shown, in this example, six pairs of flux barriers **16** and **18** can be spaced at 60 degree angles about the outer perimeter of the rotor **12**. Naturally, the rotor **12** can include as many pairs of flux barriers **16** and **18** as deemed appropriate for the environment in which the variable magnetization machine **10** is employed. Also, as shown in this example, a q-axis of the motor passes through the center of a pair of flux barriers **16** and **18**. However, the pairs of flux barriers **16** and **18** can be positioned at any suitable location with respect to the q-axis to achieve the operability of the embodiments discussed herein.

As further shown, a surface bridge **20** of the rotor **12** is present between the radially outward boundary of each flux barrier **18** and the outer circumference **22** of the rotor **12**. Furthermore, a d-axis flux bypass **24** is present between each of the adjacent pairs of flux barriers **16** and **18**. In this example, the surface bridges **20** and the d-axis flux bypasses N are made of the same material as that of the rotor **12**. However, the surface bridges **20** and the d-axis flux bypasses **24** can be made of any suitable type of material as known in the art.

In addition, a plurality of low-coercive-force magnets **26** are spaced between adjacent pairs of flux barriers **16** and **18** about the circumference of the rotor **12**. As indicated, each of these magnets **26** extend longitudinally in a perpendicular or substantially perpendicular direction with respect to portions of adjacent flux barriers **16**. However, the magnets **26** can be configured in any suitable size and shape. Also, in this example, the rotor **12** includes 6 magnets **26** which are positioned between the 6 pairs of flux barriers **16** and **18** and spaced at 60 degree intervals in a circumferential direction about the rotor **12**. However, the number of magnets **26** can change with respect to a change in the number of pairs of flux barriers **16** and **18**. Furthermore, each magnet **26** can be configured as a plurality of magnets. In this example, a d-axis passes through a center of a magnet **26**. However, the magnets **26** can be positioned at any suitable location with respect to the d-axis to achieve the operability of the embodiments discussed herein.

The stator **14** includes a plurality of stator teeth **28** and other components such as windings (not shown) which can be configured in any conventional manner. In this example, the stator teeth **28** are configured as wide stator teeth as known in the art. However, the stator teeth **28** can have any suitable size, and the stator **14** can include any number of stator teeth **28** to achieve the operability of the embodiments discussed herein. In this example, the stator teeth **28** are open to the inner circumference **30** of the stator **14**, but can be closed if desired. Also, an air gap **32** is present between the outer circumference **22** of the rotor **12** and the inner circumference **30** of the stator **14** to enable the rotor **12** to rotate unrestrictedly or substantially unrestrictedly about an axis **34**.

FIGS. **2** through **4** are diagrammatic views illustrating an example of the manner in which a controller **100** (FIG. **4**) according to the disclosed embodiments is employed in a vehicle **102** to control the variable magnetization machine **10**. The vehicle **102** can be an electric vehicle or HEV such as an automobile, truck, SUV or any other suitable type of vehicle. As understood in the art, when a driver presses the accelerator **104**, an acceleration signal is input to a controller **106**, such as an electronic control unit (ECU) or any other suitable type of controller. Also, a speed sensor **108**, such as a tachometer or any other suitable type of sensor, senses the rotational speed of, for example, a drive wheel **110** of the vehicle **102** and provides a vehicle speed signal to the controller **106**.

The controller **106** includes other conventional components such as an input interface circuit, an output interface circuit, and storage devices such as a ROM (Read Only Memory) device and a RAM (Random Access Memory) device. It will be apparent to those skilled in the art from this disclosure that the precise structure and algorithms for the controller **106** can be any combination of hardware and software that will carry out the functions of the present invention. In other words, "means plus function" clauses as utilized in the specification and claims should include any structure or hardware and/or algorithm or software that can be utilized to carry out the function of the "means plus function" clause. Furthermore, the controller **106** can communicate with the accelerator **104**, the speed sensor **108** and the other components in the vehicle **102** discussed herein in any suitable manner as understood in the art. In addition, the components of the controller **106** need not be individual or separate components, and one component or module can perform the operations of multiple components or modules discussed herein. Also, each component can include a microcontroller as discussed above or multiple components can share one or more microcontrollers.

