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[Continued on next page]

(54) Title: TORQUE CONTROL FOR AC MOTORS

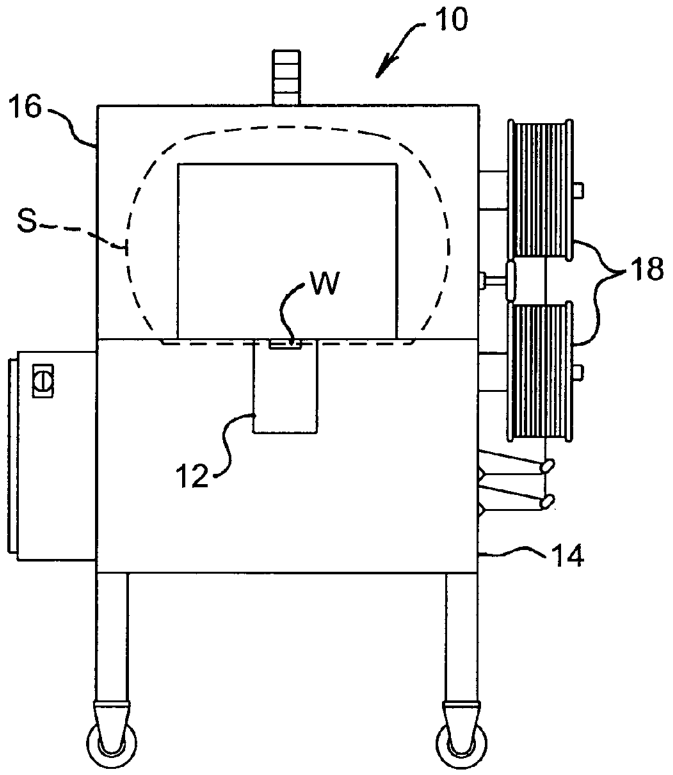

FIG 1

(57) Abstract: A system for controlling the torque of a polyphase alternating current (AC) induction motor, including: a triggerable bi-directional electronic switch (50) for conducting an AC current, when the switch is triggered, to the AC induction motor (28); a pulse width modulated (PWM) signal generator (46) for generating a PWM signal; and zero cross circuitry (58, 60, 62) for detecting zero cross points of an AC power supply (44) which occur during pulses of the PWM signal, the zero cross circuitry generating an output pulse for triggering the bi-directional electronic switch at each detected zero cross point, wherein the duty cycle of the PWM signal is set to control the average torque of the AC induction motor.

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TORQUE CONTROL FOR AC MOTORS

FIELD OF THE INVENTION

The present invention relates to torque control for alternating current (AC) polyphase induction motors.

BACKGROUND OF THE INVENTION

Torque control for AC motors in industrial applications can be implemented electromechanically or electronically. For example, tension control in a strapping machine used in the packaging industry is provided by an electromagnetic clutch that controls the torque applied to a rotatable winder driven by an AC drive motor. However, the clutch wears and requires regular maintenance to provide accurate and consistent tension control. Torque control for AC motors can be implemented electronically with modern variable speed drives with complex internal models, but require costly and not very effective electronics.

Accordingly, there exists a need for a simple and low cost electronic solution for torque control of AC induction motors in industrial applications, and particularly for torque control of the most common AC 3 phase induction motors without rotor position feedback.

SUMMARY OF THE INVENTION

One aspect of the present invention provides a system for controlling the torque of a polyphase alternating current (AC) induction motor. The system includes a triggerable bi-directional electronic switch for conducting an AC current, when the switch is triggered, to the AC induction motor. Except that this system also includes a pulse width modulator (PWM) signal generator for generating a PWM signal, and zero cross circuitry for detecting zero cross points of an AC power supply which occurs during pulses of the PWM signal. The zero cross circuitry generates an output pulse for triggering the bi-directional electronic switch at each detected zero cross point. Significantly, the duty cycle of the PWM signal is set to control the average torque of the AC induction motor.

The bi-directional electronic switch may include a bank of TRIACs, each TRIAC connecting a single phase of the AC power supply to a single phase of the AC induction motor.

The bi-directional electronic switch and zero cross circuitry may be implemented in a solid state relay.

The PWM generator may be a programmable controller with a controllable PWM output function. The PWM generator may be a programmable logic controller.

