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(54) Title: A SYSTEM AND METHOD FOR PROVIDING VARIABLE HYSTERESIS TORQUE CONTROL IN DIRECT TORQUE CONTROL ALGORITHM

(57) Abstract: A system and method for controlling torque of an AC motor using a control system having a closed loop feedback mechanism is disclosed. A novel variable hysteresis DTC control algorithm that dynamically varies the torque error band to minimize torque ripples is disclosed. The upper torque limit and lower torque limit of the torque error band is dynamically varied based on a ratio of selection of active vectors and null vectors in preceding n samples. The switching variables are chosen from the selected active voltage vectors and null vectors, wherein the selection of active voltage vectors and null vectors determines a set of inverter switching variables for the voltage source inverter coupled to the AC motor. The set of inverter switching variables is provided to a pulse-width-modulation (PWM) controller to obtain modulated switching variables. The modulated switching variables and a DC reference voltage is provided to the inverter to generate AC current.

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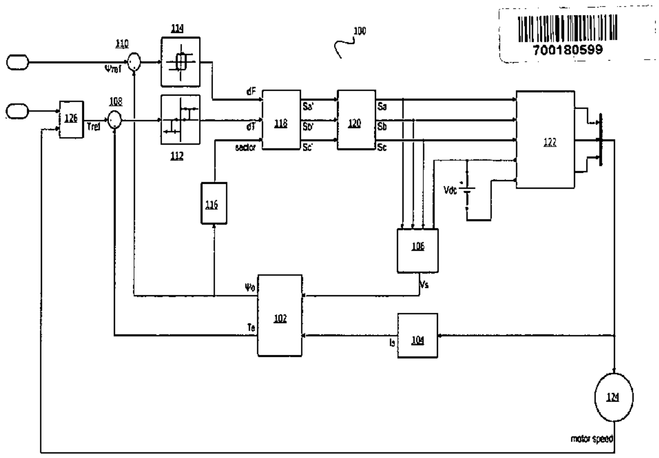

Figure 1

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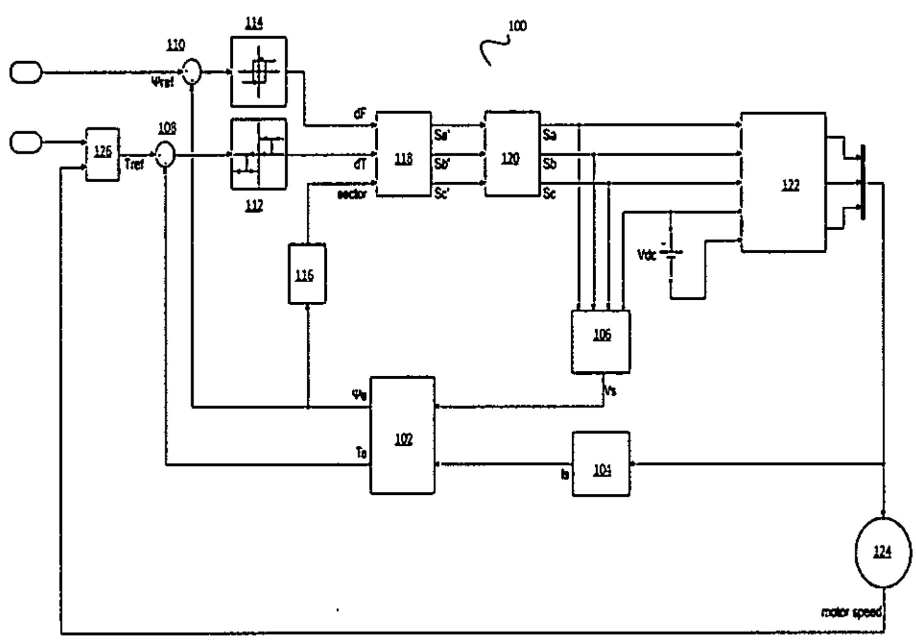
ABSTRACT

<u>A System and Method for Providing Variable Hysteresis Torque Control in Direct Torque Control Algorithm</u>

A system and method for controlling torque of an AC motor using a control system having a closed loop feedback mechanism is disclosed. A novel variable hysteresis DTC control algorithm that dynamically varies the torque error band to minimize torque ripples is disclosed. The upper torque limit and lower torque limit of the torque error band is dynamically varied based on a ratio of selection of active vectors and null vectors in preceding n samples. The switching variables are chosen from the selected active voltage vectors and null vectors, wherein the selection of active voltage vectors and null vectors determines a set of inverter switching variables for the voltage source inverter coupled to the AC motor. The set of inverter switching variables is provided to a pulse-width-modulation (PWM) controller to obtain modulated switching variables. The modulated switching variables and a DC reference voltage is provided to the inverter to generate AC current.