As further shown in FIG. **2**, the controller **106** outputs signals to control the speed and the torque of the variable magnetization machine **10** to reach the appropriate machine operating state to achieve the desired vehicle acceleration as understood in the art. For instance, the controller **106** can access an appropriate loss map from among a plurality of previously prepared loss maps that can be stored in a memory **112**. Each loss map can indicate respective loss characteristics for a respective magnetization state (M/S) as indicated. The controller **106** can then, for example, generate a loss plot which represents an amount of loss for each respective M/S and derive a minimal loss point as indicated. The controller **106** can therefore output a signal to control the variable magnetization machine **10** to achieve that ideal M/S.

As shown in FIG. **3**, the signal representing the ideal M/S is input to an M/S selection strategy module **113** which performs hysteresis control and, as discussed in more detail below, outputs a signal representing the actual M/S signal (also referred to as a target magnetization state signal M* as discussed with below with regard to FIG. **7**) and an M/S change flag signal Q. As shown in FIG. **4**, the controller **100**, which can be an M/S and torque controller, receives the signal representing the actual M/S signal and the M/S change flag signal Q, and outputs an M/S and torque control signal, such as a pulse width modulated (PWM) signal, to control the variable magnetization machine **10**. That is, the controller **100** is coupled to an e-powertrain which includes, for example, a battery **116**, an inverter arrangement **118**, and the variable magnetization machine **10**. In this example, inverter arrangement **118** can be, for example, a pulse width modulator (PWM) voltage inverter, or any other suitable type of inverter configuration as understood in the art.

As further shown in FIG. **3**, the M/S selection strategy module **113** includes a sample and hold circuit **120** that includes a switch **122** and a z-transform component **124**. The M/S selection strategy module **113** further includes a subtractor **126**, a proportional-integral (PI) compensator **128**, an absolute value circuit **130**, a comparator **132** and a comparator input component **134**.

The ideal M/S signal is input to the switch **122** of the sample and hold circuit **120** and the subtractor **126**. The subtractor **126** subtracts a feedback signal from the ideal M/S signal and outputs an error signal to the PI compensator **128**. As understood in the art, the PI compensator **128** removes a steady state error from the error signal and provides the error signal with the steady state error removed to the absolute value circuit **130** as a modified error signal. The absolute value circuit **130** outputs an absolute value of the modified error signal to the comparator **132**. The comparator **132** also receives an input signal from the comparator input component **134**. In this example, the input signal represents a value "1" but can be set to any suitable value to achieve the effects discussed herein.

The comparator **132** provides an output based on the modified error signal and the input signal to control switching of the switch **122** of the sample and hold circuit **120**. The comparator **132** also provides the output as a reset signal to the PI compensator **128** as understood in the art. The comparator **132** further provides the output as an M/S change flag signal Q to the M/S changing current pulse control module **114** of the controller **100** (See, e.g., FIGS. **7**, **14** and **22**) as discussed in more detail below.

As further shown, the z-transform component **124** provides a feedback of the actual M/S signal output by the sample and hold circuit **120** as a second input to the switch **122**. The switch **122** outputs either the ideal M/S signal or the feedback signal from the z-transform component **124** as the actual M/S signal based on the state of the output signal provided by the comparator **132**. Therefore, the components of the M/S selection strategy module **113** discussed above operate as a hysteresis control component that is configured to receive an ideal magnetization state signal, output an actual magnetization state signal based on the ideal magnetization state signal for control of a variable magnetization machine, and modify the actual magnetization state signal in accordance with an error value between the ideal magnetization state signal and the actual magnetization state signal. That is, when the error value results in the comparator **132** outputting a signal having a value that controls the switch **122** to output the modified signal from the z-transform component **124** as the actual M/S signal, the controller **100** in effect modifies the actual M/S signal in accordance with an error value between the ideal magnetization state signal and the actual magnetization state signal. Thus, the sample and hold circuit **120** (sample and hold component) that is configured to output the actual magnetization state signal and to modify the actual magnetization state signal in accordance with the error value. The M/S selection strategy module **113** configured to operate as the hysteresis control component is further configured to output the M/S change flag signal as a pulse signal in synchronization with the actual M/S signal such that the variable magnetization machine **10** is further controlled in accordance with this pulse signal.

