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(54) Title: MOTOR CONTROL SYSTEM

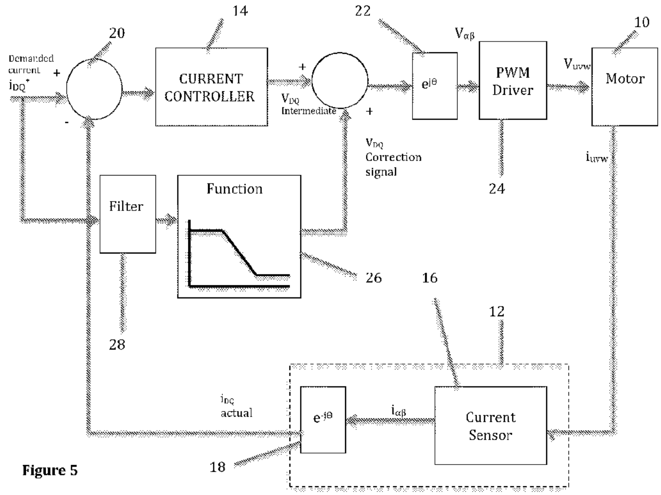

Figure 5

(57) Abstract: A control system for an electric motor comprises a controller which receives as an input a demanded motor current and produces at an output an intermediate voltage demand signal, a voltage demand signal correction means arranged to generate a voltage demand correction signal, and a combining means arranged to combine the intermediate voltage demand signal and the voltage demand correction signal to produce an actual voltage demand signal that is applied to the motor by pulse width modulation of the switches of a motor bridge driver. The correction signal compensates for unwanted non-linearities caused by interlock delays in the switching of the motor bridge switches.

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Motor Control System

Field of the Invention

The present invention relates to the control of electric motors, and in particular to the control of the voltage and current flowing in a PWM controlled electric motor.

Background to the Invention

A closed loop current controller for an electric motor 1 typically takes the form shown in Figure 1, where, using vector control provided by a suitable controller, a voltage is applied to each phase winding of the motor and the resultant generated currents measured. The measured currents are compared with a demanded current, and the difference is fed into a controller, typically a closed loop PI controller, which outputs the voltages that are to be applied to the motor in order to minimise the difference. A signal which gives the electrical position of the motor is also required in order to ensure that the voltages are applied to the motor with the correct phase. In the system of Figure 1 a position sensor is shown but the present invention is equally applicable to a position sensorless system, where the position signal is estimated from other sensor measurements.

The voltage applied to each of the motor phases is typically modulated using pulse width modulation PWM of the switches of a multiphase bridge circuit. A typical bridge circuit 2 is shown in Figure 2 of the drawings. The bridge comprises, for each phase of the motor, an upper switch connecting the phase to a positive supply rail, and a lower switch connecting the phase to an earth or negative supply rail. The PWM signals are applied to the bridge by a PWM driver 3 which controls the opening and closing of the switch. At any time the switches in an arm of the bridge may all be closed, or one may be open circuit and the other closed circuit so that the phase is connected to positive or negative supply rails. In a known prior art system the input to the PWM driver comprises the voltage output from the PI controller.

It is important to ensure that the top switch in any arm of the bridge is not ON at the same time as the bottom switch in that arm is ON, because this will short the terminals of the power supply. Therefore, an interlock delay is required between the switching of the switches. This is shown in Figure 3 of the drawings. The interlock is a period where both switches are off and introduces a dead time in which no current flows into or out of the phase.

The applicant has appreciated that the use of an interlock delay distorts the PWM pattern and this introduces a current in the motor that varies asymmetrically around the zero motor current condition. This is shown in Figure 4 of the drawings where it can be seen that a plot of the demand voltage output from the controller, against the actual motor current exhibits a non-linear behaviour around zero current. This effect is significant over a range of low currents.

Where the motor is used in an electric power steering system, the applicant has appreciated that this non-linear behaviour has a negative effect on the steering feel perceived by the driver. Furthermore, the applicant has appreciated that the non-linearity may vary from bridge to bridge, so not only is the effect of the non-linearity perceived it can feel different from one bridge driver to the next.

Summary of the Invention

The present invention provides a control system for an electric motor, the control system comprising a controller which receives as an input a demanded motor current, the controller producing at an output an intermediate voltage demand signal, a voltage demand signal correction means arranged to generate a voltage demand correction signal, and a combining means arranged to combine the intermediate voltage demand signal and the voltage demand correction signal to produce an actual voltage demand signal that is applied to the motor by pulse width modulation of the switches of a motor bridge driver, the voltage demand correction signal at least partially compensating for unwanted non-linearity in the relationship between the intermediate voltage demand signal and the motor current caused by interlock delays in the switching of the motor bridge switches.