We Claim:

1. A method of controlling torque of an AC motor using a control system having a closed loop feedback mechanism, wherein the AC motor is coupled to a voltage source inverter, the method comprising:

estimating an instantaneous output torque at a primary sampling frequency, the primary sampling frequency being reciprocal of primary sample time period;

estimating an instantaneous stator flux at a primary sampling frequency;

comparing the estimated instantaneous stator flux and a reference stator flux to determine an instantaneous flux error;

providing the instantaneous flux error to a flux hysteresis comparator, wherein the flux hysteresis comparator outputs a flux error status;

comparing the instantaneous output torque and a reference torque to determine an instantaneous torque error;

providing the instantaneous torque error to a torque hysteresis comparator, the torque hysteresis comparator outputs a torque error status based on determining if the instantaneous torque error falls within a torque error band or exceeds an upper torque limit of the torque error band or falls below a lower torque limit of the torque error band;

selecting active voltage vectors and null vectors based on the torque error status, flux error status and sector information;

dynamically varying the upper torque limit and lower torque limit of the torque error band based on a ratio of selection of active vectors and null vectors in preceding n samples;

selecting switching variables from the selected active voltage vectors and null vectors, wherein the selection of active voltage vectors and null vectors determines a set of inverter switching variables for the voltage source inverter coupled to the AC motor;

providing the set of inverter switching variables to a pulse-width-modulation (PWM) controller to obtain modulated switching variables at a secondary sample frequency, the secondary sampling frequency being reciprocal of a secondary sample time period;

providing the modulated switching variables and a DC reference voltage to the inverter to generate AC current; and

using the generated AC current to estimate the instantaneous output torque at the primary sampling frequency.

2. The method as claimed in claim 1, wherein each of the upper and lower torque limit has inner and outer torque limits, wherein outer torque limit is the torque limit in the previous N samples and inner torque limit is a predefined percentage of outer torque limit.

3. The method as claimed in claim 2, wherein the inner torque limit is 60 percent of the outer torque limit.

4. The method as claimed in claim 1, wherein the secondary sample time period is three times faster than the primary sample time period.

5. The method as claimed in claim 1, further comprising checking intensity of torque error in order to apply a 3-vector combination of active vectors and null vectors calculated at the start of the primary sample time period and application of each vector from the 3-vector combination applied at every secondary sample time period in the primary sample time period.

6. The method as claimed in claim 1, wherein the selecting null voltage vector includes selecting between a first null voltage vector, V0, and a second null voltage vector, V7.

7. A control system for controlling torque of an AC motor, wherein the control system having a closed loop feedback mechanism, the control system comprising:

a flux and torque estimator, the flux and torque estimator outputting an instantaneous stator flux and an instantaneous output torque at a primary sampling frequency;

a flux error estimator, the flux error estimator comparing the instantaneous stator flux and a reference stator flux and outputting an instantaneous flux error;

a torque error estimator, the torque error estimator comparing the instantaneous output torque and a reference torque and outputting an instantaneous torque error;

a flux hysteresis comparator coupled to the flux error estimator, the flux hysteresis comparator outputting a flux error status;

a torque hysteresis comparator coupled to the torque error estimator, the torque hysteresis comparator outputting a torque error status based on the instantaneous torque error relative to a torque error band;

a sector estimator outputting a spatial sector;

a vector selector for selecting active voltage vectors and null vectors based on the torque error status, flux error status and sector information;

a torque band controller, the torque band controller dynamically varying the upper torque limit and lower torque limit of the torque error band based on a ratio of selection of active vectors and null vectors in preceding N samples;

a switching variable selector, the switching variable selector selecting switching variables from the selected active voltage vectors and null vectors, wherein the selection of active voltage vectors and null vectors determines a set of inverter switching variables for the voltage source inverter coupled to the AC motor;

a pulse width modulator, the pulse width modulator receiving the set of inverter switching variables to obtain modulated switching variables;

a current generator, the current generator including an inverter to receive the modulated switching variables and a DC reference voltage to generate AC current; and

a feedback generator, the feedback generator uses the generated AC current to estimate the instantaneous output torque at the primary sampling frequency.