FIGS. **5** and **6** are graphs which illustrate an example of the relationship between the M/S and the d-axis current pulse that the controller **100**, along with the battery **116** and the inverter arrangement **118**, applies to the variable magnetization machine **10** during a magnetization process (FIG. **5**) and a demagnetization process (FIG. **6**). An example of components of the controller **100** will now be described with regard to FIG. **7**. As will be appreciated from the description of this embodiment and the other embodiments set forth herein, the q-axis current is reduced online using feedback, and by adding a regulated amount to the q-axis current, the torque of the variable magnetization machine **10** can be maintained constant or substantially constant.

As shown in FIG. **7**, the controller **100** in this example includes a total loss minimizing current vector command module **200**, a current regulator **202**, a rotary frame/stationary frame component **204**, and a stationary frame/rotary frame component **206**. In this example, the output of the rotary frame/stationary frame component **204** is coupled to the e-powertrain and, in particular, to the inverter arrangement **118** which provides power to the variable magnetization machine **10**.

As can be appreciated by one skilled in the art, the controller **100** preferably includes at least one microcomputer with a control program that controls the components of the controller **100** as discussed below. Thus, the microcomputer or microcomputers can be configured and programmed to embody any or all of the total loss minimizing current vector command module **200**, the current regulator **202**, the rotary frame/stationary frame component **204**, and the stationary frame/rotary frame component **206**. The controller **100** includes other conventional components such as an input interface circuit, an output interface circuit, and storage devices such as a ROM (Read Only Memory) device and a RAM (Random Access Memory) device. It will be apparent to those skilled in the art from this disclosure that the precise structure and algorithms for the controller **100** can be any combination of hardware and software that will carry out the functions of the present invention. In other words, “means plus function” clauses as utilized in the specification and claims should include any structure or hardware and/or algorithm or software that can be utilized to carry out the function of the “means plus function” clause. Furthermore, the controller **100** can communicate with the variable magnetization machine **10** in any suitable manner as understood in the art. In addition, although several of the components of the controller **100** are described as modules, these components need not be individual or separate components, and one component or module can perform the operations of multiple components or modules discussed herein. Also, each module can include a microcontroller as discussed above or multiple modules can share one or more microcontrollers.

As further shown in FIG. **7**, the total loss minimizing current vector command module **200** receives a torque command T^*_{em} and a sensed or estimated rotation speed signal a) of the rotor **12** from, for example, a controller (not shown) in response to, for example, a driver of the vehicle attempting to accelerate the vehicle **102**. In response, the total loss minimizing current vector command module **200** outputs a d-axis current signal i^*_{ds} and a q-axis current signal i^*_{qs} for selecting the optimum d-axis current id and the optimum q-axis current i_q. That is, in this example, the total loss minimizing current vector command module **200** outputs the d-axis current signal i^*_{ds} to an adder **208** and the q-axis current signal i^*_{qs} to an adder **210**.

The M/S changing current pulse control module **114** receives the sensed or estimated rotational speed signal co, as well as magnetization signal M* (also referred to as the actual M/S signal as discussed above with regard to FIG. **3**), magnetization signal M^ and the M/S change flag signal Q. An adder **208** adds output provided by the M/S changing current pulse control module **114** to the d-axis current signal i^*_{ds}, and an adder **210** adds the output provided by the M/S changing current pulse control module **114** to q-axis current signal i^*_{qs}. The adders **208** and **210** provide their outputs to the current regulator **202**, which provides d-axis current voltage signal V^{r*}_{ds} and q-axis current voltage signal V^{r*}_{qs} to the rotary frame/stationary frame component **204**. In this example, the rotary frame/stationary frame component **204** provides the voltage signals to the inverter arrangement **118**, which provides voltages V_a, V_b and V_c to the three poles of the variable magnetization machine **10**.

As further shown in FIG. **7**, current sensors **212** sense the currents associated with V_a, V_b and V_c being applied to the variable magnetization machine **10**. The current sensors **212** provide the sensed current signals I_a, I_b and I_c to the stationary frame/rotary frame component **206**. The stationary frame/rotary frame component **206** thus provides a detected d-axis current signal i^r_{ds} and a detected q-axis current signal i^r_{qs} to the current regulator **202**. As understood in the art, the current regulator **202** regulates the d-axis current voltage signal V^{r*}_{ds} and q-axis current voltage signal V^{r*}_{qs} based on the detected d-axis current signal i^r_{ds} and the detected q-axis current signal i^r_{qs} that are fed back from the stationary frame/rotor frame component **206**.

