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(54) **VARIABLE MAGNETIZATION MACHINE CONTROLLER**

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(52) **U.S. Cl.**
CPC *H02P 6/08* (2013.01); *H02P 21/0089* (2013.01); *H02P 21/28* (2016.02)

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(Continued)

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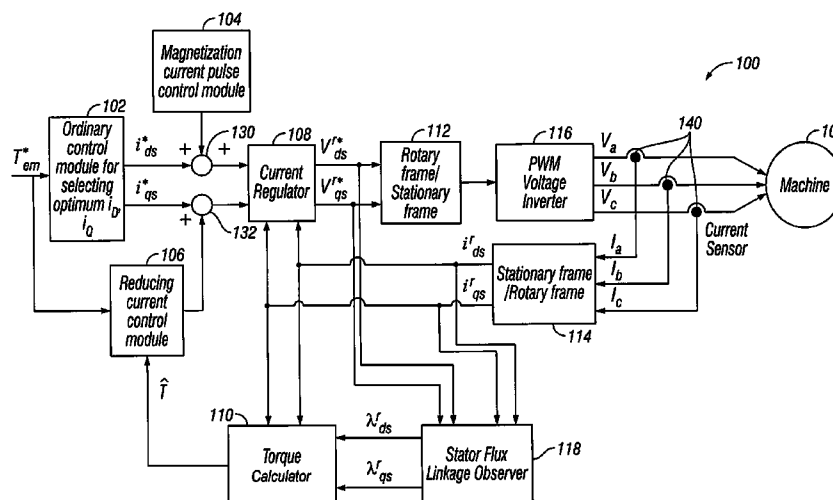
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(57) **ABSTRACT**

A variable magnetization machine controller has a current command module, a magnetization module and a reducing current module. The current command module computes a vector current command in a dq axis based on a torque command. The magnetization module applies a magnetization control pulse to a d-axis current of the vector current command. Thus, the reducing current module applies a reducing current to a q-axis current of the vector current command based on the torque command and one of an estimated torque of the variable magnetization machine and a measured torque of the variable magnetization machine.
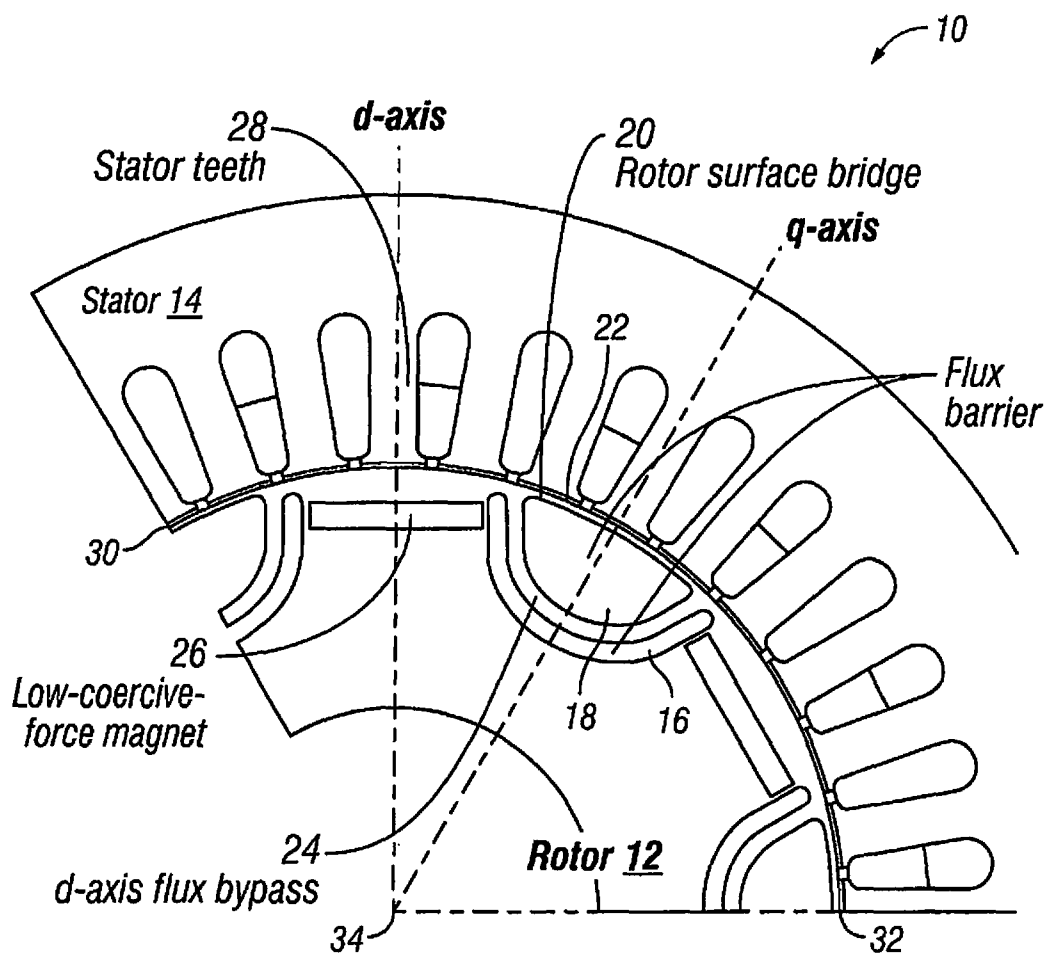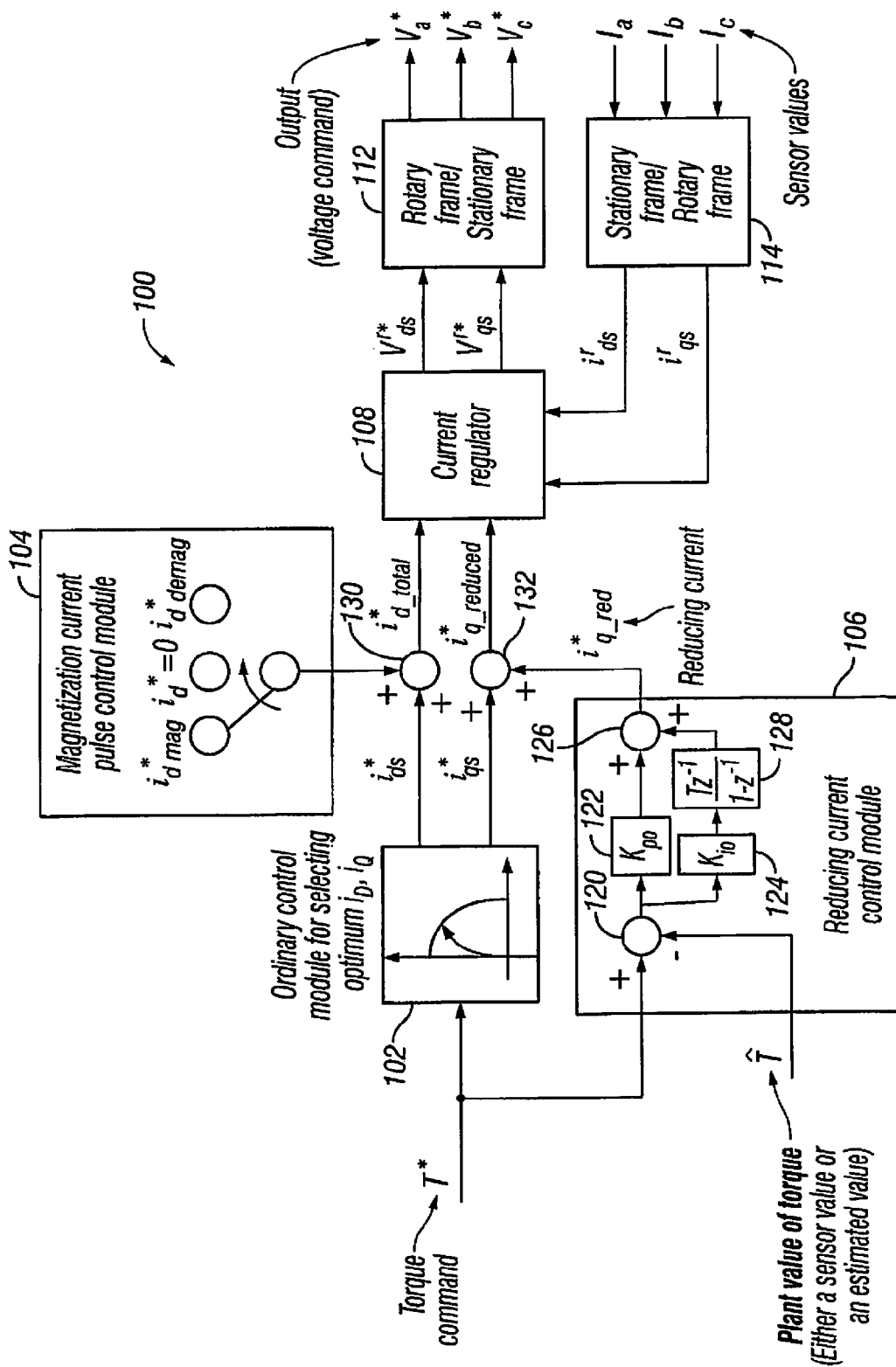
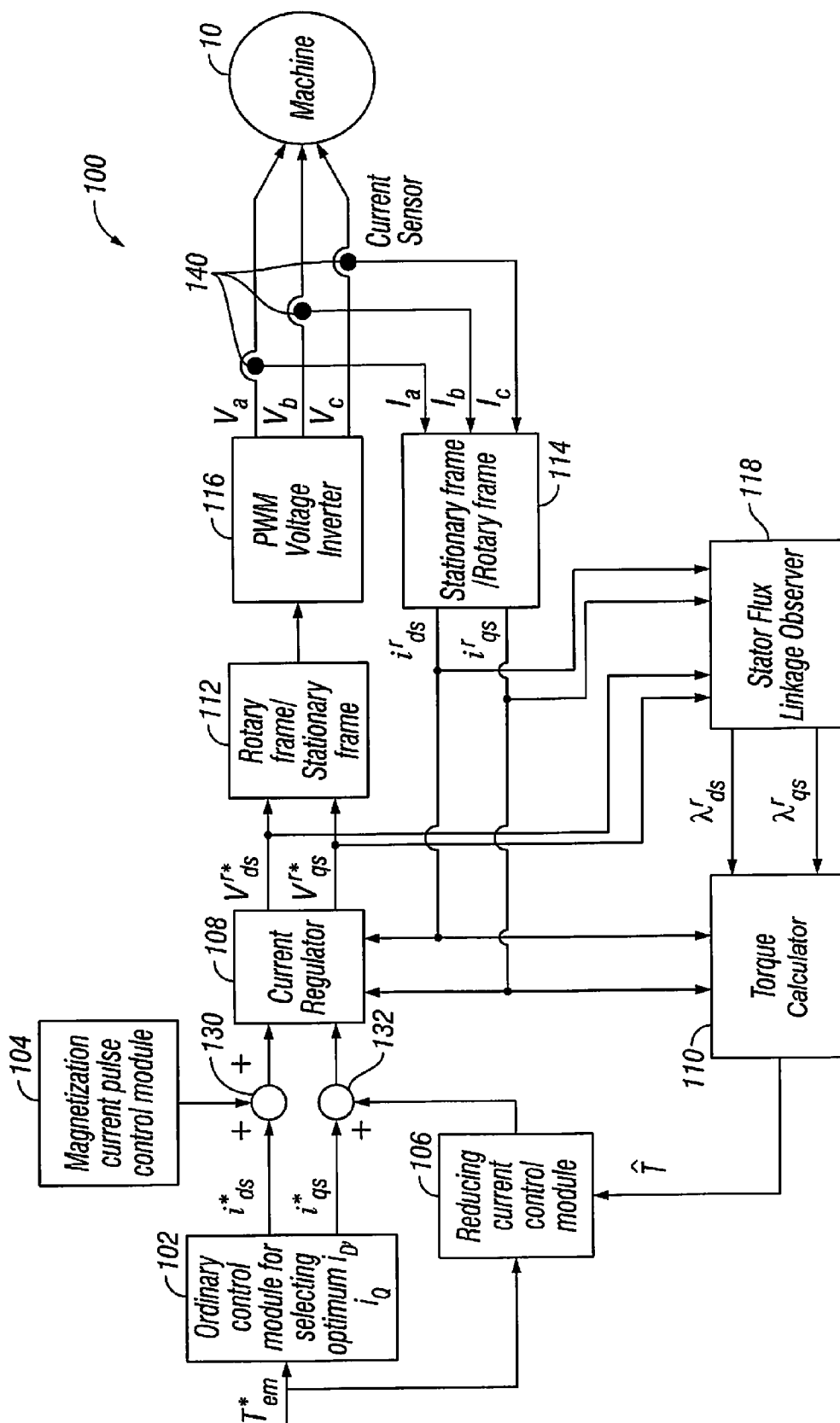**16 Claims, 19 Drawing Sheets**
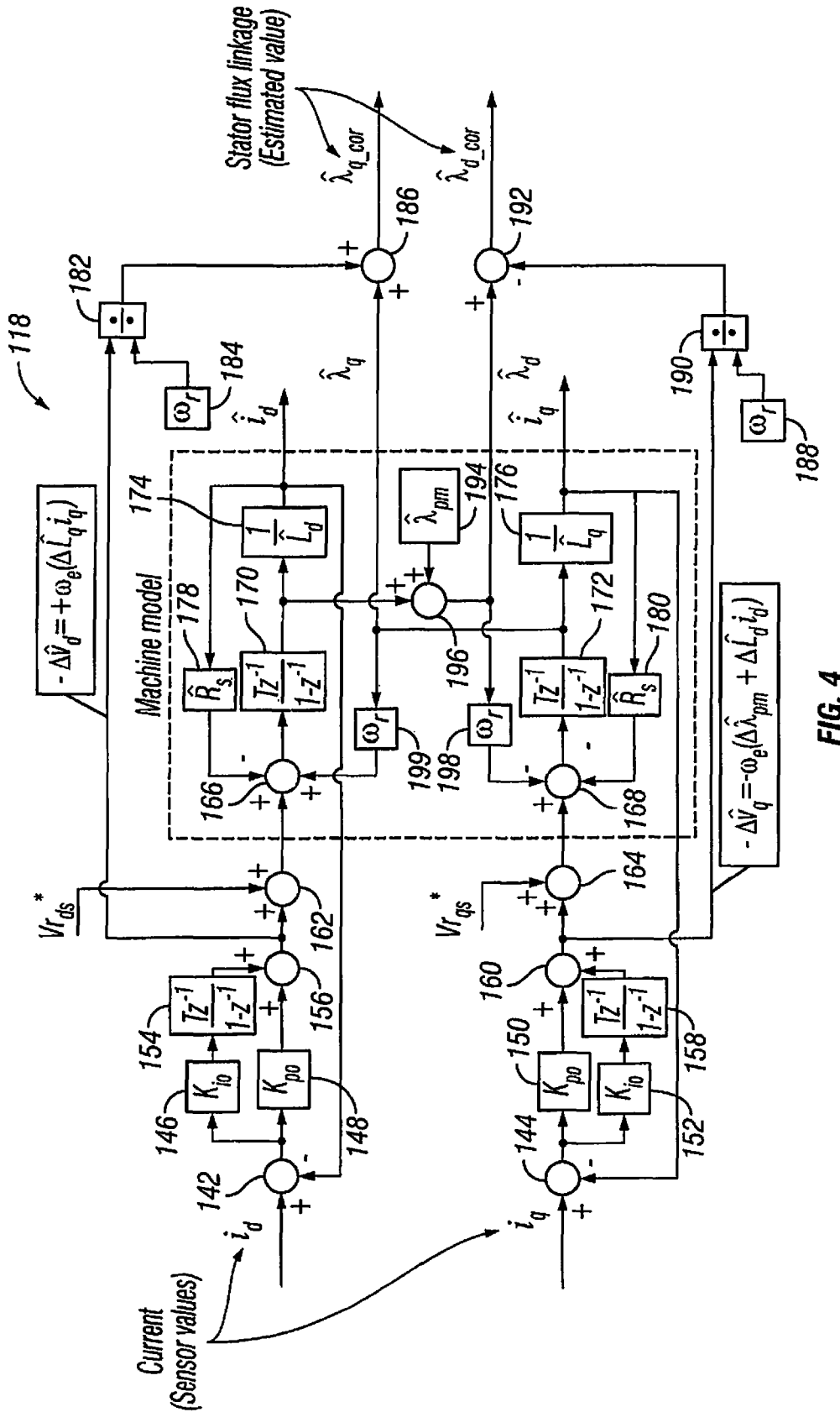
FIG. 1