8. The control system as claimed in claim 7, wherein the PWM controller is comprised of a field-programmable gate array (FPGA).

9. The control system as claimed in claim 7, wherein the control system uses a control algorithm comprised in a complex programmable logic device (CPLD).

10. The method as claimed in claim 1, wherein estimating the instantaneous output torque and the instantaneous stator flux further comprising determining an applied stator voltage and measuring a stator current.

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FIELD OF INVENTION

The present invention relates generally to an electric motor and, more particularly, to a variable hysteresis direct torque control motor controller for use with an AC electric motor.

BACKGROUND

AC machines are primarily controlled by Field Oriented Control (FOC) and Direct Torque Control (DTC) algorithms. FOC algorithms are very complex. DTC algorithm on the other hand are simple and do not require any complex calculations and mathematical transformations for operation. However, the DTC algorithm results in considerable torque ripples at the output which is highly unwanted.

Variable hysteresis DTC algorithm results in lower torque ripples as compared to conventional DTC algorithms. Moreover, it can be used as an alternative to FOC algorithm which is in-turn is used due to its low torque ripples feature. Hence, variable hysteresis DTC algorithm overcomes the disadvantages of conventional DTC and FOC algorithms.

The variable hysteresis DTC algorithm can be used without the necessity of faster processors, since the prediction of 3 vector combination is done at every primary sample time. Moreover, the variable hysteresis DTC algorithm also has the same advantages of a conventional DTC algorithm wherein, very few motor parameters need to be known, no coordinate transforms are required, no separate modulators are needed and no PI current controllers are required.

Therefore, a novel variable hysteresis DTC control system and algorithm is proposed that enables the torque error band to be varied dynamically and minimizes the torque ripples to a great extent.

SUMMARY OF THE INVENTION

Exemplary embodiments of the invention disclose a system and method for controlling torque of an AC motor using a control system having a closed loop feedback mechanism wherein the AC motor is coupled to a voltage source inverter. The disclosed system and method estimates an instantaneous output torque and an instantaneous stator flux at a primary sampling frequency. The estimated instantaneous stator flux and a reference stator flux is compared to determine an instantaneous flux error. The instantaneous flux error is provided to a flux hysteresis comparator wherein the flux hysteresis comparator outputs a flux error status. The instantaneous output torque and a reference torque is compared to determine an instantaneous torque error. The instantaneous torque error is provided to a torque hysteresis comparator wherein the torque hysteresis comparator outputs a torque error status based on determining if the instantaneous torque error falls within a torque error band or exceeds an upper torque limit of the torque error band or falls below a lower torque limit of the torque error band. The active voltage vectors and null vectors are selected based on the torque error status, flux error status and sector information. The upper torque limit and lower torque limit of the torque error band is dynamically varied based on a ratio of selection of active vectors and null vectors in preceding n samples. The switching variables are chosen from the selected active voltage vectors and null vectors, wherein the selection of active voltage vectors and null vectors determines a set of inverter switching variables for the voltage source inverter coupled to the AC motor. The set of inverter switching variables is provided to a pulse-width-modulation

(PWM) controller to obtain modulated switching variables. The modulated switching variables and a DC reference voltage is provided to the inverter to generate AC current. The generated AC current is used to estimate the instantaneous output torque at the primary sampling frequency.

BRIEF DESCRIPTION OF DRAWINGS

Other objects, features, and advantages of the invention will be apparent from the following description when read with reference to the accompanying drawings. In the drawings, wherein like reference numerals denote corresponding parts throughout the several views:

Figure 1 illustrates a schematic diagram for variable hysteresis torque control system of AC motors with dynamically variable torque error band, according to an exemplary embodiment of the invention;

Figure 2 illustrates a process for variable hysteresis torque control with dynamically variable torque error band, according to an exemplary embodiment of the invention; and

Figure 3 illustrates instantaneous error torque waveform of the variable hysteresis torque control, according to an exemplary embodiment of the invention.

DETAILED DESCRIPTION OF DRAWINGS

The following description with reference to the accompanying drawings is provided to assist in a comprehensive understanding of exemplary embodiments of the invention. It includes various specific details to assist in that understanding but these are to be regarded as merely exemplary. Accordingly, those of ordinary skill in the art will recognize that various changes and modifications of the embodiments described herein can be made without departing from the scope and spirit of the invention. In addition, descriptions of well-known functions and constructions are omitted for clarity and conciseness.

According to embodiments of the invention, a system and method for controlling torque of an AC motor is disclosed. The system and method for controlling the torque of the AC motor uses a control system having a closed loop feedback mechanism wherein the AC motor is coupled to a voltage source inverter.