Examples of operations performed by the controller **100** for reducing the voltage induced by a pulse current to a low enough level so that the inverter arrangement **118** can provide a sufficient voltage to drive the variable magnetization machine **10** even at a high speed will now be described.

As understood in the art, the d-axis voltage V_D and the q-axis voltage V_Q of the variable magnetization machine **10** can be defined by the following matrix:

$$\begin{pmatrix} V_D \\ V_Q \end{pmatrix} = \begin{pmatrix} sL_D + R & -\omega L_Q \\ \omega L_D & sL_Q + R \end{pmatrix} \begin{pmatrix} I_D \\ I_Q \end{pmatrix} + \begin{pmatrix} s\Phi_{PM} \\ \omega\Phi_{PM} \end{pmatrix}$$

$$V_{L2L\_Peak} = \sqrt{3}\sqrt{V_D^2 + V_Q^2}$$

The controller **100** can therefore reduce the d-axis voltage V_D and the q-axis voltage V_Q by reducing the values of certain terms in the matrix. In this example, the controller **100** reduces the values of the terms sL_D and $s\Phi_{PM}$ by reducing the rate of increase (e.g., the ramp or slope) of the d-axis current i_d waveform and the q-axis i_q waveform. That is, as shown in FIG. **8**, at a low speed of the variable magnetization machine **10**, the pulse of the d-axis current i_d can be relatively short. In other words, the ramp of the current id can be relatively steep because the maximum value of the d-axis i_d voltage v_d is a relatively low value. Likewise, the maximum value of the q-axis voltage v_q is also a relatively low value.

However, at a high speed of the variable magnetization machine **10**, the terms $-\omega L_Q$, ωL_D and $\omega\Phi_{PM}$ can increase to values much higher than those during the low speed operation. To deal with this drastic increase in the values, the controller **100** reduces the rate of increase of the d-axis current i_d as shown in FIG. **9**. For example, the current regulator **202** controls the d-axis current i_d, the q-axis current i_q, or both, to insure that the voltages v_q and v_d do not exceed certain prescribed values as shown in FIG. **10**. Therefore, as further shown in FIG. **10**, the absolute value of the combined voltage $|v_{dq}|$ of the d-axis voltage v_d and the q-axis voltage v_q does not exceed the maximum combined voltage Max $|v_{dq}|$. As a result, the inverter arrangement **118** can still provide a sufficient voltage to drive the variable magnetization machine **10** even at a high speed. This also allows the variable magnetization machine **10** to have more degrees of freedom balance between less voltage, less torque ripple and less loss.

As discussed above, FIGS. **8** through **10** illustrate examples of waveforms representing the d-axis current i_d and the q-axis current i_q provided by the controller **100** to control the variable magnetization machine **10** at low and high speeds. FIGS. **11** and **12** illustrate examples of waveforms representing the d-axis current id and the q-axis current i_q provided by the controller **100** to control the variable magnetization machine **10** at low and high voltages. As can be appreciated from FIGS. **8**, **9**, **11** and **12**, the relationships between the d-axis current i_d and the q-axis current i_q and their respective pulse lengths are similar for a low voltage that the controller **100** provides to the variable magnetization machine **10** to operate at a low speed (FIGS. **8** and **11**) and a high voltage that the controller **100** provides to the variable magnetization machine **10** to operate at a high speed (FIGS. **9** and **12**). Thus, the controller **100** prevents the absolute value of the combined voltage $|v_{dq}|$ of the d-axis voltage v_d and the q-axis voltage v_q from exceeding the maximum combined voltage Max $|v_{dq}|$ even when the controller **100** provides a high voltage to the variable magnetization machine **10** to cause the variable magnetization machine **10** to operate at a high speed.

In addition, the controller **100** can control the rising and falling of the d-axis current is and the q-axis current i_q so that their waveforms have a smoother pulse tip as shown in the graphs of FIG. **13**. When current is large, the terms $-\omega L_Q$ and ωL_D are large, and thus the ramp rate is reduced only when the current is large. Furthermore, as shown in FIG. **14**, a low pass filter (LPF) arrangement **214** including one or more low pass filters can be provided at the outputs of the magnetization current pulse control module **114** so that the output of the magnetization current pulse control module **114** is filtered before being received by the adders **208** and **210**. With the inclusion of the LPF arrangement **214**, the controller **100** can provide the d-axis current i_d and the q-axis current i_q with waveforms have a smoother pulse shape as shown in the graphs of FIG. **15**.