FIG. 2

FIG. 3

FIG. 4
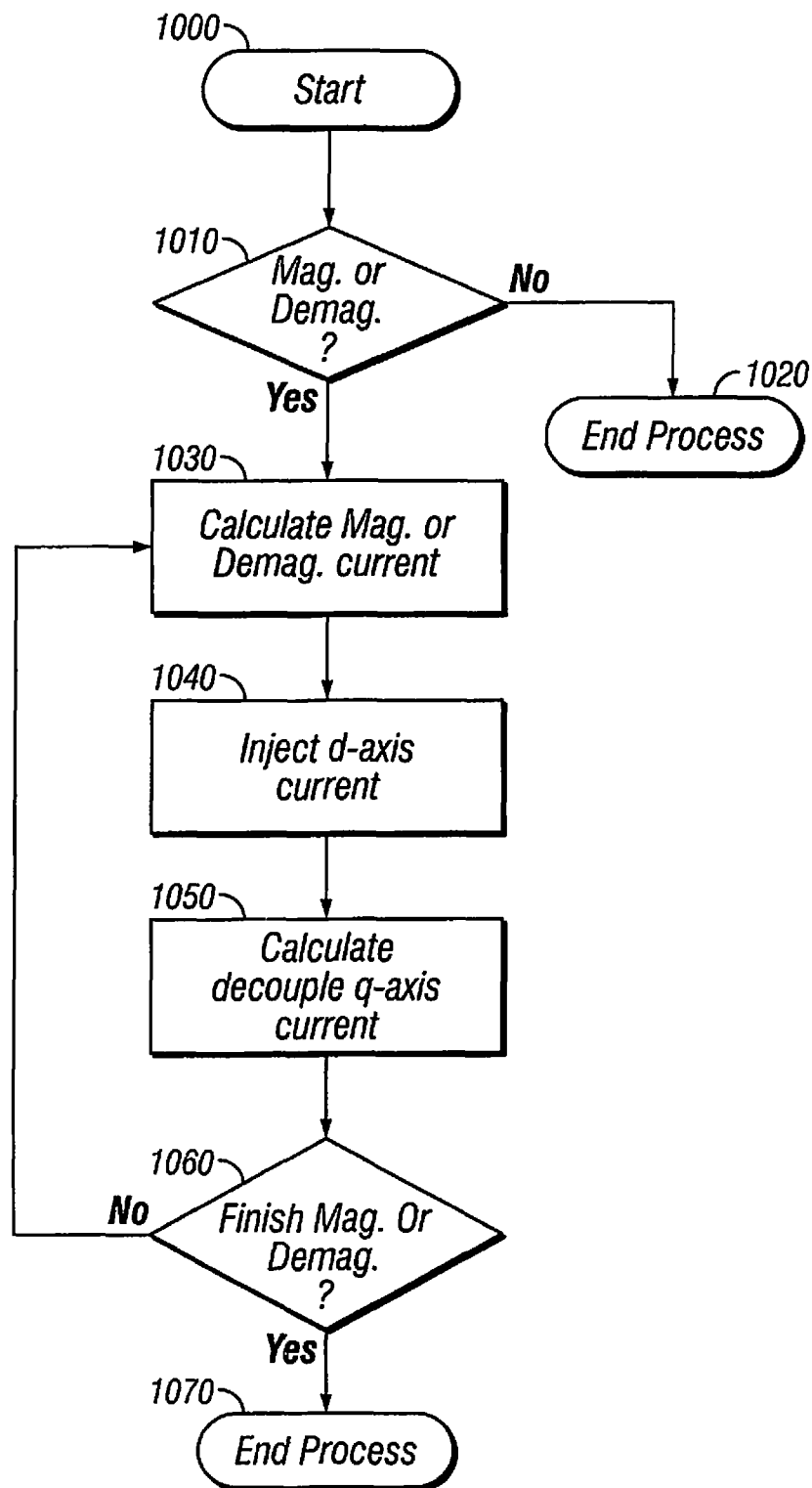
FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

Magnetization process

Conventional technique 1:
Only D-axis current

Conventional technique 2:
Look-up table
(Off-line regulation)

New technique:
On-line regulation

$i_q(A)$

Current limit circle

$i_d(A)$

FIG. 11

Demagnetization process

New technique:

Conventional technique 2:

Conventional technique 1:

$i_q(A)$

Current limit circle

$i_d(A)$

FIG. 12

FIG. 13

FIG. 14

FIG. 15
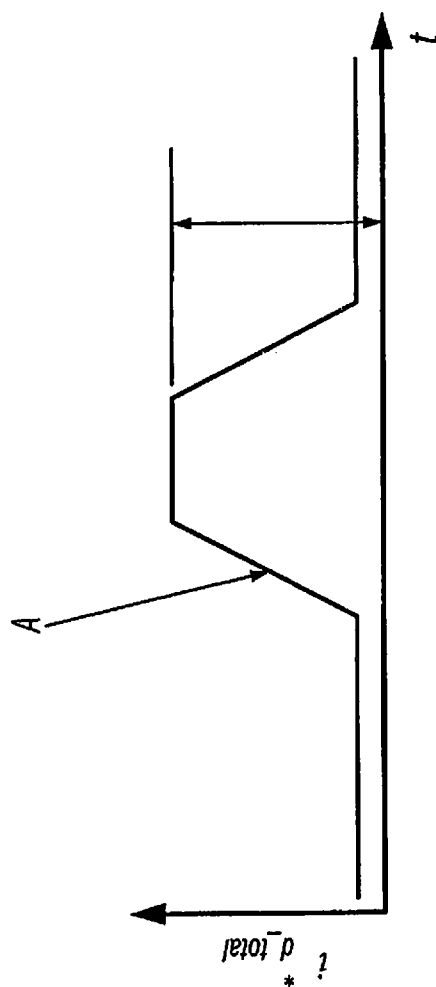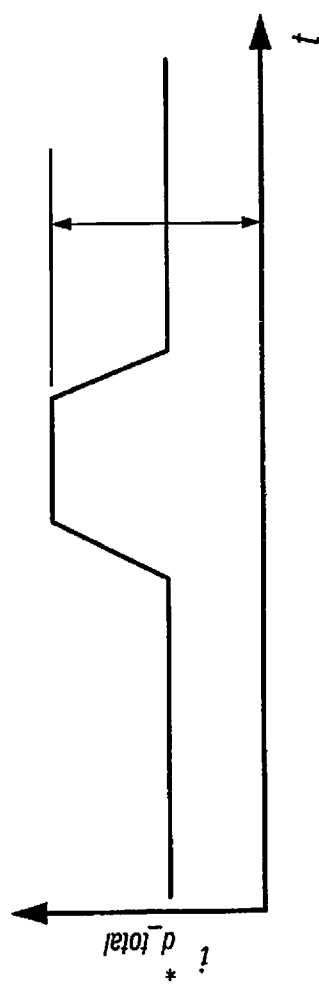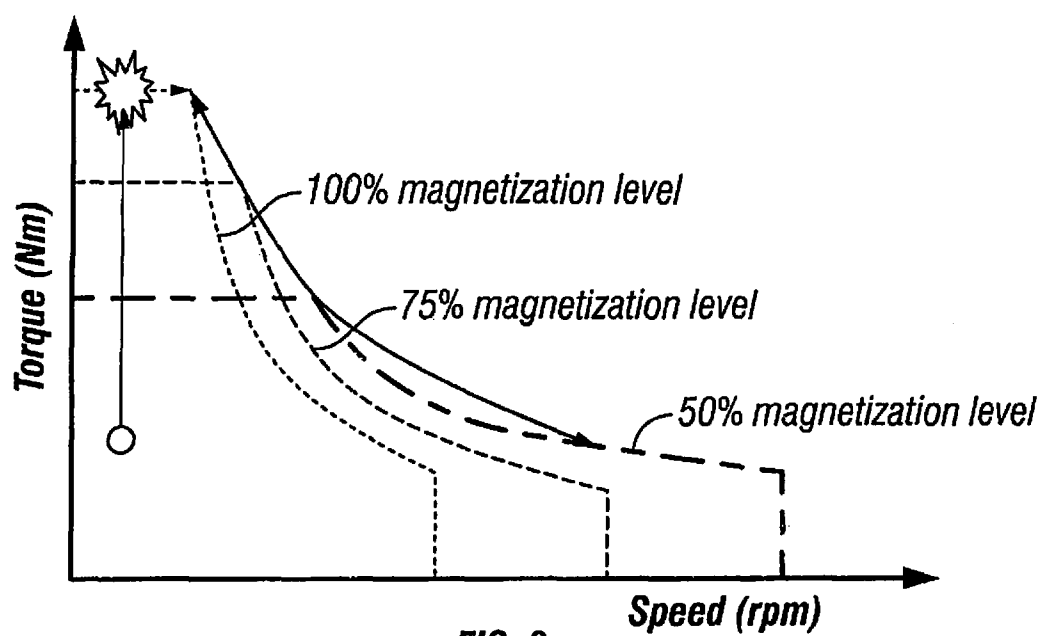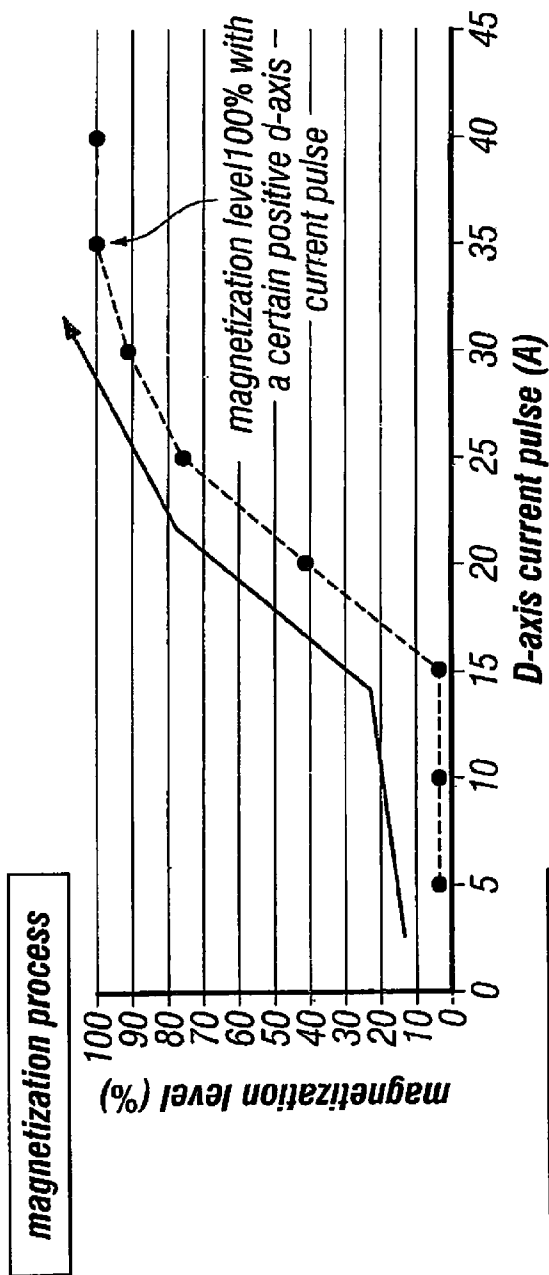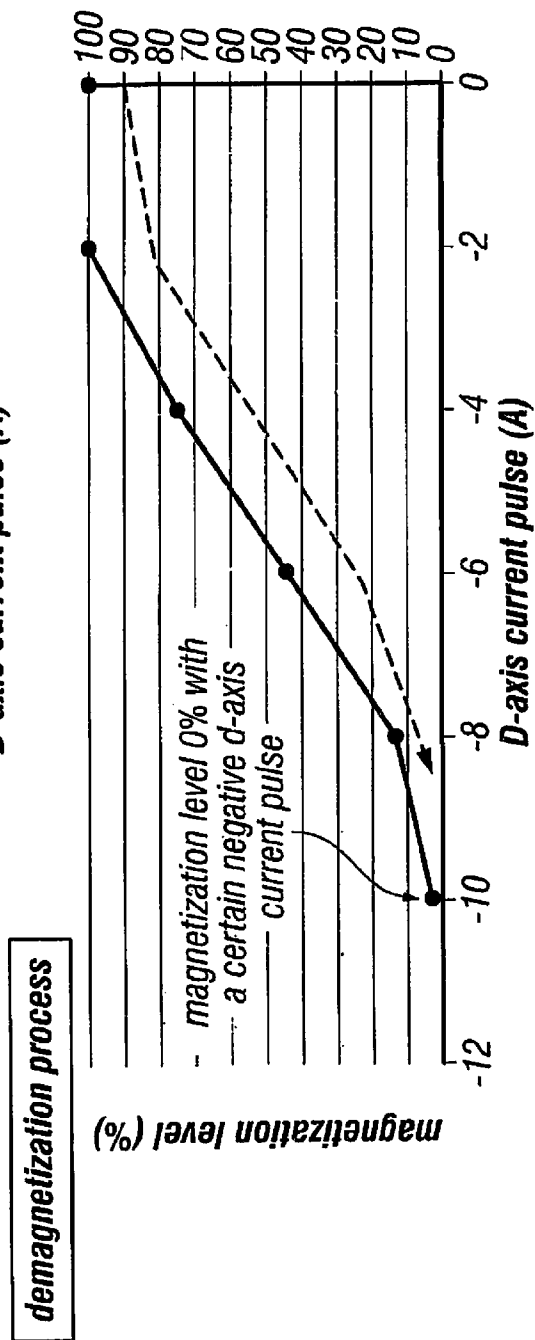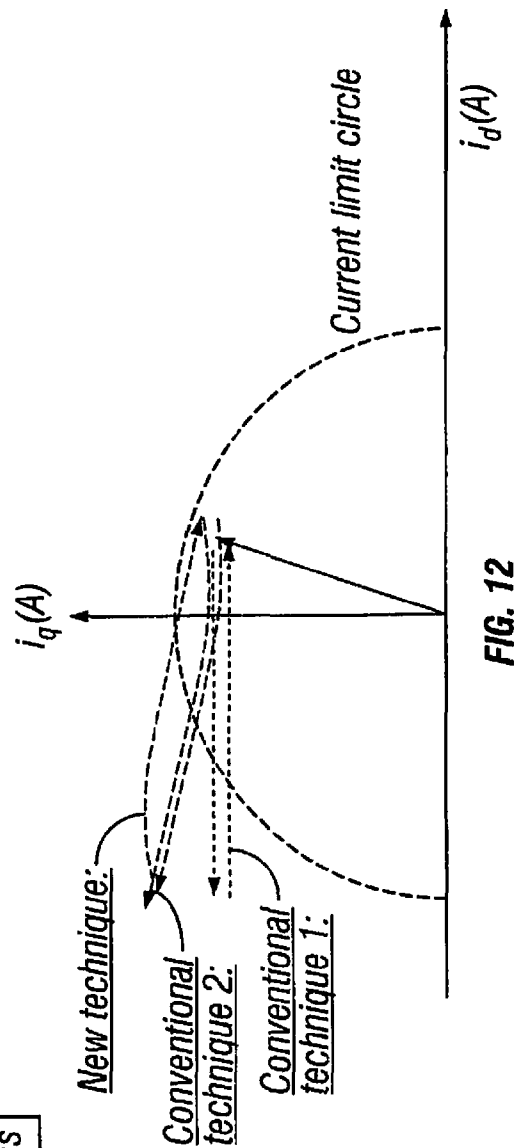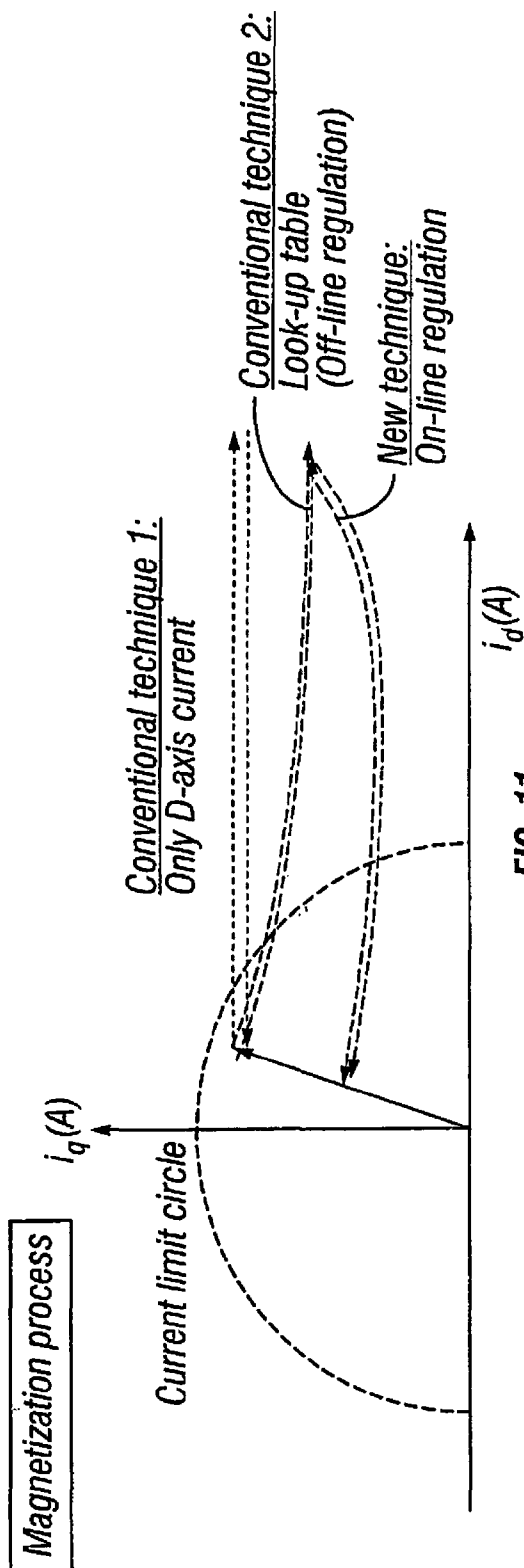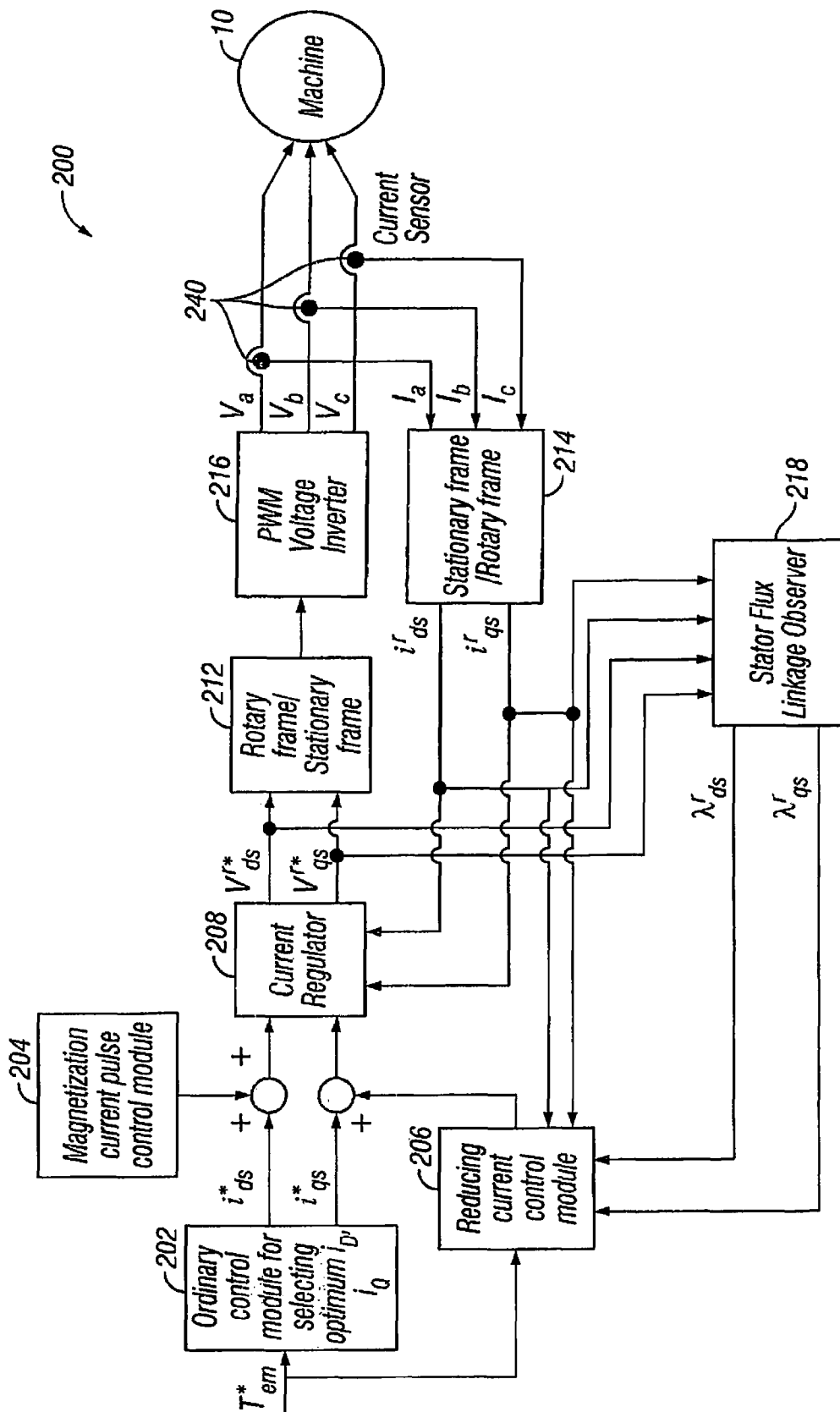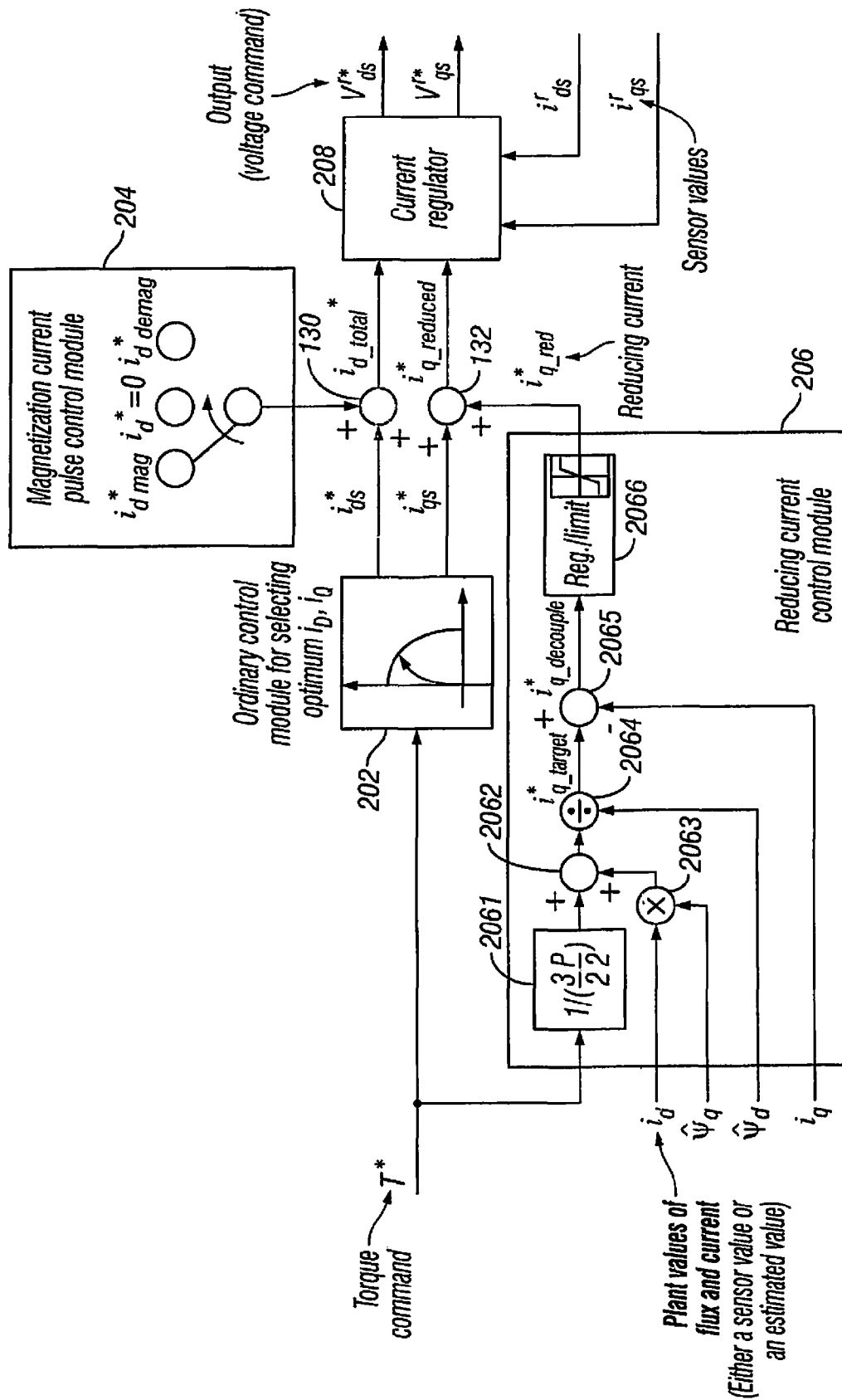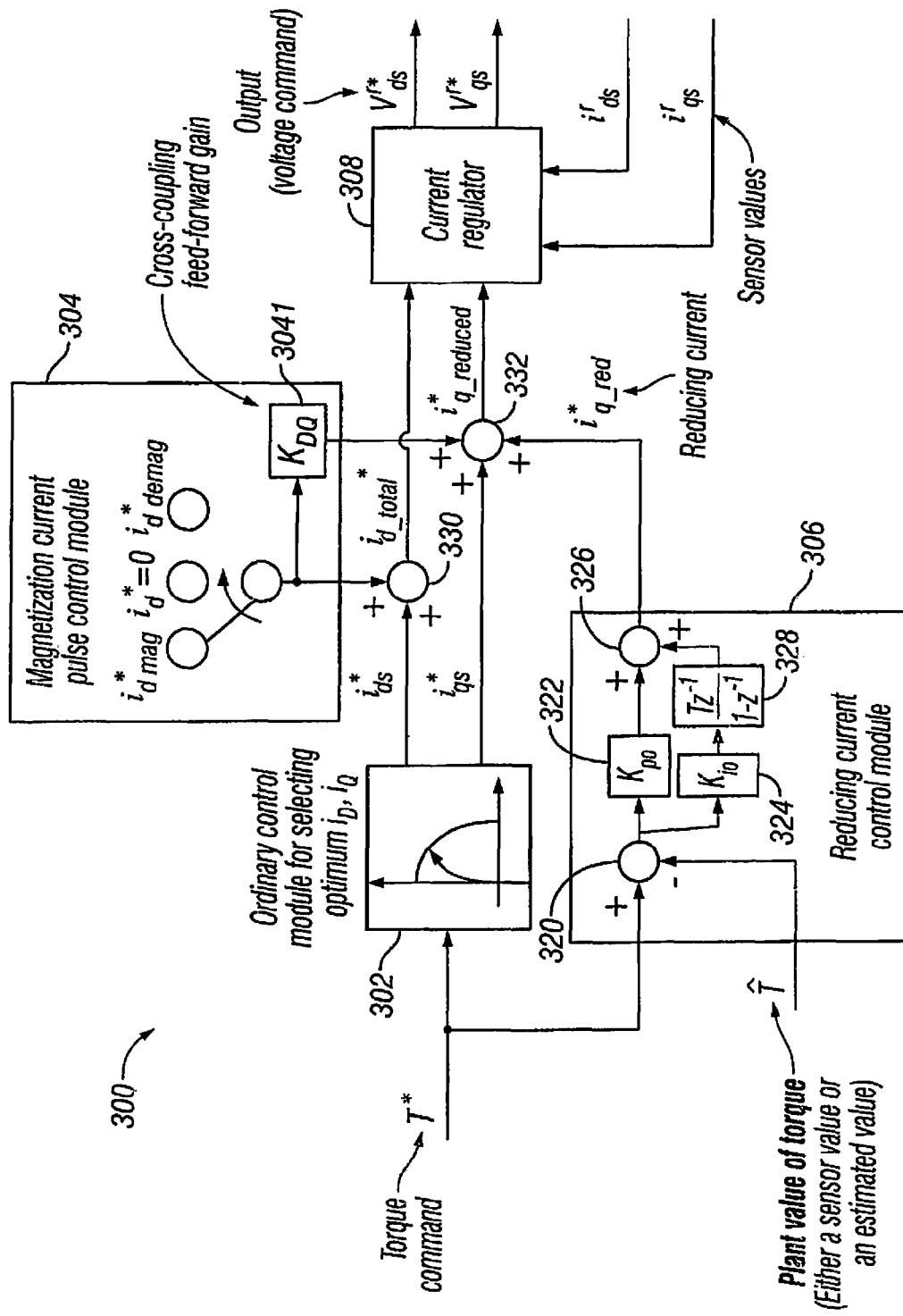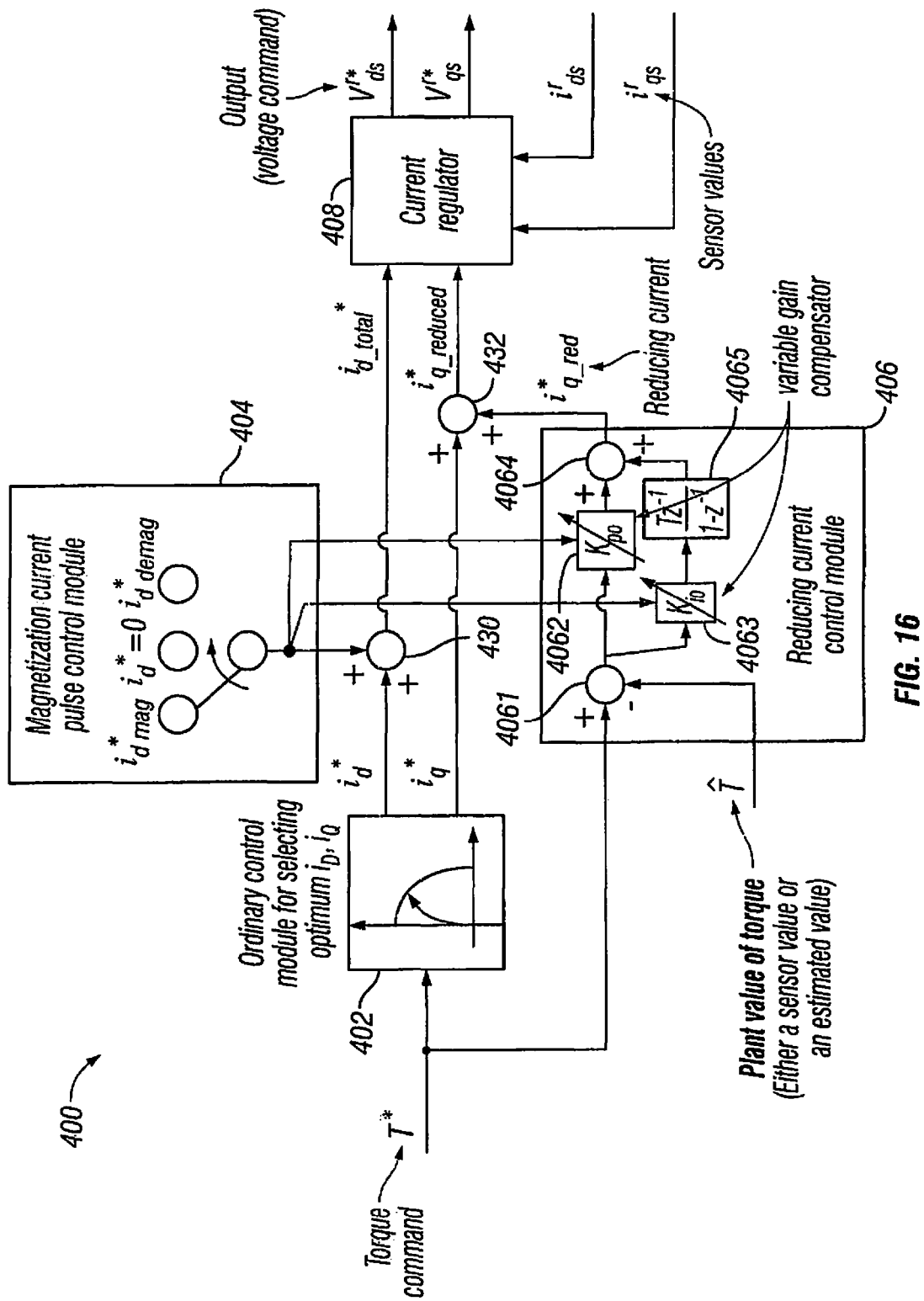
FIG. 16