Figure 1 illustrates a schematic diagram of an exemplary control system 100 for variable hysteresis torque control with dynamically variable torque error band, according to an embodiment of the invention.

According to an embodiment, the control system may use a control algorithm comprised in a complex programmable logic device (CPLD).

According to an embodiment, in control system 100, the electromagnetic flux and torque may be independently controlled and optimized in order to keep the stator flux linkage and torque errors within the flux and torque hysteresis bands. A flux and torque estimator module 102 may estimate an instantaneous stator flux and an instantaneous motor output torque at a primary sampling frequency. According to an embodiment, the primary sampling frequency may be reciprocal of a primary sample time period.

According to an embodiment, the flux and torque estimator module 102 may take stator voltage and currents as input and may estimate an instantaneous stator flux and an instantaneous motor output torque.

According to an embodiment, the instantaneous stator flux may be estimated using formulae given below:

$$\lambda_{\alpha\beta} = \lambda_\alpha + j\lambda_\beta = \int v_{\alpha\beta} - R_s i_{\alpha\beta}\, dt$$

$$\lambda_\beta = \int v_\beta - R_s i_\beta\, dt$$

$$\lambda_\alpha = \int v_\alpha - R_s i_\alpha\, dt$$

According to an embodiment, the instantaneous output torque may be estimated using formulae given below:

$$T_e = \frac{3}{2} p(\lambda_\alpha I_\beta - \lambda_\beta I_\alpha)$$

According to another embodiment, a stator current estimator 104 may measure 3-phase current that is supplied to the machine and transforms it to a stationary frame of reference using Clarke transformations i.e. 3 phase components (I_A I_B I_C) are transformed into stator components (I_α I_β). Accordingly, the stator current may bc calculated using formula:

$$I_{est} = I_\alpha + jI_\beta = \frac{2}{3}\left(I_A e^{j0} + I_B e^{j\frac{2\pi}{3}} + I_C e^{j\frac{4\pi}{3}}\right)$$

According to another embodiment, a stator voltage estimator 106 may measure 3-phase voltage that is supplied to the machine and transforms it to a stationary frame of reference using Clarke transformations i.e. 3 phase components (V_A V_B V_C) are transformed into stator components ($V\alpha$ $V\beta$). Accordingly, the stator voltage may be calculated using formula:

$$V_{est} = V_\alpha + jV_\beta = \frac{2}{3}\left(V_A e^{j0} + V_B e^{j\frac{2\pi}{3}} + V_C e^{j\frac{4\pi}{3}}\right)$$

At block 110, the instantaneous stator flux, Ψe, and a reference stator flux, Ψ_{Ref}, may be compared to output an instantaneous flux error, e_Ψ. The instantaneous flux error, e_Ψ, may be fed into a flux hysteresis comparator 114 to output a flux error status, d_Ψ. According to an embodiment, the flux hysteresis comparator 114 may be a two-level controller, i.e., the comparator 114 may yield a value of either a -1 or 1. According to an embodiment, the value -1 may indicate the flux to be decreased and the value 1 may indicate the flux to be increased.

At block 108, the estimated output torque, Te, and a reference torque, T_{Ref}, may be compared to output an instantaneous torque error, eT. According to an embodiment, the reference torque may be calculated by a PI controller by comparing the reference speed with the actual speed of the AC machine 124. The instantaneous torque error, eT, is fed into a torque hysteresis comparator 112 which outputs a torque error status, dT. According to an embodiment, the torque hysteresis comparator 112 may be a three-level controller, i.e., the comparator 112 may yield a value of 1, −1 or 0, depending upon whether the torque is to be increased, decreased or remain unchanged. According to an embodiment, the value -1 may indicate the torque to be decreased, the value 1 may indicate the flux to be increased and the value 0 may indicate the torque to be constant.

At block 116, a sector may be calculated from an estimated flux angle.

At block 118, vectors (V0-V7) may be selected based on the flux error status, torque error status and sector calculation using a vector selection algorithm in the vector selector 118.

According to an embodiment, the vectors V1-V6 may be called as active vectors and V0 & V7 may be callcd as null vectors.

According to an embodiment, the vector selector 118 generates a three-vector combination that gets applied for the sample time.