The AC power supply must be low impedance direct AC mains supply.

Another aspect of the invention provides a method for controlling the torque of a polyphase AC induction motor. The method includes the steps of: generating a PWM signal; detecting zero cross points of an AC power supply which occur during pulses of the PWM signal; triggering a bi-directional electronic switch for conducting an AC current to the AC induction motor at each detected zero cross point; and setting the duty cycle of the PWM signal to control the average torque of the AC induction motor.

In yet another aspect of the invention provides a winding machine having a rotatable winder driven by a polyphase AC induction motor, including a system for controlling the torque of the motor as described hereabove. In one or more embodiments, the winding machine may be a strapping machine.

A still further aspect of the invention provides a method for controlling tension in a strapping machine having a rotatable winder driven by a polyphase AC induction motor via a variable torque electromagnetic clutch. The method includes the steps of: directing transmitting torque from the motor to the winder without clutch slip; and controlling the tension in a strap mounted on the winder by controlling the torque to the motor by a method as described hereabove.

Whilst the invention is suitable for use in controlling tension in a strapping machine having a rotatable winder driven by a polyphase AC induction motor via a variable torque electromagnetic clutch, it is to be understood that the invention is also applicable to a number of other industrial processes, such as force producing platens that provide variable pressure for compression and squaring. The invention is suitable for use with many processes where a pulsating and variable torque is required for a short duty cycle.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be further described by way of example only with reference to the accompanying drawings, in which:

Figure 1 is a front view of an exemplary strapping machine illustrating selected components and arrangements of the machine;

Figure 2 is a schematic illustration of the strapping head forming part of the strapping machine shown in Figure 1;

Figure 3 is a circuit diagram of a system for controlling the torque of a 3-phase AC induction motor forming part of the strapping machine shown in Figure 1;

Figure 4 shows various wave forms generated at different points in the system shown in Figure 3;

Figure 5 illustrates operation of the system shown in Figure 3 under different duty cycles; and

Figures 6 and 7 are exemplary torque-speed curves for standard AC motors suitable for use with the system shown in Figure 3.

Referring now to Figure 1, there is shown generally a strapping machine 10 having a strapping head 12. The strapping machine 10 includes a frame 14 for supporting a strapping chute 16 around which the strap S is advanced during a strapping operation. One or more strap dispensers 18 supplies strap material S to the strapping head 12. The overall arrangement and operation of such a strapping machine is disclosed, for example, in United States Patent 4,605,456 and 5,299,407.

The strapping head 12 is that portion of the machine 10 that withdraws or pulls the strap S from the dispenser 18, feeds the strap S through the chute 16, grasps the leading edge E of the strap so as to bring it into contact with a trailing portion T, and tensions the trailing portion T so as to tension the load L. In the illustrated embodiment, the strapping machine 10 includes a separate welding head (shown schematically at W) for sealing the overlapping strap portions E, T to one another to effect a seal, a schematic illustration of which is shown in Figure 2. A cutter (not shown) severs the strap S at the supply end (namely, the trailing end E) to free the strap load L.

The strapping head 12 includes a plurality of rollers 22, 24 and a rotatable winder 26. The rollers 22, 24 serve to both feed strap S through the chute 16 around the load L, and to retract or rewind (wind) the strap S to tension the strap S around the L. In the illustrated embodiment, the rollers 22, 24 include a driven roller 22 and an idler roller 24 that rotates only in frictional cooperation with the driven roller 22.

The rollers 22, 24 are operably connected to a drive (not shown) such as a belt drive or a direct drive, to provide rotational movement to the driven roller 22. In the illustrated embodiment, a 3-phase AC induction motor 28 is configured for driving the rotatable winder 26 either directly or via a gearbox and is operably connected to the winder 26 by a variable torque electromagnetic clutch 30. Such an arrangement will be understood and appreciated by those skilled in the art.