FIG. 18

In case of a negative salient machine ($L_Q > L_D$)

magnetization pulse current

Kpo,Kio

t
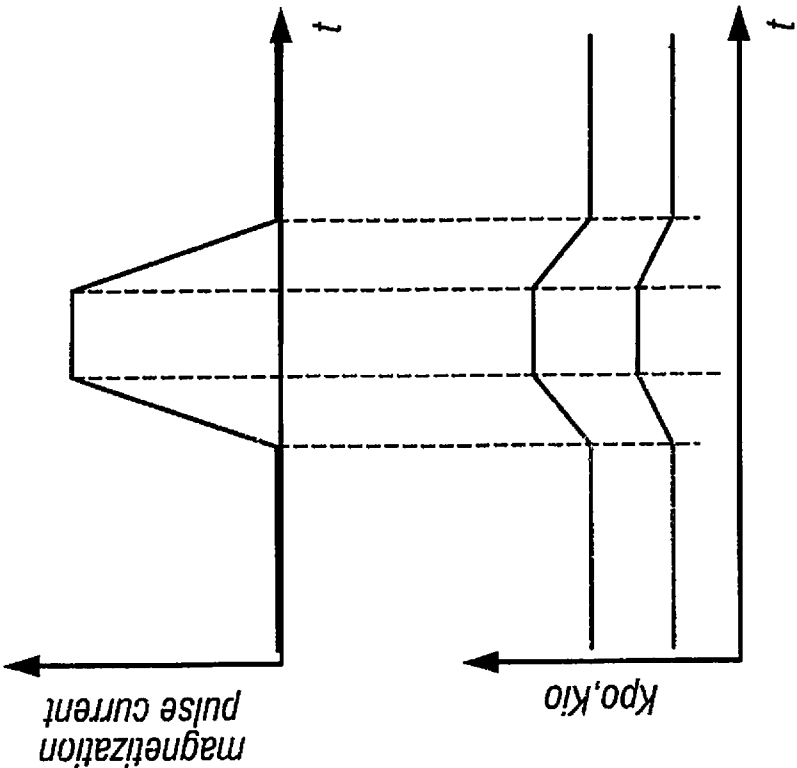
FIG. 17

In case of a positive salient machine ($L_D > L_Q$)