According to an embodiment, the vector selector 118 may receive input from the torque error estimator and a current width of the torque hysteresis band. Using the current torque hysteresis band width, an inner width and an outer width may be calculated at the same instant where outer width is equivalent to the calculated width and inner width is a predefined percentage of outer width. According to an embodiment, the inner width may be 60 percentage of the outer width.

The vector selector 118 may check a position of the error torque in the bands. From analysis, it was found that whenever the error torque is within the torque band then null vectors are used, but they may be used more often or else the system might oscillate. The vector selector 118 may include a torque band controller that dynamically varies the torque band of torque hysteresis comparator 112 based on a ratio of selection of active vectors and null vectors in preceding N samples and determines if the torque band is to be increased or decreased. According to an embodiment, we dynamically vary the limit such that in past N samples if more null vectors are selected, the torque band is decreased, and if more active vectors are selected, the torque band is increased. According to an exemplary embodiment, if a ratio of active to null vectors is more than 3, it implies that more active vectors are selected than required, so the band should be increased by 5% of the previous width. According to another exemplary embodiment, if ratio of active to null vectors is less than 3, it implies that more null vectors are selected than required, so the band should be decreased by 5% of the previous width.

According to an embodiment, the vector selector 118 may further check intensity of torque error in order to apply a 3-vector combination of active vectors and null vectors calculated at the start of the primary sample time period and application of each vector from the 3-vector combination applied at every secondary sample time period in the primary sample time period.

According to an exemplary embodiment, if the error torque is in the inner band and active vector V3 is selected by the vector selection algorithm then final 3 combination vector may be 377 for entire sampling time. If the error torque is in between inner and outer band, and active vector V3 is selected by the vector selection algorithm then final 3 combination vector may be 337 for entire sampling time. If the error torque is outside the outer band and active vector V3 is selected by the vector selection algorithm then final 3 combination vector may be 333 for entire sampling time.

According to an embodiment, the vector selection algorithm enables to achieve automatic minimum torque band limit as per the speed and the torque of the motor.

The vector selector 118 may further include a switching variable selector that selects switching variables from the selected active voltage vectors and null vectors, wherein the selection of active voltage vectors and null vectors determines a set of inverter switching variables for the voltage source inverter coupled to the AC motor.

A pulse width modulator controller 120 may receive a set of inverter switching variables to obtain modulated switching variables. According to an embodiment, the modulated switching variables may be obtained at a secondary sampling frequency wherein the secondary sampling frequency is reciprocal of a secondary sample time period. According to another embodiment, the secondary sample time period may be three times faster than the primary sample time period. According to an embodiment, the PWM may consist of a pulse width modulator (PWM). According to an embodiment, the PWM may consist of a FPGA and generates a PWM signal to a voltage source inverter 122. According to an exemplary embodiment, the PWM signal may consist of a first vector from a three vector combination for first Ts/3 sample time, a second vector from the three vector combination for the second Ts/3 sample time and a third vector from the three vector combination for the third Ts/3 sample time.

A current generator includes a voltage source inverter 122 to receive the modulated switching variables and a DC reference voltage to generate AC current.

A feedback generator may use the generated AC current and provide it to the stator voltage estimator 106 to estimate the instantaneous output torque at the primary sampling frequency.

Figure 2 illustrates a block diagram of the process 200 for variable hysteresis torque control with dynamically variable torque error band, according to an embodiment of the invention.

At step 202, an instantaneous output torque and an instantaneous stator flux at a primary sampling frequency may be estimated.

At step 204, the estimated instantaneous stator flux may be compared with a reference stator flux to determine an instantaneous flux error. Similarly, the estimated instantaneous output torque may be compared with a reference torque to determine an instantaneous torque error.

At step 206, instantaneous flux error may be provided to a flux hysteresis comparator to output a flux error status and the instantaneous torque error may be provided to a torque hysteresis comparator to output a torque error status. The torque hysteresis comparator may output a torque error status based on determining if the instantaneous torque error falls within a torque error band or exceeds an upper torque limit of the torque error band or falls below a lower torque limit of the torque error band.

At step 208, active voltage vectors and null vectors may be selected based on the torque error status, flux error status and sector information.

At step 210, the upper torque limit and lower torque limit of the torque error band may be dynamically varied based on a ratio of selection of active vectors and null vectors in preceding n samples.

At step 212, switching variables may be selected from the selected active voltage vectors and null vectors. The selection of active voltage vectors and null vectors may determine a set of inverter switching variables for the voltage source inverter coupled to the AC motor.

At step 214, the set of inverter switching variables may be provided to a pulse-width-modulation (PWM) controller to obtain modulated switching variables at a secondary sample frequency.