The applicant has appreciated that the modification of the voltage output from the controller by the use of an appropriate feed forward term within the control loop of the system can be used to remove or at least modify the effects of switching interlock dead time around the zero current point of the motor.

The voltage demand correction signal may compensate by wholly removing the effect of non-linearity due to the interlock delays. Removing the non-linearity improves the steering feel at low motor currents and especially around zero current.

Alternatively the voltage demand correction signal may modify the effect of non-linearity to leave a known amount of non-linearity between the intermediate voltage demand signal and the motor current. For example, it may not remove the non-linearity completely but may bring it into line with a predefined desired non-linearity. This may be useful where a steering system has been tuned to a bridge driver circuit with a certain non-linearity only for a different bridge circuit with a different non-linearity to be used, which may not be compatible with the tuning. As tuning is expensive, this may be used during the life cycle of a steering system to keep the non-linearity in a known range as new bridge drivers are developed.

The controller may comprise a PI controller and may include, at an input stage, a comparator which generates a current difference signal dependent upon the difference between the demanded motor current and the actual current flowing in the motor.

It is preferred that the correction signal generating means generates a voltage demand correction signal that is a function of the demanded motor current, taking as an input a signal that is derived from the demanded motor current. This is preferred because the demanded motor current signal will typically be less noisy than the actual measured currents. The voltage demand correction signal may be a function of the current demand signal in the stationary DQ frame.

The voltage demand correction signal generating means may alternatively generate a voltage demand correction signal that is a function of the actual measured current signal.

The current signal (demanded or actual) prior to being input to the correction signal generating means may be passed through a filter so that the bandwidth of the signal fed to the correction signal generating means does not exceed the bandwidth of the controller.

The cut off frequency of the filter may be matched to the controller bandwidth. It may comprise a first order low pass filter. The filter may be of the form:

$$\frac{a}{1+bz^{-1}}$$

Where a and b are constants.

In one arrangement for instance, the function may use $a=1$ and $b=0.5$ as constants.

The voltage demand correction signal may be defined, for each filtered demand (or actual) current value as the difference between the ideal motor current/intermediate demand voltage and the actual motor current/intermediate demand voltage characteristic. The voltage demand correction signal may therefore comprise a voltage value.

The values of the voltage demand correction signal may be generated using a look up table stored in memory, which holds a set of values of input values (either the demanded current or the actual current as appropriate) and a corresponding set of correction signal voltage values. Where the demanded (or actual) motor current is not identical to a stored current value in the table, a correction signal may be generated by interpolating from the two nearest stored current values, ideally one above and one below the demanded current value.

The system may include multiple look up tables stored in a memory and a selection means for selecting one of the look up tables dependent on a property of the bridge driver. This allows the controller to compensate easily for different bridge drivers. The voltage demand signal correction means may be arranged to apply the selected look up table when generating the correction signal.

The selection means may comprise a user operable interface through which the user can manually select the appropriate table.

Of course, instead of a look up table the correction means may use other methods of generating a correction signal from an input current demand signal or measured current. For instance, a non-linear mathematical function may be used that defines the relationship between the current and the correction signal.

The memory may be programmable and the controller may be arranged to learn the non-linearity between the intermediate demand voltage output from the controller and the motor current around zero current due to the interlock delay so as to generate a relationship between demanded motor current value and the correction signal value that is required to correct or at least partially correct the non-linearity. The controller may include a test mode during which the learning occurs.

The control system may include a current sensing means arranged to produce a current sensing output indicative of the electric current in the motor.

The motor may have stationary windings and a rotor, which rotates relative to the windings. The current sensing means may comprise a current sensor arranged to measure current in the motor windings. The current may be measured as two components in the frame of reference of the windings. The current sensing means may comprise transformation means arranged to transform the measured current into the frame of reference of the rotor, for example as torque-generating and non-torque-generating components.

The controller may be arranged to output an intermediate demanded voltage in a frame of reference which is stationary, which may be the frame of reference of the windings and defined, for example, as α and β components, or in a rotating frame of reference, which may be the frame of reference of the rotor, and defined, for example, as D and Q axis components.

Where the intermediate demand voltage is in the DQ frame, the voltage demand correction signal may also be in the DQ frame, and similarly the demanded current signal.