magnetization pulse current

Kpo,Kio

t

FIG. 19

$\lambda_{m\_disired}$

$\lambda_{m\_allowed}$

6041

Max. mag.
Cmd. model

ω

V_{DC}

Min

6042

$\lambda^{*\_feasible}_{m\_level}$

6043

Magnet mag. vs
required current table

i_{d_target}

$\lambda^{*\_feasible}_{m\_level}$

i_{d_target}

Δi_d

+

i_d

6045

−

6044

Current pulse
generator

i_{d_mag}
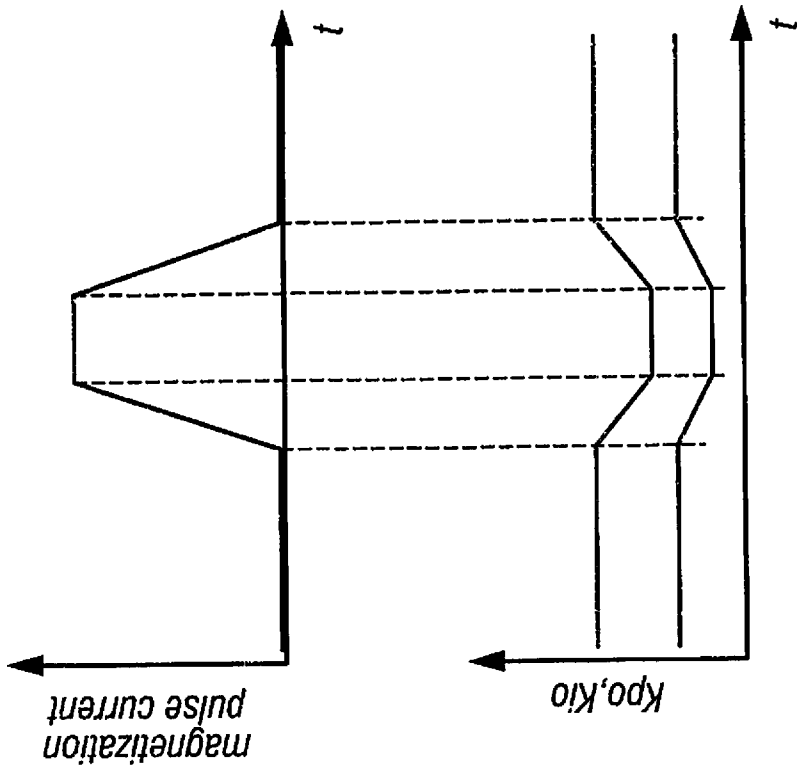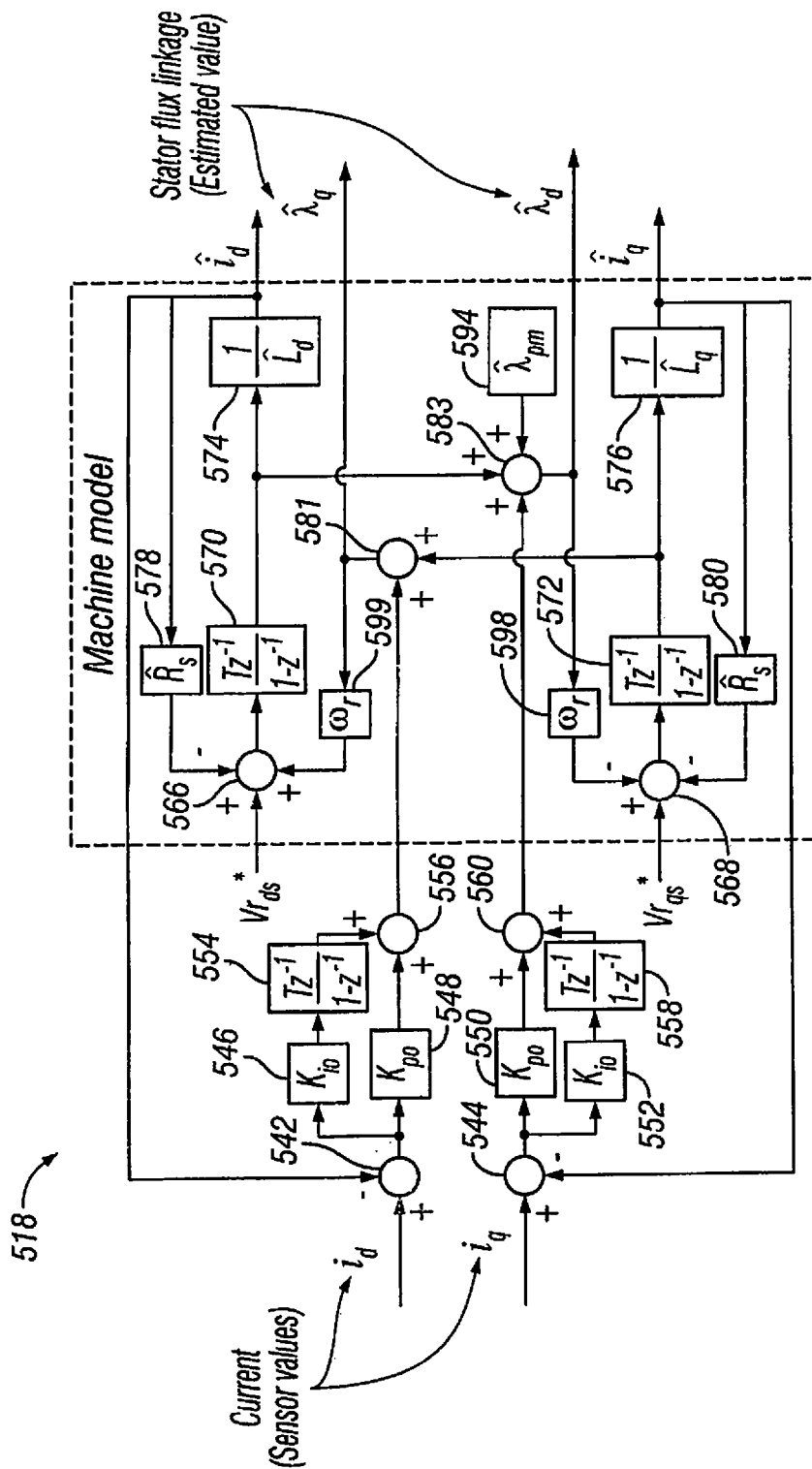
FIG. 20

FIG. 21

FIG. 22

FIG. 23

FIG. 24

VARIABLE MAGNETIZATION MACHINE CONTROLLER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a U.S. National stage application of International Application No. PCT/US2013/048562, filed Jun. 28, 2013, the contents of which is hereby incorporated herein by reference.

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 for changing the magnetization level of a variable magnetization machine, such as an electric motor employed in an electric or hybrid electric vehicle.

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.