In addition, the controller **100** can be configured to provide the d-axis current i_d and the q-axis current i_q with any type of waveforms that are suitable for achieving the advantages discussed herein, namely, limiting the combined voltage $|v_{dq}|$ of the d-axis voltage v_d and the q-axis voltage v_q from exceeding the maximum combined voltage Max $|v_{dq}|$ even when the controller **100** provides a high voltage to the variable magnetization machine **10** to cause the variable magnetization machine **10** to operate at a high speed. For instance, the controller **100** can be configured to provide the d-axis current i_d and the q-axis current i_q with sinusoidal waveforms as shown in the graphs of FIG. **16**.

As shown in the graphs of FIGS. **17** and **18**, the controller **100** can reduce the value of the q-axis current i_q before increasing the d-axis current i_d to achieve high speed/high torque operation of the variable magnetization machine **10**. By doing this, the q-axis voltage v_q is reduced during the high speed/high torque operation and thus, the combined voltage $|v_{dq}|$ of the d-axis voltage v_d and the q-axis voltage v_q does not exceed the maximum combined voltage Max $|v_{dq}|$ even during this high speed/high torque operation. The controller **100** can also reduce the value of the q-axis current i_q before increasing the d-axis current i_d during the high voltage operation of the variable magnetization machine **10** as shown, for example, in the graphs of FIGS. **19** and **20** to achieve this same effect of limiting the combined voltage $|v_{dq}|$ of the d-axis voltage v_d and the q-axis voltage v_q from exceeding the maximum combined voltage Max $|v_{dq}|$ during this high voltage operation. The controller **100** can even reduce the value of the q-axis current i_q to zero or substantially zero as shown in the graph of FIG. **21** if necessary to insure that the combined voltage $|v_{dq}|$ of the d-axis voltage v_d and the q-axis voltage v_q does not exceed the maximum combined voltage Max $|v_{dq}|$.

As shown in FIG. **22**, the controller **100** can include an ordinary control module **220** instead of the total loss minimizing current vector command module **200** as discussed above. The controller **100** can further be configured to include a decoupling current control module **222**, a torque calculator **224**, a stator flux linkage observer **226** and an Iq pulse selector **228**. The stator flux linkage observer **226**, which can also be referred to as a stator flux linkage estimator, can be configured to estimate the stator flux linkage by adding a compensation value that is obtained from an L(Y−Yh) reference in a Luenburger style observer for machine electrical state variables associated with the variable magnetization machine **10**. This can provide more accurate torque estimation, and reduce pulsating torque. In this example, the stator flux linkage observer **226** receives the detected d-axis current signal i^r_{ds} and the detected q-axis current signal i^r_{qs} and provides estimated stator flux linkage signals λ^r_{ds} and λ^r_{qs} to the torque calculator **224**. The torque calculator **224** calculates the value of a sensed or estimated torque $T^{\hat{}}$ based on the estimated stator flux linkage signals λ^r_{ds} and λ^r_{qs}, the detected d-axis current signal i^r_{ds} and the detected q-axis current signal i^r_{qs} that are fed back from the stationary frame/rotary frame component **206**.

The ordinary control module **220** and the decoupling current control module **222** receive a torque command T^*_{em} from, for example, a controller (not shown) in response to, for example, a driver of the vehicle attempting to accelerate the vehicle. In response, the ordinary control module **220** outputs a d-axis current signal i^*_{ds} and a q-axis current signal i^*_{qs} for selecting the optimum d-axis current i_d and the optimum q-axis current i_q. Thus, the ordinary control module **220**, which can also be referred to as a current command module, computes a vector current command in a dq axis based on a torque command T^*_{em}. The decoupling current module **222** in this example computes the reducing current based on a difference between the torque command T^*_{em} and the estimated torque $T^{\hat{}}$ provided by the torque calculator **224**. As further shown, the decoupling current control module **222** provides the reducing current to the Iq pulse selector **228**. Thus, the controller **100** can control the Iq pulse selector **228** to provide the output from the M/S changing current trajectory control module **114** to the adder **208**, the reducing current from the decoupling current control module **222** to the adder **210**, or a value of 0 to the adder **210** as indicated to adjust the value of the q-axis current signal i^*_{qs} as desired to attain the type of current waveforms discussed herein. The Iq pulse selector **228** selects which input signal to be output according to the M/S change flag signal Q and the rotational speed signal ω indicating the rotational speed of the variable magnetization machine **10**. When the M/S change flag signal Q is low, that is, not during an M/S change period, the Iq pulse selector **228** outputs a zero since no additional q-axis current i_q is required for the variable magnetization machine **10**. When the M/S change flag signal Q is high and the rotational speed signal ω indicates that the rotational speed of the variable magnetization machine **10** is low, the Iq pulse selector **228** outputs the output that is provided by the decoupling current control module **222**. When the M/S change flag signal Q is high and the rotational speed signal ω indicates that the rotational speed of the variable magnetization machine **10** is high, the Iq pulse selector **228** outputs the output that is provided by the M/S changing current trajectory control module **114** to reduce the voltage output by the current regulator **202**. Further details of the ordinary control module **220**, the decoupling current control module **222**, the torque calculator **224** and the iq pulse selector **228** are disclosed in International Application No. PCT/US2013/048562 referenced above.