At step 216, the modulated switching variables and a DC reference voltage may be provided to the inverter to generate AC current.

At step 218, the generated AC current may be used to estimate the instantaneous output torque at the primary sampling frequency.

Figure 3 illustrates a torque oscillation waveform of the variable hysteresis torque control, according to an exemplary embodiment of the invention. Figure 3 further illustrates working of the vector selection algorithm, according to another exemplary embodiment of the invention.

The vector selection algorithm may generate a vector depending on flux error status, torque error status and sector calculations. According to an embodiment, the vector selection algorithm may further generate a three-vector combination which is dependent on intensity of error and a vector selected for the current sample. According to another embodiment, intensity of error may be dependent on estimated error torque and current width of torque hysteresis band (dT).

In Figure 3, dT may describe the error torque band that is dynamic in nature. The waveform is the instantaneous error torque that is a difference between a reference and estimated torque. According to an embodiment, dT is further divided into two bands say inner and outer band. According to another embodiment, the inner band is a predefined percentage of the outer band. According to an exemplary embodiment, the inner band may be 60% of outer band and outer band may be the current width of the torque hysteresis comparator.

According to an exemplary embodiment, points A1, A2 and A3 may be the test points where vectors may be selected. According to an embodiment, a time stamp between A1, A2 and A3 may be Ts.

According to an exemplary embodiment, at point A1, error torque may be above the outer torque band and vector selected by vector selection algorithm is 5, so the final 3 vector combination 555 may be selected for the duration of Ts. The final vector combination 555 implies first vector (viz 5) out of '3 vector combination' 555 may be applied for first Ts/3 sample time, second vector (viz 5) out of '3 vector combination' 555 may be applied for second Ts/3 sample time and third vector (viz 5) out of '3 vector combination' 555 may be applied for third Ts/3 sample time. According to an embodiment, the application of vector 5 for entire T_s sampling time may reduce the difference between reference torque and estimated torque.

According to another exemplary embodiment, after Ts time, at point A2, say the vector selected by vector selection algorithm may be 3 and since the error torque is between outer and inner band the vector selection algorithm may decide to apply '3 vector combination' 377 for duration T_s, i.e. vector 3 for $T_s/3$ time, vector 7 for second $T_s/3$ time and vector 7 for remaining $T_s/3$ time. The application of vector 7 after $T_s/3$ shows the error torque may decrease. According to another exemplary embodiment, if '3 vector combination' 333 is used, the error may extend above the error torque band at the end of T_s.

According to yet another exemplary embodiment, at point A3, vector 2 may be selected by vector selection algorithm and since error torque is below outer torque band, the algorithm may decide to apply '3 vector combination' 222 for duration Ts.

These combinations are kept in a database and is used by the vector selection algorithm to vary dT (error torque band) after every N samples (N*Ts) depending on the ratio of Active to Null vectors.

The disclosed control algorithm enables the error torque to be within the range. Moreover, the range may be optimized to provide the least torque ripples at the output.

In the drawings and specification there has been set forth preferred embodiments of the invention, and although specific terms are employed, these are used in a generic and descriptive sense only and not for purposes of limitation. Changes in the form and the proportion of parts, as well as in the substitution of equivalents, are contemplated as circumstances may suggest or render expedient without departing from the spirit or scope of the invention.

Throughout the various contexts described in this disclosure, the embodiments of the invention further encompass computer apparatus, computing systems and machine-readable media configured to carry out the foregoing systems and methods. In addition to an embodiment consisting of specifically designed integrated circuits or other electronics, the present invention may be conveniently implemented using a conventional general purpose or a specialized digital computer or microprocessor programmed according to the teachings of the present disclosure, as will be apparent to those skilled in the computer art.

Appropriate software coding can readily be prepared by skilled programmers based on the teachings of the present disclosure, as will be apparent to those skilled in the software art. The invention may also be implemented by the preparation of application specific integrated circuits or by interconnecting an appropriate network of conventional component circuits, as will be readily apparent to those skilled in the art.