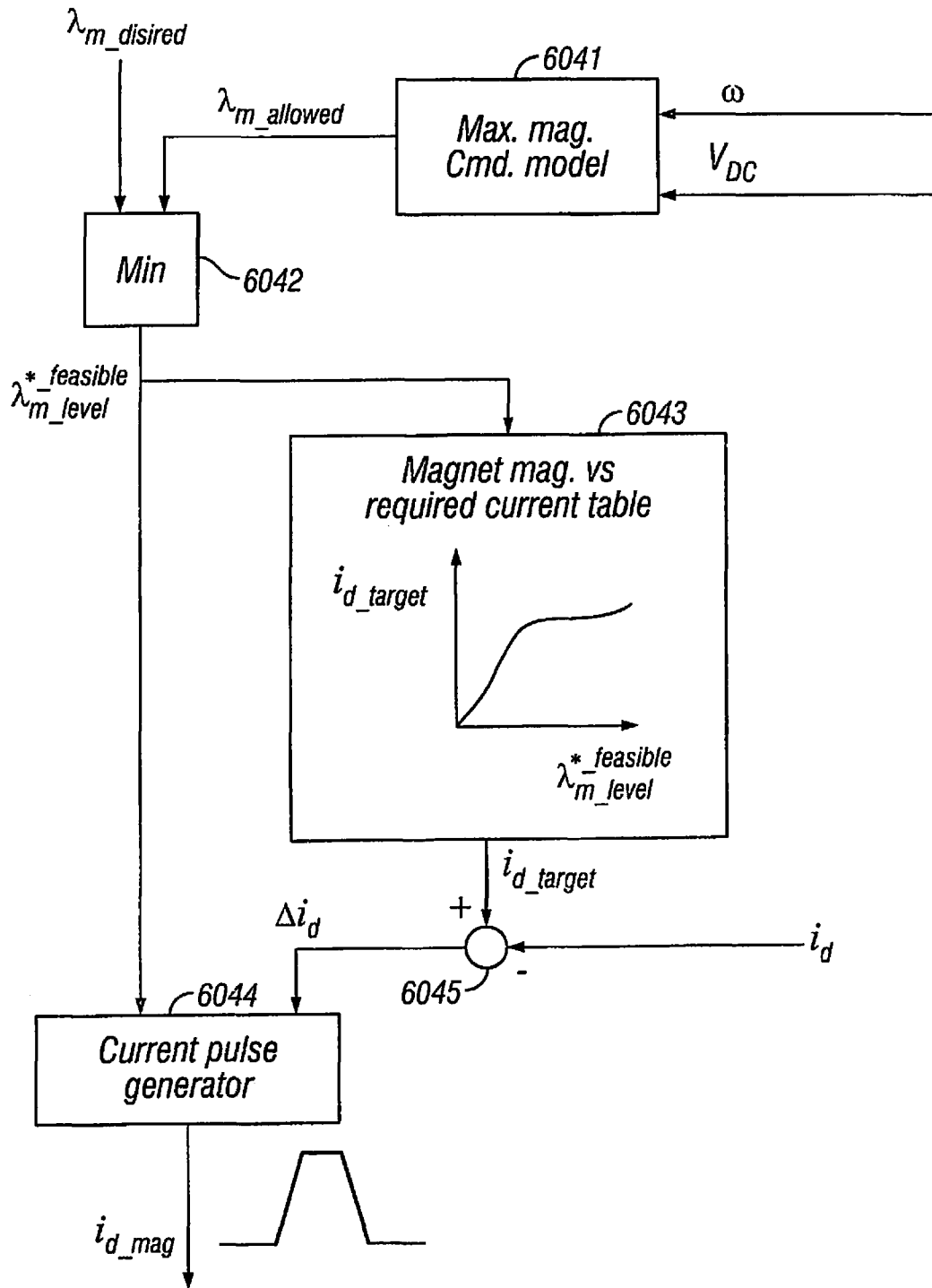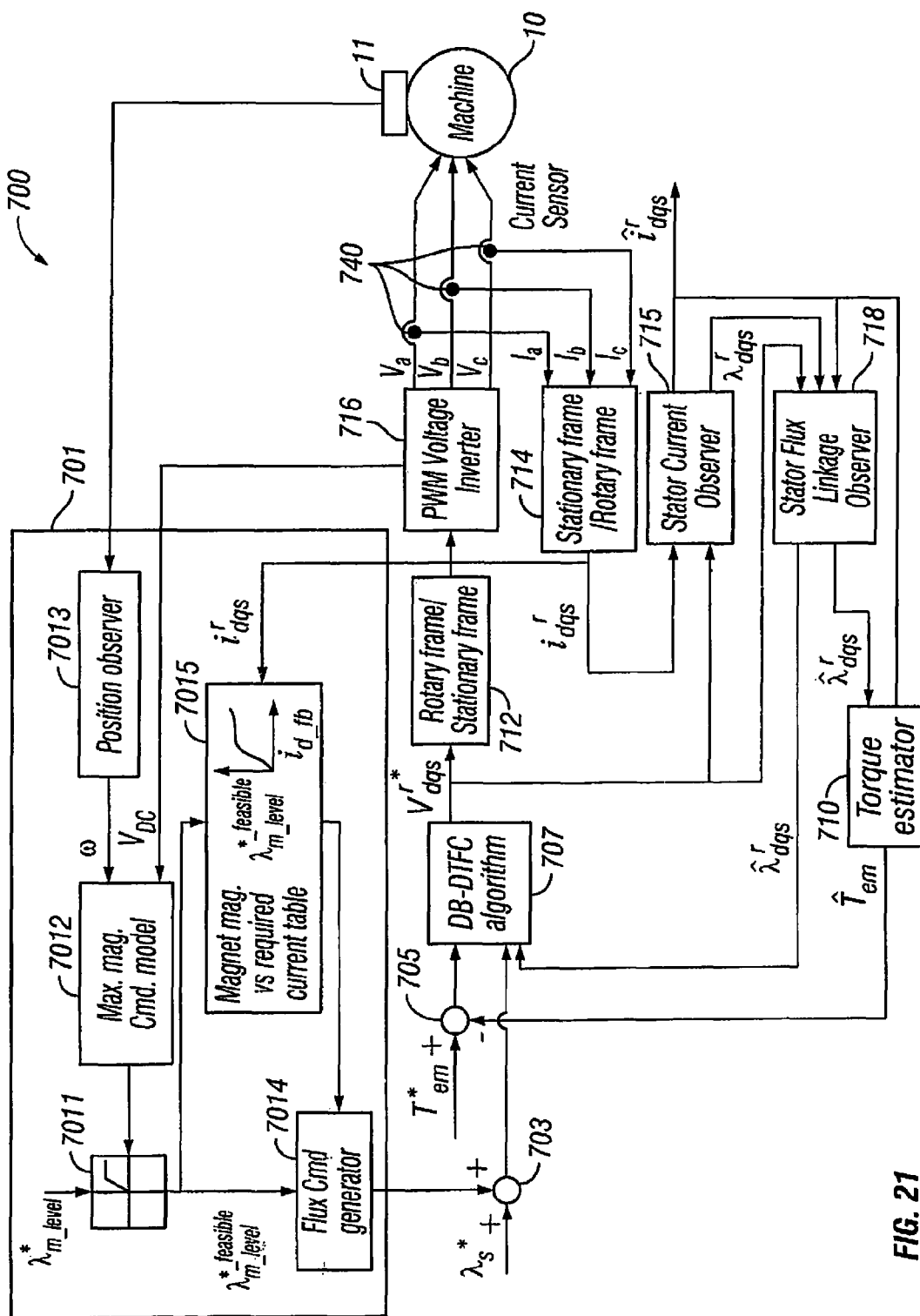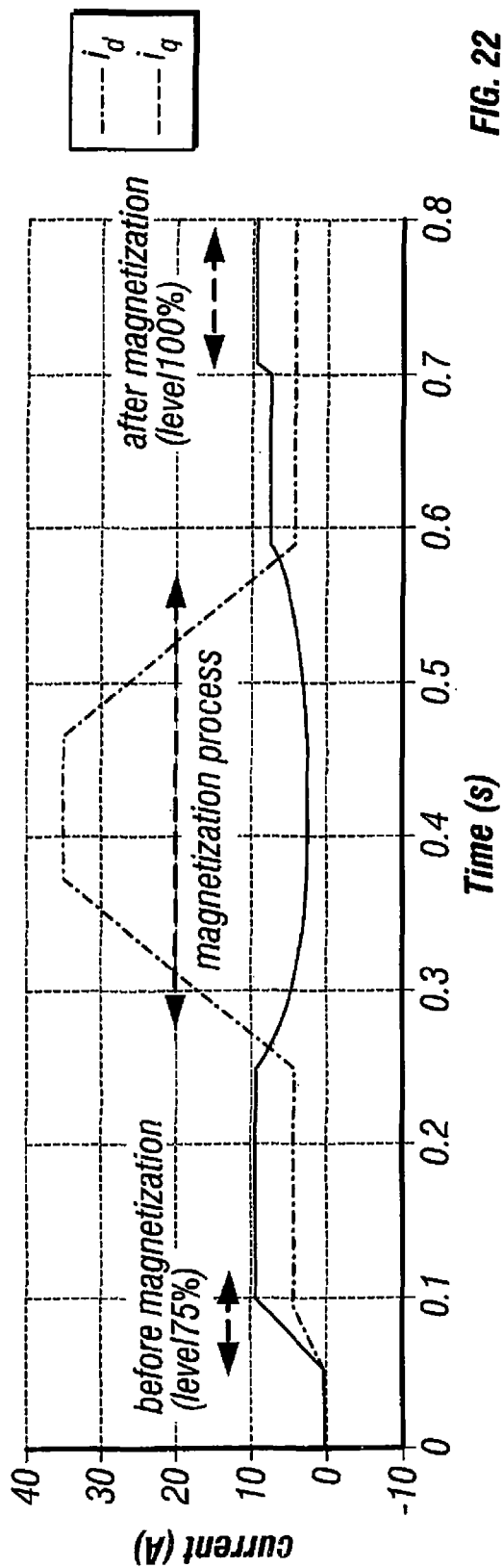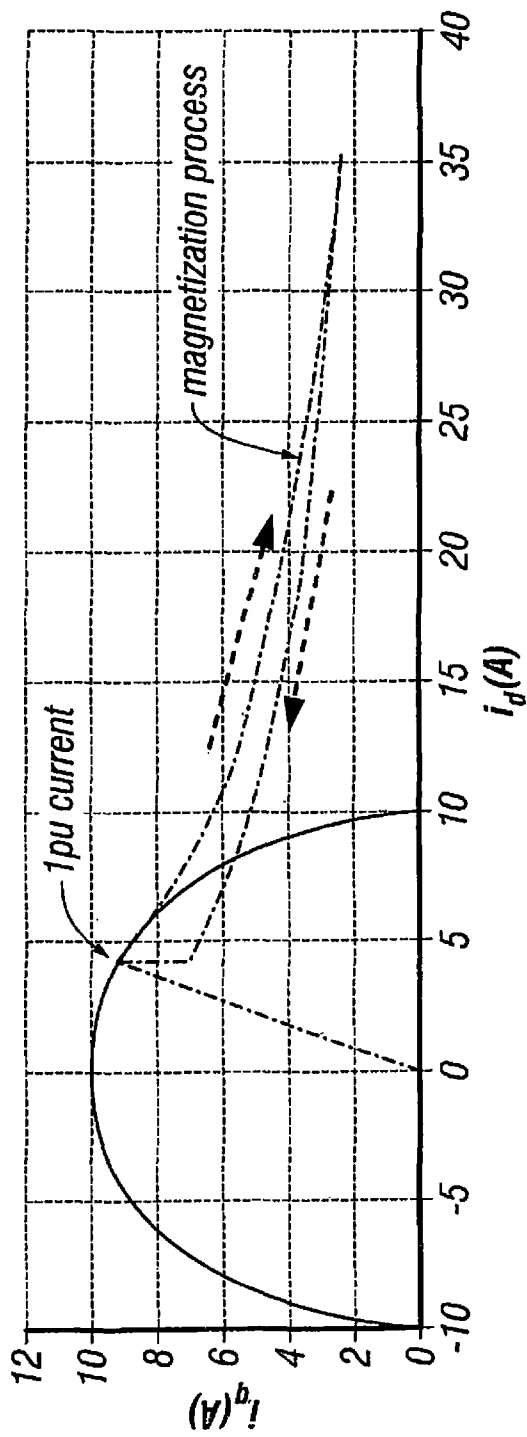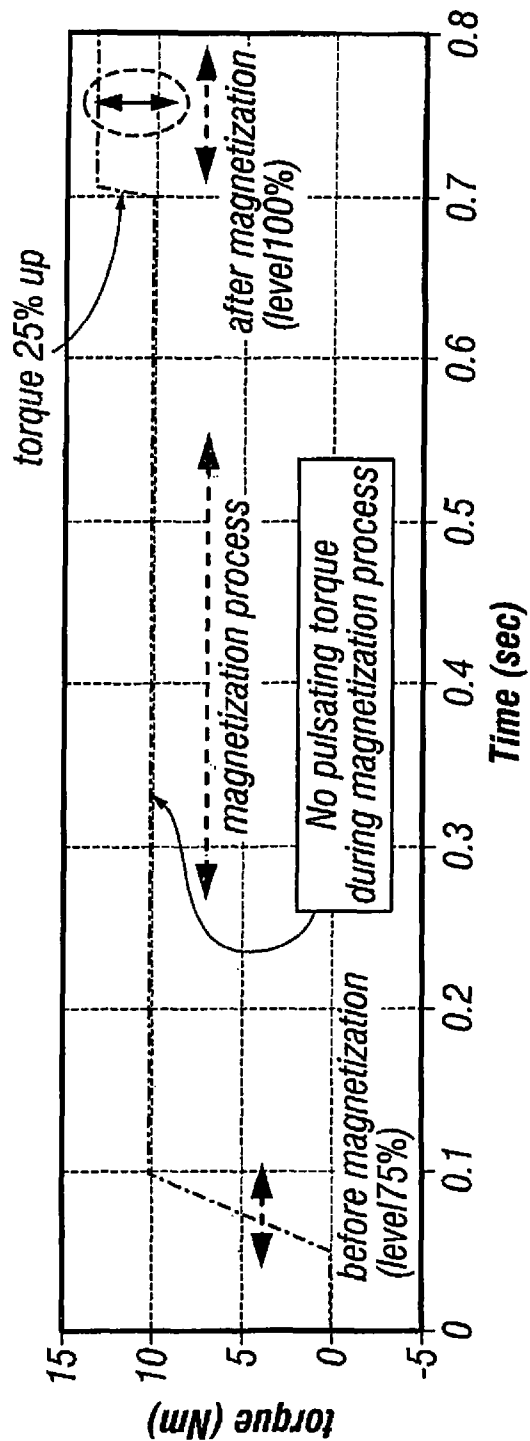Electric vehicles and HEVs can employ an electric motor having variable magnetization characteristics as understood in the art. For example, the magnetization level of the motor can be increased to increase the torque generated by the motor. Accordingly, when the driver attempts to accelerate the vehicle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

Certain techniques exist for increasing the magnetization level of such an electric motor. In one technique (conventional technique 1), only the d-axis current of the motor is increased. This results in the electric motor outputting a pulsating torque that pulsates due to the pulsating d-axis current and also due to changes in the magnetization level. In another technique (conventional technique 2), such as that described in JP 2009-153296, a controller can set the magnetization level of the motor based on values retrieved from a look-up table. In doing so, the controller can regulate the d-axis current and also the q-axis current. However, as understood in the art, because the q-axis current is determined using open loop (feed forward) control, a 2-dimensional look-up table is necessary to maintain a constant torque output by the motor. As further understood in the art, creating such a look-up table is very complicated and time consuming. Also, since open loop control is used, the same look-up table may not necessarily be useful with different motors due to the different characteristics of the individual motors, even if those motors are manufactured in mass production.

SUMMARY

Accordingly, it is desirable to provide an improved controller for a variable magnetization machine, such as a variable magnetization motor for a vehicle.

In view of the state of the known technology, one aspect of a variable magnetization machine controller according to the disclosed embodiments comprises a current command

module, a magnetization module and a reducing current module. The current command module computes a vector current command in a dq axis based on a torque command. The magnetization module applies a magnetization control pulse to a d-axis current of the vector current command. Thus, the reducing current module applies a reducing current to a q-axis current of the vector current command based on the torque command and one of an estimated torque of the variable magnetization machine and a measured torque of the variable magnetization machine.

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;

FIG. 2 is an exemplary block diagram of components of a variable magnetization machine controller according to a disclosed embodiment;

FIG. 3 is an exemplary block diagram illustrating the components shown in FIG. 2 and additional components of the variable magnetization machine controller according to a disclosed embodiment;

FIG. 4 is an exemplary block diagram of the stator flux linkage observer shown in FIG. 3;

FIG. 5 is a flowchart illustrating an example of operations performed by the variable magnetization machine controller shown in FIG. 3;

FIG. 6 is a graph illustrating an example of a d-axis current signal in relation to time as output by the variable magnetization machine controller shown in FIG. 3 for a small d-axis current signal;

FIG. 7 is a graph illustrating an example of a d-axis current signal in relation to time as output by the variable magnetization machine controller shown in FIG. 3 for a large d-axis current signal;

FIG. 8 is a graph illustrating an example of torque of the variable magnetization machine in relation to speed of the variable magnetization machine as shown in FIG. 1;

FIG. 9 is a graph illustrating an example of the magnetization level in relation to a d-axis current pulse during magnetization of the variable magnetization machine as shown in FIG. 1;

FIG. 10 is a graph illustrating an example of the magnetization level in relation to a d-axis current pulse during demagnetization of the variable magnetization machine as shown in FIG. 1;

FIG. 11 is a graph illustrating an example of the behavior of the d-axis current signal during a magnetization process of the variable magnetization machine as performed by the variable magnetization machine controller as compared to conventional magnetization processes;

FIG. 12 is a graph illustrating an example of the behavior of the d-axis current signal during a demagnetization process of the variable magnetization machine as performed by the variable magnetization machine controller as compared to conventional demagnetization processes;

FIG. 13 is an exemplary block diagram illustrating components of the variable magnetization machine controller according to another disclosed embodiment;

FIG. 14 is an exemplary block diagram illustrating examples of the ordinary control module, magnetization current pulse control module, reducing current control module and current regulator of the variable magnetization machine controller shown in FIG. 13;

FIG. **15** is an exemplary block diagram illustrating examples of the ordinary control module, magnetization current pulse control module, reducing current control module and current regulator of another embodiment of the variable magnetization machine controller;

FIG. **16** is an exemplary block diagram illustrating examples of the ordinary control module, magnetization current pulse control module, reducing current control module and current regulator of another embodiment of the variable magnetization machine controller;

FIG. **17** is a graph illustrating an example of the magnetization pulse current output by an embodiment of the variable magnetization machine controller when controlling a positive salient variable magnetization machine;

FIG. **18** is a graph illustrating an example of the magnetization pulse current output by an embodiment of the variable magnetization machine controller when controlling a negative salient variable magnetization machine;

FIG. **19** is an exemplary block diagram of another embodiment of a stator flux linkage observer of a variable magnetization machine controller according to an embodiment described herein;

FIG. **20** is an exemplary block diagram of an example of a magnetization current pulse control module of a variable magnetization machine controller according to an embodiment described herein;

FIG. **21** is an exemplary block diagram of another embodiment of a magnetization current control module with a deadbeat-direct torque flux control algorithm;

FIG. **22** is a graph illustrating an example of current with respect to time during a magnetization process performed by an embodiment of the variable magnetization machine controller described herein;

FIG. **23** is a graph illustrating an example of a relationship between q-axis current and q-axis current during a magnetization process performed by an embodiment of the variable magnetization machine controller described herein; and

FIG. **24** is a graph illustrating an example of torque of a variable magnetization machine during a magnetization process performed by an embodiment of the variable magnetization machine controller described herein.

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, includes a rotor **12** and a stator **14**. 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 appro-

priate 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 **24** are made of the same material as 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** extends 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 to enable the rotor **12** to rotate unrestrictedly or substantially unrestrictedly about an axis **34**.