As can be appreciated from the above, the embodiments of the controller **100** described herein that is capable of reducing the voltage induced by a pulse current to a low enough level so that the inverter can provide a sufficient voltage to drive the variable magnetization machine even at a high speed.

General Interpretation of Terms

In understanding the scope of the present invention, the term "comprising" and its derivatives, as used herein, are intended to be open ended terms that specify the presence of the stated features, elements, components, groups, integers, and/or steps, but do not exclude the presence of other unstated features, elements, components, groups, integers and/or steps. The foregoing also applies to words having similar meanings such as the terms, "including", "having" and their derivatives. Also, the terms "part," "section," "portion," "member" or "element" when used in the singular can have the dual meaning of a single part or a plurality of parts. The terms of degree such as "substantially", "about" and "approximately" as used herein mean a reasonable amount of deviation of the modified term such that the end result is not significantly changed.

While only selected embodiments have been chosen to illustrate the present invention, it will be apparent to those skilled in the art from this disclosure that various changes and modifications can be made herein without departing from the scope of the invention as defined in the appended claims. For example, the size, shape, location or orientation of the various components can be changed as needed and/or desired. Components that are shown directly connected or contacting each other can have intermediate structures disposed between them. The functions of one element can be performed by two, and vice versa. The structures and functions of one embodiment can be adopted in another embodiment. It is not necessary for all advantages to be present in a particular embodiment at the same time. Every feature which is unique from the prior art, alone or in combination with other features, also should be considered a separate description of further inventions by the applicant, including the structural and/or functional concepts embodied by such features. Thus, the foregoing descriptions of the embodiments according to the present invention are provided for illustration only, and not for the purpose of limiting the invention as defined by the appended claims and their equivalents.

What is claimed is:

1. A variable magnetization machine control system comprising:

a controller configured to detect a magnetization state of a variable magnetization machine and carry out a control to change the magnetization state of the variable magnetization machine based on the detected magnetization state,

the controller being further configured to output a control signal indicating a speed and a torque of the variable magnetization machine for controlling the speed and the torque of the variable magnetization machine, configured to output an ideal magnetization state of a low-coercive-force magnet of the variable magnetization machine based on the speed and the torque indicated by the control signal, and configured to adjust a shape of a d-axis current waveform and a shape of a q-axis current waveform in accordance with the ideal magnetization state of the low-coercive-force magnet of the variable magnetization machine to generate an adjusted d-axis current waveform and an adjusted q-axis current waveform that provide a driving voltage to drive the variable magnetization machine at a predetermined speed associated with the ideal magnetization state of the low-coercive-force magnet of the variable magnetization machine while maintaining the driving voltage below a predetermined maximum magnitude, and

the controller being configured to adjust the d-axis current waveform and the q-axis current waveform by reducing pulse widths of the d-axis current waveform and the q-axis current waveform for a high driving voltage relative to pulse widths of the d-axis current waveform and the q-axis current waveform for a low driving voltage that is lower than the high driving voltage.

2. The variable magnetization machine control system according to claim **1**, wherein

the controller is configured to adjust the d-axis current waveform and the q-axis current waveform by changing their respective pulse width to generate the adjusted d-axis current waveform and the adjusted q-axis current waveform having changed respective pulse widths.