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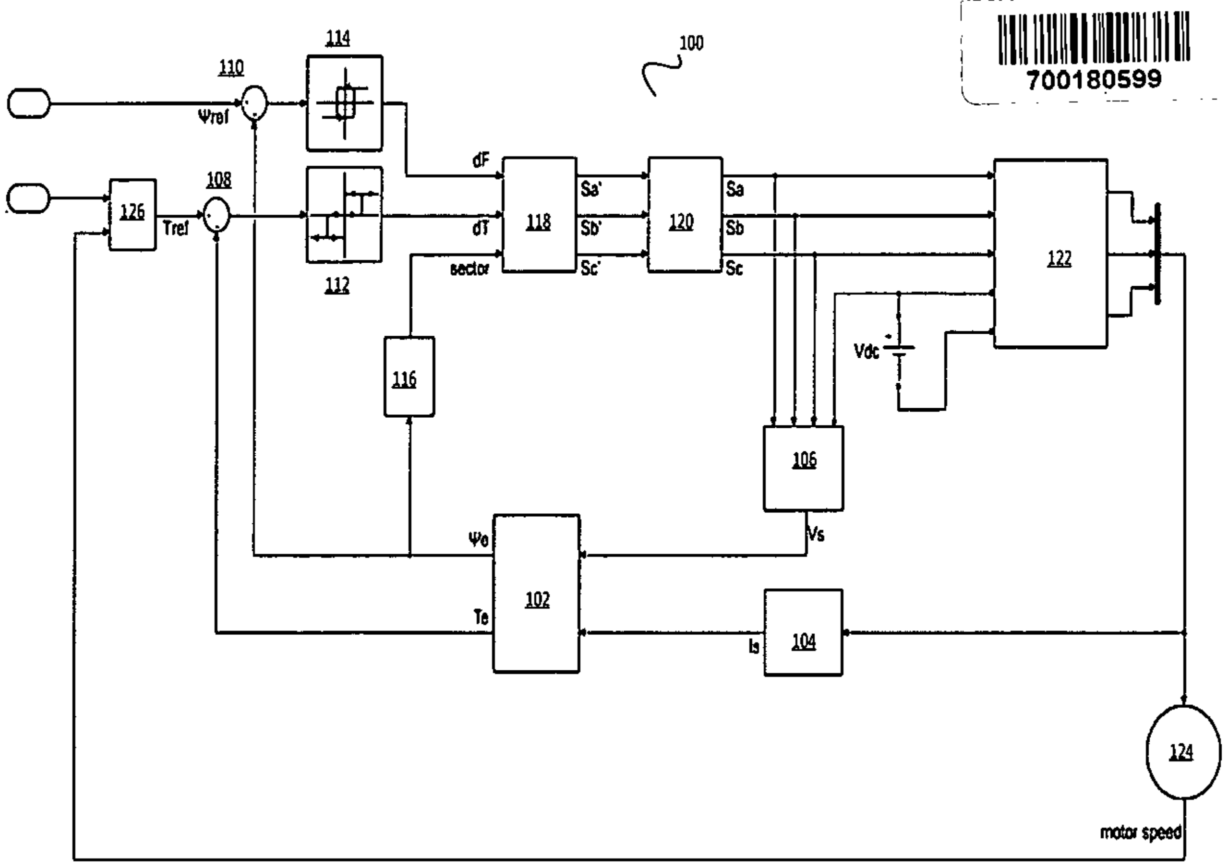