A variable magnetization machine controller **100** according to a disclosed embodiment will now be described with reference to FIGS. **2** through **4**. 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, the variable magnetization machine controller **100** includes an ordinary control module **102**, a magnetization current pulse control module **104**, a reducing current control module **106**, a current regulator **108** and a torque calculator **110**. The variable magnetization machine controller **100** further includes a rotary frame/stationary frame component **112**, a stationary frame/rotary frame component **114**, a pulse width modulator (PWM) voltage invertor **116** and a stator flux linkage observer **118**. The variable magnetization machine controller **100** is electrically coupled to

the variable magnetization machine **10** as shown. As can be appreciated from FIGS. **2** and **3**, FIG. **2** illustrates examples of features of the ordinary control module **102**, the magnetization current pulse control module **104** and the reducing current control module **106**, but does not illustrate the torque calculator **110**, the pulse width modulator (PWM) voltage invertor **116** and the stator flux linkage observer **118** shown in FIG. **3**.

The variable magnetization machine controller **100** preferably includes at least one microcomputer with a control program that controls the components of the variable magnetization machine controller **100** as discussed below. The variable magnetization machine 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 variable magnetization machine 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 variable magnetization machine 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 variable magnetization machine 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 shown in FIGS. **2** and **3**, the ordinary control module **102** and the reducing current control module **106** receive a torque command T* 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 **102** 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 **102**, 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*. For example, the reducing current module **106** in this example computes the reducing current based on a difference between the torque command T* and the estimated torque T. This can provide a feedback system with an easier calculation.

That is, as shown in more detail in FIG. **2**, the reducing current control module **106** in this example includes a subtractor **120** that subtracts the value of a sensed or estimated torque T from the value of the torque command T* and outputs this difference to a plurality of gain components **122** and **124**. For example, as shown in FIG. **3**, the value of torque T can be provided by the torque calculator **110** as discussed in more detail below. The output of gain component **122** is provided to an adder **126** and the output of the gain component **124** is provided to a z-transform component **128**. The adder **126** therefore adds the output of the gain component **122** and the output of the z-transform component **128** to produce a reducing current signal i*$_{q\_red}$. Thus, the reducing current control module **106**, also referred to simply as a reducing current module, applies a reducing current to

a q-axis current of the vector current command based on the torque command and one of an estimated torque of the variable magnetization machine and a measured torque of the variable magnetization machine **10**. Thus, the variable magnetization machine controller **100** is insensitive or substantially insensitive to a parameter deviation or differences in each variable magnetization machine **10**.

As shown in FIGS. **2** and **3**, the ordinary control module **102** outputs the d-axis current signal i*$_{ds}$ to an adder **130** and the q-axis current signal i*$_{qs}$ to an adder **132**. As further shown in FIG. **2**, the magnetization current pulse control module **104** includes circuitry for providing one of three signals in this example. Namely, the magnetization current pulse control module **104** can output a signal i*$_{d\ mag}$ which the adder adds to the d-axis current signal i*$_{ds}$, a value of 0 which the adder adds to the d-axis current signal i*$_{ds}$ (i.e., no change to the d-axis current signal i*$_{ds}$) or a signal i*$_{d\ demag}$ as discussed below. Thus, the magnetization current pulse control module **104** can be configured to vary an amplitude of the magnetization control pulse according to the vector current command output by the control module **102**, which can also be referred to as the current command module. This enables the magnetization or demagnetization to be performed independent of the torque condition of the variable magnetization machine **10**. The magnetization current pulse control module **104**, which can also be referred to as a magnetization module, applies the magnetization control pulse to a d-axis current of the vector current command. Also, to simplify the calculations, the magnetization current pulse control module **104** can set the amplitude of the magnetization control pulse to a value such that a sum of the magnetization control pulse and a value of current i$_d$* provide a d-axis current which obtains a prescribed magnetization level for the variable magnetization machine **10**.

Furthermore, as shown in FIGS. **2** and **3**, the adder **132** adds the reducing current signal i*$_{q\_red}$ to the q-axis current signal i*$_{qs}$ to produce a reduced current signal i*$_{q\_reduced}$. The adders **130** and **132** provide their outputs to the current regulator **108**, 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 **112**. In this example, the rotary frame/stationary frame component **112** provides the voltage signals to the PWM voltage inverter **116**, which provides voltages V$_a$, V$_b$ and V$_c$ to the three poles of the variable magnetization machine **10**.

The variable magnetization machine controller **100** further includes current sensors **140** that sense the currents associated with V$_a$, V$_b$ and V$_c$ being applied to the variable magnetization machine **10**. The current sensors **140** provide the sensed current signals I$_a$, I$_b$ and I$_c$ to the stationary frame/rotary frame component **114**. The stationary frame/rotary frame component **114** 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 **108** and the torque calculator **110**. As understood in the art, the current regulator **108** regulates the d-axis current voltage signal V^{r}*$_{ds}$ and q-axis current voltage signal V^{r}*$_{qs}$ based on the 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 **114**.

As further shown in FIG. **3** and in more detail in FIG. **4**, the stator flux linkage observer **118**, 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**. That is, a compensation value that is obtained

from a value that is a difference between an output of an observer and a plant can be added with a compensation of a proportional integral (PI) controller, and this sum is then added to a state of the observer to produce a Luenburger style observer.

This can provide more accurate torque estimation, and reduce pulsating torque. In this example, the stator flux linkage observer 118 receives the d-axis current signal i^r_{ds} and the detected q-axis current signal i^r_{qs} and provides these signals to subtractors 142 and 144. The subtractor 142 provides an output to gain components 146 and 148, and the subtractor 144 provides an output to gain components 150 and 152. The output of the gain component 146 is provided to a z-transform component 154 and the output of the gain component 148 is provided to an adder 156. The adder 156 therefore adds the output of the gain component 148 and the output of the z-transform component 154. Likewise, the output of the gain component 152 is provided to a z-transform component 158 and the output of the gain component 150 is provided to an adder 160. The adder 160 therefore adds the output of the gain component 150 and the output of the z-transform component 158.

The output of the adder 156 is provided to an adder 162 which adds that output to the d-axis current voltage signal V^{r*}_{ds} that is output by the current regulator 108 as discussed above. Also, the output of the adder 160 is provided to an adder 164 which adds that output to the q-axis current voltage signal V^{r*}_{dq} that is output by the current regulator 108. The output of the adder 162 is provided to an adder/subtractor 166 and the output of the adder 164 is provided to an adder/subtractor 168. The output of the adder/subtractor 166 is provided to a z-transform component 170 and the output of the adder/subtractor 168 is provided to a z-transform component 172. The output of the z-transform component 170 is provided to inductance component 174, which provides an output d-axis current signal i_d. The output of the z-transform component 172 is provided to inductance component 176, which provides an output q-axis current signal i_q. Furthermore, the output of the inductance component 174 is fed back via resistance component 178 to the adder/subtractor 166, and the output of inductance component 174 is fed back via resistance component 180 to adder/subtractor 168.

As further shown, the output of the adder 156 is provided to a divider 182 which divides the output of adder 156 with a sensed or estimated rotation signal ω_r of the rotor 12 output by component 184 and provides an output to an adder 186. Also, the output of adder 160 is provided to a divider 190 which divides the output of the adder 160 with a sensed or estimated rotation signal ω_r of the rotor 12 output by a component 188 and provides an output to a subtractor 192.

As further shown in FIG. 4, a component 194 provides a signal to an adder 196. The adder 196 adds the output of the signal from the component 194 to a signal provided by the z-transform component 170. The output of the adder 196 is provided to a component 198 which provides an output to the adder 168. Hence, the adder/subtractor 168 subtracts the signal provided by a component 180 from the signals provided by the adder 164 and the component 198 to provide the output signal to the z-transform component 172. The output of the z-transform component 172 is further provided to a component 199 and to adder 186. Hence, the adder/subtractor 166 subtracts the output of the component 178 from the signals provided by the adder 162 and the component 199 to provide the output signal to the z-transform component 170.

Furthermore, the adder 186 adds the output of the component 199 to the output of divider 182 to provide an estimated stator flux linkage signal λ_{q_cor}, and the subtractor 192 subtracts the output of divider 190 form the output of adder 196 to provide an estimated stator flux linkage signal λ_{d_cor}. Accordingly, the torque calculator 110 shown in FIG. 3 calculates the value of a sensed or estimated torque T based on the estimated stator flux linkage signals λ_{d_cor} and λ_{q_cor} (which are represented by λ^r_{ds} and λ^r_{qs} in FIG. 3), 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 114.

FIG. 5 is a flowchart illustrating an example of operations performed by the variable magnetization machine controller 100 and by the other embodiments of the variable magnetization machine controller described herein. These operations can be performed by the controller or controller incorporated into the components of the variable magnetization machine controller 100 as discussed above.

After beginning the process in Step 1000, the process determines whether the variable magnetization machine 10 is to be magnetized or demagnetized. If not, the process ends in step 1020. However, if the variable magnetization machine 10 is to be magnetized or demagnetized, the processing calculates the magnetization or demagnetization current in step 1030. In step 1040, the variable magnetization machine controller 100 applies the d-axis current to the variable magnetization machine 10 in the manner described above with regard to FIGS. 2 through 4. In step 1050, the processing calculates the decouple q-axis current. Then, the processing determines in step 1060 whether the magnetization or demagnetization process has been completed. If so, the processing ends in step 1070. However, if the magnetization or demagnetization process has not been completed, the processing returns to step 1030 and repeats as discussed above.

As shown in FIGS. 6 and 7, the height of the pulse A of the current signal output by adder 130 shown in FIGS. 2 and 3 is regulated so that the peak value of the pulse can achieve the value to successively obtain a desired magnetization level of the variable magnetization machine 10. As can be appreciated from FIGS. 6 and 7, the variation of the level of the current signal is greater for a small current value as shown in FIG. 6 than for a large current value as shown in FIG. 7.

FIG. 8, on the other hand, illustrates an example of the relationship between the torque of the variable magnetization machine 10 and speed of the variable magnetization machine 10 for a 50% magnetization level, a 75% magnetization level and a 100% magnetization level. Thus, variable magnetization machine controller 100 can control the magnetization level of the variable magnetization machine 10 can be in order to have a full torque output when, for example, acceleration of the vehicle is needed to pass another vehicle. The magnetization level can be increased up to 100% for max torque production, and the speed of the vehicle can be increased to a high speed while the variable magnetization machine 10 is being demagnetized. In this example, torque increases by 25% with a same current amplitude, which means that the magnetization level of the variable magnetization machine 10 increases. Furthermore, FIG. 9 is a graph illustrating an example of the magnetization level in relation to a d-axis current pulse during magnetization of the variable magnetization machine 10, and FIG. 10 is a graph illustrating an example of the magnetization level in relation to a d-axis current pulse during demagnetization of the variable magnetization machine 10.

Therefore, as can be appreciated from the descriptions herein, the variable magnetization machine controller **100** controls the magnetization level of the variable magnetization machine **10** by controlling the d-axis current pulse while controlling the q-axis current to keep torque constant. The operations performed by the variable magnetization machine controller **100** can be insensitive to the difference in each machine or the parameter deviations of the machines and is implemented easily and quickly.

FIG. **11** is a graph illustrating an example of the behavior of the d-axis current signal during a magnetization process of the variable magnetization machine **10** as performed by the embodiments of the variable magnetization machine controller as compared to conventional magnetization processes. As can be appreciated from FIG. **11**, the amplitude of the q-current i_q due to the operations of the variable magnetization machine controller **100** and the other embodiments discussed herein is less than for the conventional techniques during the magnetization process. Also, as can be appreciation from FIG. **12**, the amplitude of the q-current i_q due to the operations of the variable magnetization machine controller **100** and the other embodiments discussed herein is greater than for the conventional techniques during the demagnetization process. Hence, as can be appreciated from FIG. **8**, the speed of the variable magnetization machine **10** can be increased more rapidly at the lower magnetization level that can be more effectively achieved as shown in FIG. **12**.

Another disclosed embodiment is shown in FIGS. **13** and **14**. The variable magnetization machine controller **200** is electrically coupled to the variable magnetization machine **10** and includes an ordinary control module **202**, a magnetization current pulse control module **204**, a reducing current control module **206**, a current regulator **208** and a torque calculator **210**. The variable magnetization machine controller **200** further includes a rotary frame/stationary frame component **212**, a stationary frame/rotary frame component **214**, a pulse width modulator (PWM) voltage invertor **216**, a stator flux linkage observer **218** and current detectors **240**. Except for the reducing current control module **206** as discussed below, the components **202**, **204**, **208**, **210**, **212**, **214**, **216**, **218** and **240** are configured the same or in a similar manner as corresponding components **102**, **104**, **108**, **110**, **112**, **114**, **116**, **118** and **140** of the variable magnetization machine controller **100** discussed above and thus, their descriptions are not repeated here.