3. The variable magnetization machine control system according to claim **2**, wherein

the controller is configured to change the respective pulse width the d-axis current waveform and the q-axis current waveform in accordance with the speed of the variable magnetization machine.

4. The variable magnetization machine control system according to claim **2**, wherein

the controller is configured to change the respective pulse width the d-axis current waveform and the q-axis current waveform in accordance with an estimated voltage for changing the magnetization state of the variable magnetization machine.

5. The variable magnetization machine control system according to claim **1**, wherein

the controller is configured to adjust the d-axis current waveform and the q-axis current waveform by changing their respective pulse shape to generate the adjusted d-axis current waveform and the adjusted q-axis current waveform having changed respective pulse shapes.

6. The variable magnetization machine control system according to claim **5**, wherein

the d-axis q-axis current waveforms are trapezoidal waveforms; and

the controller comprises a low-pass filter that is configured smooth the trapezoidal d-axis and q-axis current waveforms.

7. The variable magnetization machine control system according to claim **5**, wherein

the changed respective pulse shapes are sinusoidal waveforms.

8. The variable magnetization machine control system according to claim **1**, wherein

the controller is configured to reduce a magnitude of the q-axis current waveform to generate the adjusted q-axis current waveform.

9. The variable magnetization machine control system according to claim **8**, wherein

the controller is configured to reduce the magnitude of the q-axis current waveform in accordance with the torque and the speed of the variable magnetization machine.

10. The variable magnetization machine control system according to claim **8**, wherein

the controller is configured to reduce the magnitude of the q-axis current waveform in accordance with an estimated voltage for changing the magnetization state of the variable magnetization machine.

11. The variable magnetization machine control system according to claim **8**, wherein

the controller is configured to reduce the magnitude of the q-axis current waveform to zero.

12. The variable magnetization machine control system according to claim **1**, wherein

the controller comprises a torque regulator configured to adjust the torque of the variable magnetization machine in accordance with an operating condition of the variable magnetization machine.

13. A variable magnetization machine control system comprising:

a controller configured to detect a magnetization state of a variable magnetization machine and carry out a control to change the magnetization state of the variable magnetization machine based on the detected magnetization state,

the controller being further configured to output a control signal indicating a speed and a torque of the variable magnetization machine for controlling the speed and the torque of the variable magnetization machine, configured to output an ideal magnetization state of a low-coercive-force magnet of the variable magnetization machine based on the speed and the torque indicated by the control signal, and configured to adjust a shape of a d-axis current waveform and a shape of a q-axis current waveform in accordance with the ideal magnetization state of the low-coercive-force magnet of the variable magnetization machine to generate an adjusted d-axis current waveform and an adjusted q-axis current waveform that provide a driving voltage to drive the variable magnetization machine at a predetermined speed associated with the ideal magnetization state of the low-coercive-force magnet of the variable magnetization machine while maintaining the driving voltage below a predetermined maximum magnitude, and

the controller being configured to adjust the d-axis current waveform and the q-axis current waveform by making slopes at leading and trailing edges of the d-axis current waveform and the q-axis current waveform for a high driving voltage more gentle relative to slopes at leading and trailing edges of the d-axis current waveform and the q-axis current waveform for a low driving voltage that is lower than the high driving voltage.

14. A variable magnetization machine control system comprising:

a controller configured to detect a magnetization state of a variable magnetization machine and carry out a control to change the magnetization state of the variable magnetization machine based on the detected magnetization state,

the controller being further configured to output a control signal indicating a speed and a torque of the variable magnetization machine for controlling the speed and the torque of the variable magnetization machine, configured to output an ideal magnetization state of a low-coercive-force magnet of the variable magnetization machine based on the speed and the torque indicated by the control signal, and configured to adjust a shape of a d-axis current waveform and a shape of a q-axis current waveform in accordance with the ideal magnetization state of the low-coercive-force magnet of the variable magnetization machine to generate an adjusted d-axis current waveform and an adjusted q-axis current waveform that provide a driving voltage to drive the variable magnetization machine at a predetermined speed associated with the ideal magnetization state of the low-coercive-force magnet of the variable magnetization machine while maintaining the driving voltage below a predetermined maximum magnitude, and

the controller being configured to reduce a magnitude of the q-axis current waveform to generate the adjusted q-axis current waveform prior to increasing a magnitude of the d-axis current waveform.

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