Figure 1

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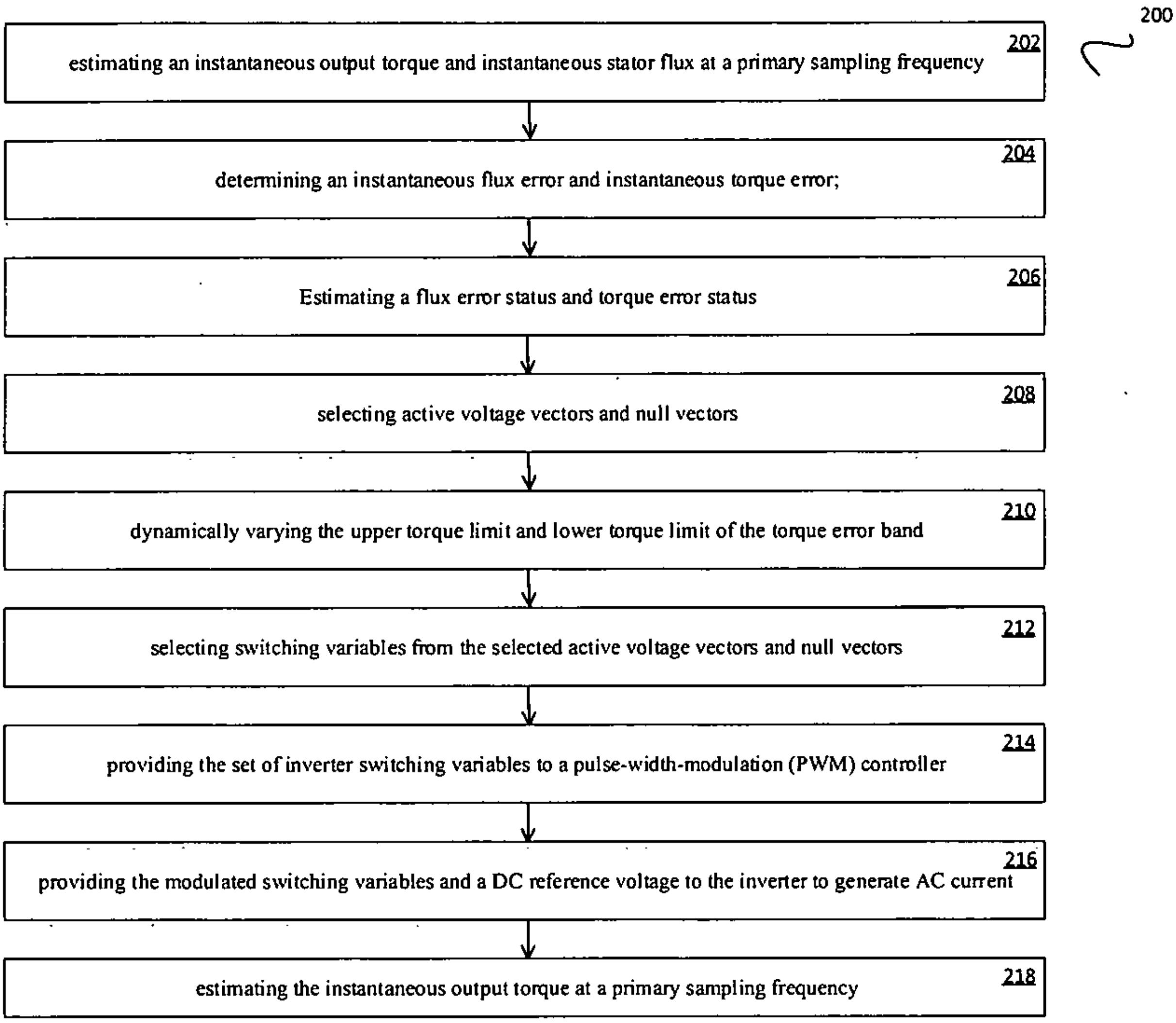

Figure 2

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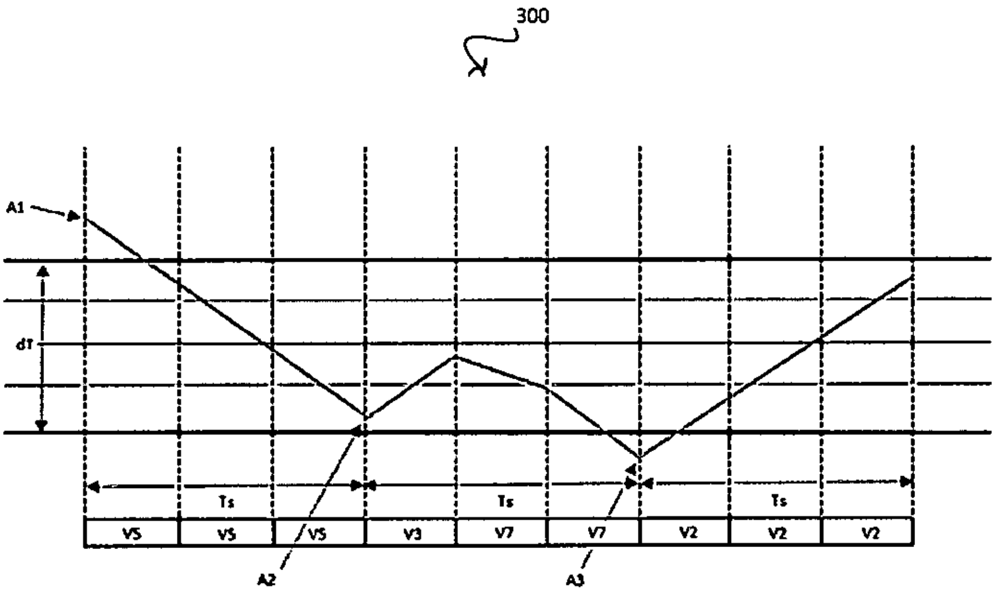

Figure 3

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