Preferred embodiments of the present invention will now be described by way of example only with reference to the accompanying drawings.

Figure 1 is a diagram of a known closed loop current control system for a motor;

Figure 2 is a diagram showing the switches of a bridge driver used in the system of Figure 1;

Figure 3 is a diagram showing the effect of interlock delay between opening and closing of the switches in one arm of the bridge, leading to dead time in which no current flows in a phase of the motor;

Figure 4 is a plot showing the voltage demand signal applied to the bridge driver versus the actual motor current with the non-linearity due to interlock delay clearly visible;

Figure 5 is a control circuit in accordance with the present invention that corrects the effect of interlock delay;

Figure 6 is a diagram showing the relationship between the value of a correction signal and the demanded current as defined by a look up table stored in a memory; and

Figure 7 shows the effect applying the correction signal has on the linearity of the motor.

Description of a Preferred Embodiment

Referring to Figure 5 a motor 10 is controlled by a closed loop motor current control system according to an embodiment of the invention comprising a current sensing system 12 and a current controller 14. The current sensing system 12 comprises a current sensor 16 arranged to measure the currents i_U, i_V, i_w in the three phases of the motor, which comprise stationary windings, and output a signal indicative of the current vector in the stationary coordinates having α and β components. The output of the current sensor may be corrected for noise if required so as best to indicate the actual current in the motor phases. The current sensing system further comprises a coordinate transformation block 18 arranged to convert the current vector from the α and β components in the stationary reference from, to D and Q components i_D and i_Q defining the current vector in the rotor reference frame, which rotates relative to the fixed windings, with the Q axis current being the torque generating component and the D axis current being non-torque-generating. A comparator 20 receives the D and Q currents from the current sensing system 12 and compares them with demanded D and Q current components to generate an error signal. The current controller 14 receives the current error and outputs a demanded voltage vector, in the form of a D and Q axis voltage demand V_{DQ} calculated to reduce the current error so that the measured current vector approaches the demanded current vector. A further transformation block 22 receives the voltage demand from the current controller and converts it to α and β components $V_{\alpha\beta}$ which are input to a PWM driver 24 which is arranged to control a number of switches of a motor drive bridge to apply voltages to the phase windings of the motor 10 in a PWM pattern which produces the net voltage in the windings having a magnitude and direction corresponding to the voltage demand vector.

The PWM driver converts the voltage demand signal fed into the driver into PWM signals for the top and bottom switches of a motor drive bridge. Figure 2 shows a typical bridge. To ensure that the top switch in any arm of the bridge is not open when the bottom switch of the same arm is open, an interlock delay is introduced. This is applied either in the PWM driver on by the bridge itself. This introduces non-linearity to the PWM pattern and to the motor current around zero current because the PI controller, like all controllers of that kind, assumes a linear relationship between the voltage demand and the motor current. This expected linear relationship between current and voltage in an ideal motor with no interlock is governed by Ohms law where $V=IR$. i.e. V is proportional to I because the resistance of a phase winding of an ideal motor is constant. The effect of the interlock is to introduce times where the motor resistance is in effect very large (in practice around 8 times the normal resistance) which causes the current in the motor for a given voltage to be lower than expected.

The control system is therefore arranged to apply a correction signal to the output of the PI controller which modifies the demand voltage, producing an actual demand voltage in the DQ frame that is fed to the PWM driver in place of the intermediate voltage demand output from the controller 14. The correction signal corrects for the effect of the interlock delay.

The correction signal is generated by a correction signal generating means 26, as a function of the current demand signal IDQ, and is based on values stored in a look up table in a memory. The input to the correction signal generating means in the example of Figure 5 is the demanded motor current.

Prior to feeding the demanded motor current signal into the voltage demand correction means it is passed through a filter. In this example a discrete first order low pass filter 28 is used. Of course this filter could form a part of the correction means. The function of the filter is to ensure that the bandwidth of the demanded current signal that is used to generate the voltage demand correction signal does not exceed the bandwidth of the controller 14. By ensuring the bandwidth of the correction signal does not exceed that of the intermediate voltage demand signal which would have a detrimental effect on the behaviour of the PI controller.

Figure 6 is a plot of demanded current I_{DQ} against correction signal voltage in the DQ frame for correcting the non-linearity shown in Figure 4. Note that the plot is in effect an inverse of the non-linearity that is to be corrected and the values for the correction signal are equal to the difference between the ideal characteristic and the actual characteristic at any point along the V/I plot curve of Figure 4.