In this embodiment, the reducing current control module **206** can calculate the reducing current signal $i^*_{q\_red}$ based on the sensed or estimated stator flux linkage signals λ^r_{ds} and λ^r_{qs} (which are represented by ψ_d and ψ_q in FIG. **14**), 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 **114** (which are represented by i_d and i_q in FIG. **14**). That is, as shown in FIG. **13**, the reducing current control module **206** includes a component **2061** that receives the torque command T* and provides an output to an adder **2062**. Considering the equation

$$T^* = \frac{3}{2}\frac{P}{2}(\hat{\psi}_d i_q - \hat{\psi}_q i_d)$$

and since the torque command is known and stator flux linkage observer **218** indicates values of $\psi_d\psi_q$, the target value for the q-axis current can be calculated as

$$i_{q\_target} = \left(T^* \Big/ \left(\frac{3}{2}\frac{P}{2}\right) + i_d \psi_q\right) \Big/ \psi_a$$

and the reducing value for the 1-axis current is given as;

$$i_{q\_decouple} = i_{1\_target} - i_{q\_measured}.$$

The reducing current control module **206** further includes a multiplier **2063** that multiplies signals i_d and ψ_q and provides the multiplied signal to adder **2062**. The adder **2062** sends the added signal to a divider **2064** that divides the added signal with signal ψ_d and provides an output signal $i^*_{q\_target}$ to a subtractor **2065**. The subtractor **2065** subtracts the signal i_q from the signal $i^*_{q\_target}$ to provide an output signal $i^*_{q\_decouple}$. The signal $i^*_{q\_decouple}$ is provided to a regulator/limiter **2066**, which provides the output signal reducing current signal $i^*_{q\_red}$ to the adder **132**.

Another disclosed embodiment is shown in FIG. **15**. The variable magnetization machine controller **300**, a portion of which is shown in FIG. **15**, is electrically coupled to the variable magnetization machine **10** (not shown in FIG. **15**). In this example, the variable magnetization machine controller **300** includes an ordinary control module **302**, the magnetization current pulse control module **304**, the reducing current control module **306**, the current regulator **308** and the adders **330** and **332**. The variable magnetization machine controller **300** further includes other components similar to those of the variable magnetization machine controller **100** discussed above such as a rotary frame/stationary frame component **112**, a stationary frame/rotary frame component **114**, a pulse width modulator (PWM) voltage invertor **116**, a stator flux linkage observer **118**, current detectors **140** and other components as discussed above with regard to FIGS. **2** through **4**. Except for the magnetization current pulse control module **304** and the adder **332** as discussed below, the components **302**, **306**, **308**, **320**, **322**, **324**, **326**, **328**, **330** and the other components not shown are configured the same or in a similar manner as corresponding components **102**, **106**, **108**, **120**, **122**, **124**, **126**, **128**, **130** and the other components of the variable magnetization machine controller **100** discussed above and thus, their descriptions are not repeated here.

As shown in FIG. **15**, the magnetization current pulse control module **304** includes a cross-coupling feed-forward gain component **3041**, which provides a gain signal to adder **332**. The adder **332** therefore adds the gain signal to the q-axis current signal i^*_{qs} and the reducing current signal $i^*_{q\_red}$, and provides the reduced current signal $i^*_{q\_reduced}$ to the current regulator **308** which operates as discussed above.

Another disclosed embodiment is shown in FIG. **16**. The variable magnetization machine controller **400**, a portion of which is shown in FIG. **16**, is electrically coupled to the variable magnetization machine **10** (not shown in FIG. **16**). In this example, the variable magnetization machine controller **400** includes an ordinary control module **402**, the magnetization current pulse control module **404**, the reducing current control module **406**, the current regulator **408** and adders **430** and **432** of the variable magnetization machine controller **400**. The variable magnetization machine controller **400** further includes other components similar to those of the variable magnetization machine controller **100** discussed above such as a rotary frame/stationary frame component **112**, a stationary frame/rotary frame component **114**, a pulse width modulator (PWM) voltage invertor **116**, a stator flux linkage observer **118**, current detectors **140** and other components as discussed

above with regard to FIGS. **2** through **4**. Except for the magnetization current pulse control module **404** and the reducing current control module **406** as discussed below, the components **402**, **408**, **430** and **432**, and the other components not shown, are configured the same or in a similar manner as corresponding components **102**, **108**, **130**, **132** and the other components of the variable magnetization machine controller **100** discussed above and thus, their descriptions are not repeated here.

As further shown in FIG. **16**, the reducing current control module includes a subtractor **4061** that subtracts the torque signal T from the torque command T* and provides an output signal to variable gain compensators **4062** and **4063**. The gains of the variable gain compensators **4062** and **4063** are controlled based on the signal output by magnetization current pulse control module **404** (magnetization module) as indicted. Thus, the magnetization module **404** provides a magnetization control pulse to regulate a gain of proportional-integral compensators **4062** and **4063** according to a value of the magnetization control pulse. This can provide a wide bandwidth in a broader operating condition, and thus suppress pulsating torque. The reducing current control module **406** can thus add a reducing current to the q-axis current according to the magnetization control pulse that the magnetization module **404** outputs. This can reduce the magnitude of the reducing current, which has a lag because of feed back, and can make up for the amount by feed forward, thus reducing pulsating torque in the variable magnetization machine **10**.

The outputs of variable gain compensator **4062** is provided to an adder **4064**, and the output of variable gain compensator **4063** is provided to a z-transform component **4065**. The adder **4064** adds the output of the variable gain compensator **4062** and the z-transform component **4065**. The output of the adder **4064** is provided as the reducing current signal i*$_{q\_red}$ to the adder **432**. The adder **432** therefore adds the gain signal to the q-axis current signal i*$_{qs}$ and the reducing current signal i*$_{q\_red}$, and provides the reduced current signal i*$_{q\_reduced}$ to the current regulator **408** which operates as discussed above. Thus, as can be appreciated from the above and the graphs in FIGS. **17** and **18**, the reducing current control module **406** can operate to reduce a gain for a positive pulse for the variable magnetization machine **10** configured as a positive salient pole machine, and to increase the gain for the positive pulse for the variable magnetization machine **10** configured as a negative salient pole machine. This can stabilize the control module **406** in a broader operating condition of the variable magnetization machine **10**.

An example of a variation of the stator flux linkage observer **118** as shown in FIG. **4** is shown in FIG. **19**. The stator flux linkage observer **518** shown in FIG. **19** receives the d-axis current signal i$^r_{ds}$ and the detected q-axis current signal i$^r_{qs}$ and provides these signals to subtractors **542** and **544**. The subtractor **542** provides an output to gain components **546** and **548**, and the subtractor **544** provides an output to gain components **550** and **552**. The output of gain component **546** is provided to a z-transform component **554** and the output of gain component **548** is provided to an adder **556**. The adder **556** therefore adds the output of the gain component **548** and the output of the z-transform component **554**. Likewise, the output of gain component **552** is provided to a z-transform component **558** and the output of gain component **550** is provided to an adder **560**. The adder **560** therefore adds the output of the gain component **550** and the output of the z-transform component **558**. These

components are similar to the corresponding components **142** through **160** as shown in FIG. **4** and described above.

As further shown in FIG. **19**, the stator flux linkage observer **518** includes an adder **566** that receives the d-axis current voltage signal V$^{r*}_{ds}$ that is output by the current regulator **108** as discussed above. The stator flux linkage observer **518** further includes an adder **568** that receives the q-axis current voltage signal V$^{r*}_{qs}$ that is output by the current regulator **108**. The output of adder **566** is provided to a z-transform component **570** and the output of adder **568** is provided to a z-transform component **572**. The output of z-transform component **570** is provided to component **574**, which provides an output d-axis current signal i$_d$. The output of the z-transform component **572** is provided to a component **576**, which provides an output q-axis current signal i$_q$. Furthermore, the output of component **574** is fed back via component **578** to the adder **566**, and the output of the component **576** is fed back via a component **580** to the adder **568**. These components are similar to corresponding components **166** through **180** as discussed above.

As further shown, the output of the adder **556** is provided to another adder **581**, and the output of the adder **560** is provided to another adder **583**. The adder **581** adds the output of the adder **556** to the output of the z-transform component **572** to provide an estimated stator flux linkage signal λ$_{q\_cor}$ as discussed above. The adder **581** further provides this estimated stator flux linkage signal λ$_{q\_cor}$ to t a component **599** which provides its output to the adder **566**. The adder thus adds this output the output of adder **162** and the component output to **578**, and provides the added output to the z-transform component **170** as discussed above. The adder **583** adds the output of the z-transform component **570** to the output of the adder **560** and the output of component **594**, and provides the added output as an estimated stator flux linkage signal λ$_{d\_cor}$. The adder **583** further provides the estimated stator flux linkage signal λ$_{d\_cor}$ to a component **598** that provides an output to the adder **568**. Thus, the adder **568** adds the output of the component **598** and the output of the component **580** to the q-axis current voltage signal V$^{r*}_{qs}$ and provides the added output to the z-transform component **572**.

An example of a variation of the magnetization current pulse control module **104** as shown in FIG. **2** is shown in FIG. **20**. The magnetization current pulse control module **604** includes a module **6041**, a module **6042**, a lookup table **6043**, a current pulse generator **6044** and a subtractor **6045**. The module **6041** determines the maximum allowed signal λ$_{m\_allowed}$ based on an angle signal ω representing a detected or estimated angle of the rotor **12** and a voltage signal V$_{DC}$. The module **6042** determines the minimum feasible signal λ*$^{feasible}_{m\_level}$ based on the desired signal level λ$_{m\_desired}$ and the maximum allowed signal level λ$_{m\_allowed}$. The module **6042** outputs the minimum feasible signal λ*$^{feasible}_{m\_level}$ the lookup table target **6043** and to the current pulse generator **6044**. The lookup table **6043** outputs a target current signal i$_{d\_target}$ to subtractor **6045** based on the signal λ*$^{feasible}_{m\_level}$. The subtractor subtracts the signal i$_d$ from the target signal i$_{d\_target}$ and provides a signal Δi$_d$ to the current pulse generator **6044**. The current pulse generator **6044** outputs a pulse signal i$_{d\_mag}$ based on the signals λ*$^{feasible}_{m\_level}$ and Δi$_d$. For example, the magnetization current pulse control module **604** outputs the pulse signal i$_{d\_mag}$ to adder **130** as shown in FIGS. **2** and **3**.

Another disclosed embodiment is shown in FIG. **21**. The variable magnetization machine controller **700** shown in FIG. **21** is electrically coupled to the variable magnetization machine **10**. In this example, the variable magnetization

the reducing current module is further configured to compute the reducing current based on a difference between the torque command and the estimated torque.

3. The variable magnetization machine controller according to claim 1, wherein

the magnetization module is further configured to provide the magnetization control pulse to regulate a gain of a proportional-integral compensator according to a value of the magnetization control pulse.

4. The variable magnetization machine controller according to claim 1, wherein

the reducing current module is configured to reduce a gain for a positive pulse for the variable magnetization machine configured as a positive salient pole machine, and to increase the gain for the positive pulse for the variable magnetization machine configured as a negative salient pole machine.

5. The variable magnetization machine controller according to claim 1, wherein

the magnetization module is further configured to alter the reducing current according to the magnetization control pulse that the magnetization module outputs.

6. The variable magnetization machine controller according to claim 1, further comprising

a torque estimator configured to calculate the estimated torque based on a dq-axis vector of an estimated stator flux linkage of the variable magnetization machine and a measured current provided to the variable magnetization machine.

7. The variable magnetization machine controller according to claim 6, further comprising

a stator flux linkage estimator configured to estimate the stator flux linkage by adding a compensation value that is obtained from a value that is a difference between an output of an observer and a plant with a compensation of a proportional integral controller to produce a sum value that is then added to a state of the observer to produce a Luenburger style observer for machine electrical state variables associated with the variable magnetization machine.

8. The variable magnetization machine controller according to claim 1, wherein

the magnetization module is further configured to vary an amplitude of the magnetization control pulse according to the vector current command output by the current command module.

9. The variable magnetization machine controller according to claim 8, wherein

the magnetization module is further configured to set the amplitude of the magnetization control pulse to a value such that a sum of the magnetization control pulse and a value of current i_d^* provide a d-axis current which obtains a prescribed magnetization level for the variable magnetization machine.

10. The variable magnetization machine controller according to claim 1, wherein

the magnetization control pulse is a trapezoidal pulse which prevents a stator reaction $L_d^* di_d/dt$ of the variable magnetization machine from exceeding a value that is permitted for a voltage source that provides a voltage to the variable magnetization machine.

11. A method for controlling a variable magnetization machine controller comprising:

computing a vector current command in a dq axis based on a torque command;

applying a magnetization control pulse to a d-axis current of the vector current command; and

applying a reducing current to a q-axis current of the vector current command based on the torque command and one of an estimated torque of the variable magnetization machine and a measured torque of the variable magnetization machine.

12. The method according to claim 11, wherein

the applying of the reducing current includes calculating the reducing current based on a difference between the torque command and the estimated torque.

13. The method according to claim 11, further comprising altering reducing current according to the magnetization control pulse that the magnetization module outputs.

14. The method according to claim 11, further comprising calculating the estimated torque based on a dq-axis vector of an estimated stator flux linkage of the variable magnetization machine and a measured current provided to the variable magnetization machine.

15. The method according to claim 11, wherein

the applying of the magnetization control pulse includes varying an amplitude of the magnetization control pulse according to the vector current command.

16. The method according to claim 15, wherein

the applying of the magnetization control pulse includes setting the amplitude of the magnetization control pulse to a value such that a sum of the magnetization control pulse and a value of current i_d^* provide a d-axis current which obtains a prescribed magnetization level for the variable magnetization machine.

*   *   *   *   *