The correction signal is added to the intermediate voltage demand signal in this example to produce the actual voltage demand signal fed to the PWM driver 24. In an alternative it could have the opposite sign to the intermediate voltage demand signal and be subtracted from that signal. In other arrangements the correction signal could be a scaling factor that is multiplied with the intermediate demand signal, or which is divided into the intermediate demand signal.

Figure 7 is a plot showing the effect of the voltage demand correction signal on the relationship between the intermediate voltage demand signal generated by the controller and the actual current in the motor. As can be seen it is far more linear and closer to the ideal because of the correction applied by the correction signal. The actual voltage demand signal is no longer a linear function of the demanded current, the non-linearity compensating for the reverse non-linearity in the V-I transfer function of the bridge.

The control system may advantageously be used in an electric power steering system where the motor applies an assistance torque to the steering that assists a driver to turn the wheel. Correcting the non-linearity around the zero current may greatly improve the steering feel as perceived by a trained driver.

Whilst the embodiment shown fully removes the effect of the non-linearity around zero current, or at least gets close to fully removing it, the invention may be applied such that the non-linearity is not fully removed but instead is corrected to bring the non-linearity into line with a predefined non-linearity. For instance, where a system has been designed around a first non-linear function that is characteristic of a known bridge circuit and then a different bridge circuit with a different non-linearity is used, the invention may be used to make the different bridge circuit appear to give the same performance as the first bridge. This ensures that the motor performs consistently regardless of which bridge is used. In some applications, such as an electric power steering system, this may be critical to providing consistent performance and a good steering feel for a given steering tune, removing the need to retune the steering system which is a time consuming process.

CLAIMS

1. A control system for an electric motor, the control system comprising a controller which receives as an input a demanded motor current, the controller producing at an output an intermediate voltage demand signal, a voltage demand signal correction means arranged to generate a voltage demand correction signal, and a combining means arranged to combine the intermediate voltage demand signal and the voltage demand correction signal to produce an actual voltage demand signal that is applied to the motor by pulse width modulation of the switches of a motor bridge driver, the voltage demand correction signal at least partially compensating for unwanted non-linearity in the relationship between the intermediate voltage demand signal and the motor current caused by interlock delays in the switching of the motor bridge switches.

2. A control system according to claim 1 in which the controller comprises a PI controller that includes, at an input stage, a comparator which generates a current difference signal dependent upon the difference between the demanded motor current and the actual current flowing in the motor.

3. A control system according to claim 1 or claim 2 in which the correction signal generating means generates a voltage demand correction signal that is a function of the demanded motor current, taking as an input a signal that is derived from the demanded motor current.

4. A control system according to claim 3 in which the current demand signal input to the voltage demand signal correction means is passed through a filter so that the bandwidth of the signal fed to the correction signal generating means does not exceed the bandwidth of the controller.

5. A control system according to claim 4 in which the cut off frequency of the filter is matched to the controller bandwidth.

6. A control system according to claim 4 of claim 5 in which the filter comprises a first order low pass filter.

7. A control system according to any preceding claim in which the voltage demand correction signal compensates by wholly removing the effect of non-linearity due to the interlock delays.

8. A control system according to claim 1 in which the voltage demand correction signal modifies the effect of non-linearity to leave a known amount of non-linearity between the intermediate voltage demand signal and the motor current.

9. A control system according to any preceding claim in which the values of the voltage demand correction signal are generated using a look up table stored in a memory, which holds a set of values of input current values and a corresponding set of correction signal voltage values.

10. A control system according to claim 9 including more than one look up table stored in a memory and a selection means for selecting one of the look up tables dependent on a property of the bridge driver.

11. A control system according to any preceding claim in which the controller is arranged to output an intermediate demanded voltage in the frame of reference of the rotor, and defined as D and Q axis components, and wherein the voltage demand correction signal is also be in the DQ frame.

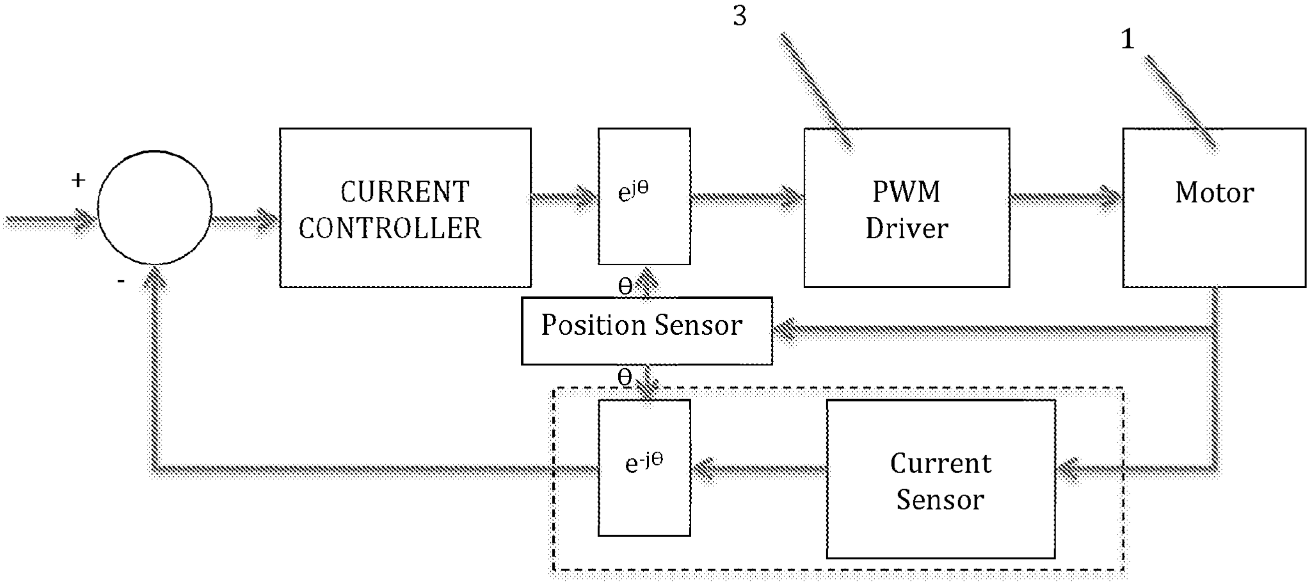

Figure 1

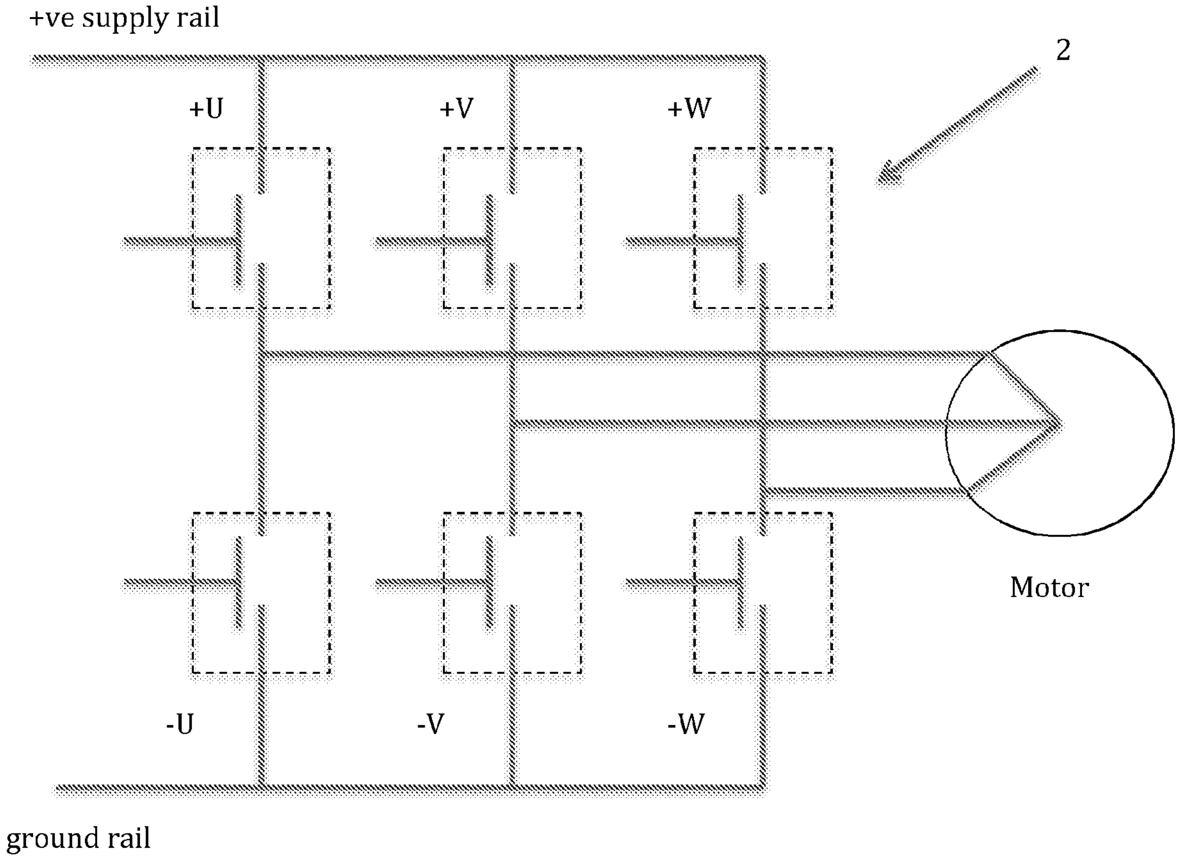

Figure 2

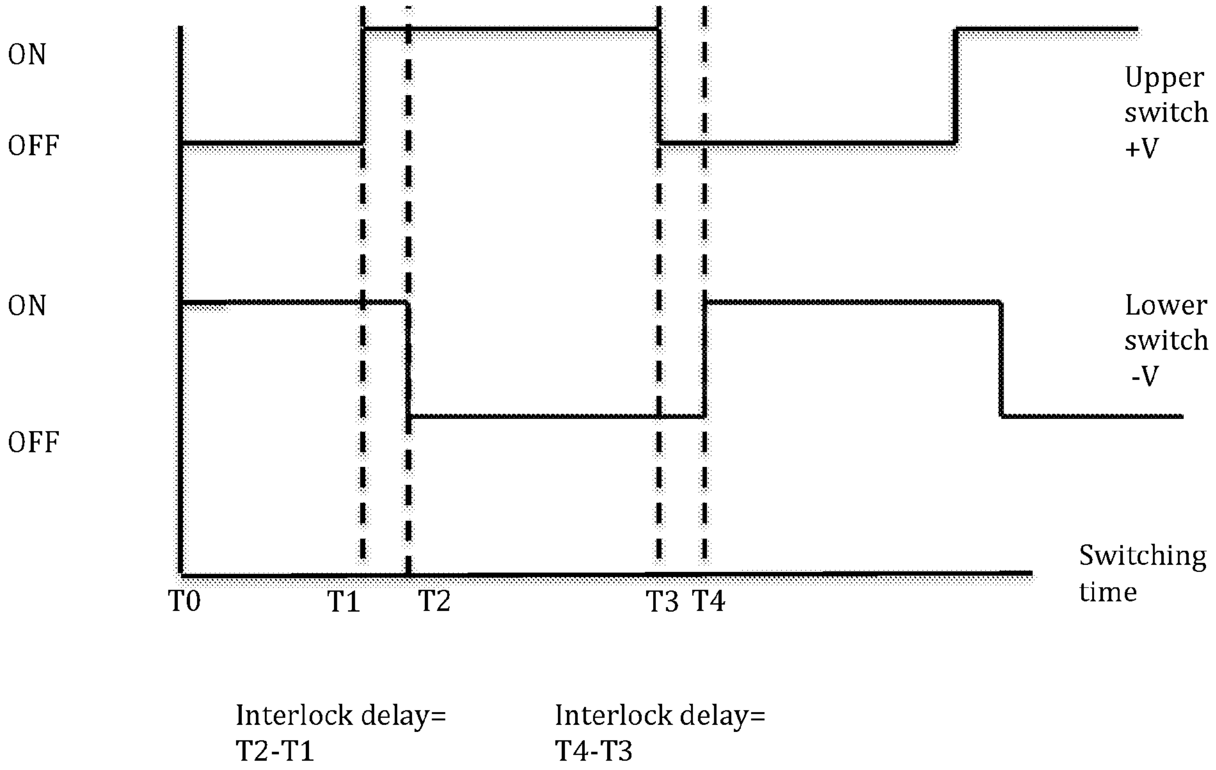

Figure 3

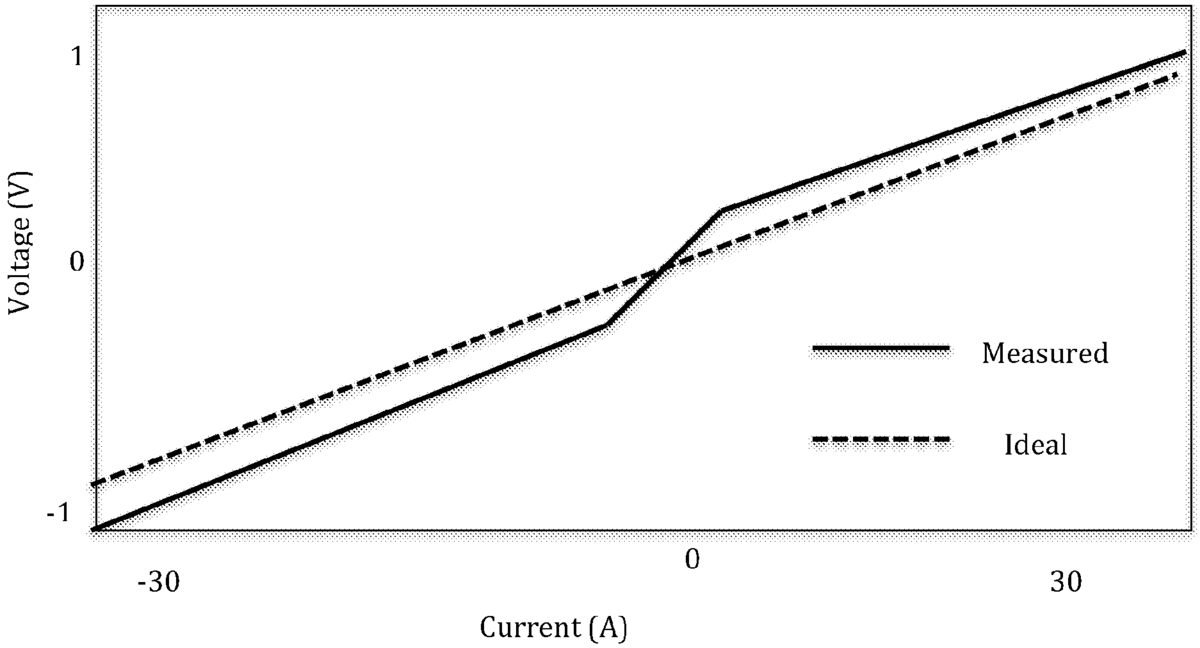

Figure 4

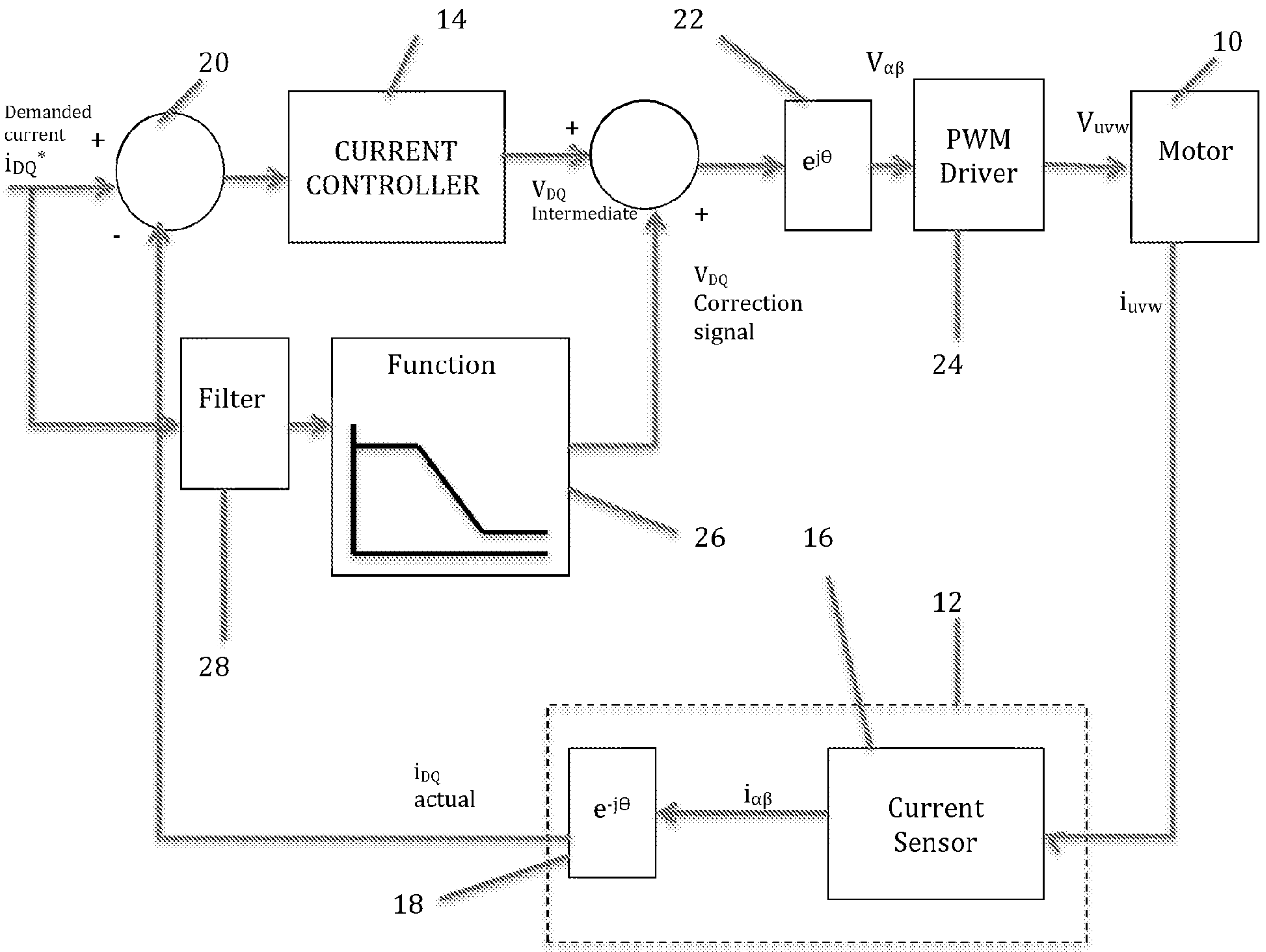

Figure 5

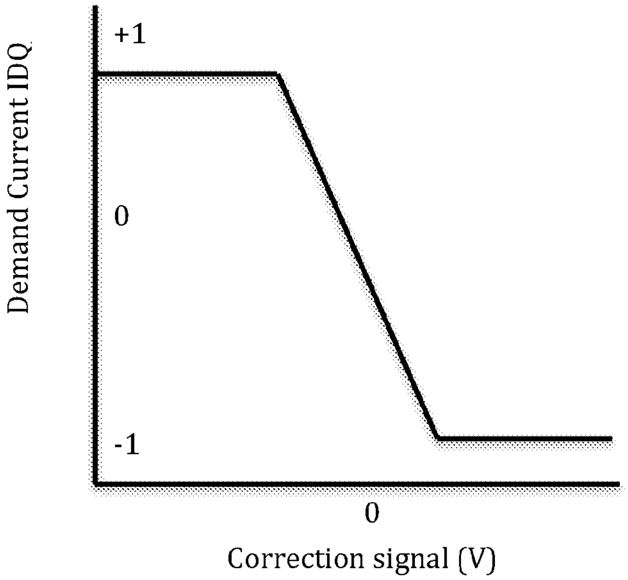

Figure 6

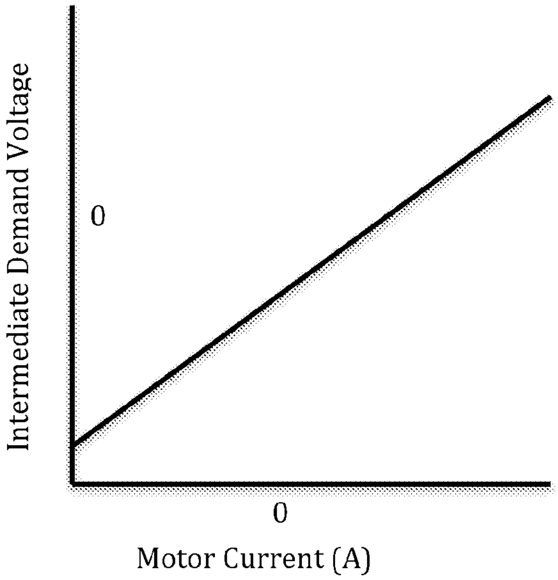

Figure 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2016/053961

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02P21/00
ADD. H02M1/38

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

B. FIELDS SEARCHED

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

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 872 710 A (KAMEYAMA TOMOHISA [JP]) 16 February 1999 (1999-02-16) column 1, line 29 - column 2, line 36; figures 6-8 column 4, line 49 - column 5, line 11; claims 1,2; figure 1 -----	1-11

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

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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

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

"&" document member of the same patent family

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

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International application No
PCT/GB2016/053961

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