Figure 3 depicts one embodiment of the system 40 for controlling the torque of the AC induction motor 28. The system 40 may be implemented with off-the-shelf electronic components mounted in a panel supplying power to the strapping machine 10. The system 40 includes an Alan Bradley 156-A10BB3 solid state contactor 42 coupled between a 3-phase mains AC power supply 44 and the AC induction motor 28, and an Alan Bradley 1763-L16BBB MicroLogix 1100 programmable logic controller (PLC) 46 coupled to the mains AC power supply 44 and the solid state contactor 42. A power supply 48 is connected between the mains AC power supply 44 and the PLC 46, in order to provide a 24 volt DC power supply to drive the PLC 46. It will be appreciated that the system can alternatively be implemented with other commercially available solid state relays having zero cross switching functions, and other commercially available programmable PWM generators.

The solid state contactor 42 includes a triggerable bi-directional electronic switch 50 for conducting an AC current, when the switch is triggered, from the mains AC power supply 44 to the AC induction motor 28. The electronic switch 50 includes a bank of TRIACs 52, 54 and 56 (otherwise known as anti-parallel Silicon-Controller Rectifiers or SCRs). Each TRIAC 52, 54 and 56 connects a single phase of the mains AC power supply 44 to a single phase of the AC induction motor 28.

Zero cross circuits 58, 60 and 62 are respectively associated with the TRIACs 52, 54 and 56. Each zero cross circuit is an electrical circuit that starts operation with the AC load voltage/current at close to the zero point. The purpose of each zero cross circuit is to start conduction of each associated TRIAC as soon as possible, so that the input and output voltages and waveforms are as close as possible. The point where the line voltage is zero volts is called the zero cross point. The TRIACs 52, 54 and 56 and associated zero cross circuits 58, 60 and 62 are respectively connected to the main AC power supply 44 by means of contacts 64, 66 and 68 driven by a relay of coil whose role is only to select the phase direction that determines the motor direction.

The PLC 46 includes a Pulse Width Modulation (PWM) output function to control the duty cycle, or “turn-on time”, of signals PWM0 at 10 Hz and PWM1 at 100 Hz. The signal PWM0 is applied to the control point 70 so that the the triacs are selected for conduction by the zero cross circuit, thereby conducting each TRIAC between a single phase of the mains AC power supply 44 and a single phase of the AC induction motor 28, during the turn-on time of the PWM signal. The signal PWM1 at 100 Hz at a variable duty cycle is used to provide conventional control of the electromagnetic clutch 30 by means of a DC solid state relay coil 72 and associated semiconductor switch (not shown) connecting the electromagnetic clutch 30 to the AC induction motor 28. This is equivalent to providing variable current flux into the clutch from any other source.

Operation of the torque control system 40 will now be explained with reference to Figure 4, which shows various waveforms generated at different points in the torque control system 40. The waveform 80 represents a single phase only of the voltage from the mains AC power supply 44. For the sake of clarity, a single phase only is represented, although similar waveforms will be understood to exist for each of the 3-phases supplied to the AC induction motor 28. The mains voltage waveform 80 has an essentially sinusoidal form and a frequency of typically 50 to 60 Hz mains frequency depending upon the country in question.

The waveform 82 represents the signal PWM0. The PWM0 waveform has a known frequency of, in this case, 10 Hz (9 -13 Hz). A single pulse is generated each cycle of the PWM0 waveform. The duration or width of that pulse is able to be set by programming of the PLC 46 to thereby set the duty cycle of the PWM0 waveform.

During pulses of the waveform PWM0, the zero cross circuits 58, 60 and 62 are operable. Accordingly, as shown in the waveform 84, the zero cross circuits 58, 60 and 62 generate output pulses for triggering the TRIACs 52, 54 and 56 at each detected zero cross point in the mains voltage waveform 80. The output pulses of the waveform 84 cause the TRIACs 52, 54 and 56 to conduct in either direction, so that the output waveform 86 applied to the AC induction motor 28 closely matches the mains voltage waveform 80 during conduction of the TRIACs 52, 54 and 56.

As can be seen in Figure 5, varying the duty cycle of the waveform PWM0 will vary the period during which each of the TRIACs 52, 54 and 56 conducts during each cycle, and thereby control the torque applied to the AC induction motor 28. Because the 10 Hz PWM0 waveform is not mains-locked, the temporal position at which each zero cross point occurs within pulses of the waveform PWM 0 will vary.

It should be understood that the various waveforms shown in this Figure are illustrative only. In an actual implementation of the torque control system 10, the shape and relative timing of the various waveforms will notably be affected by the interaction of the three phases on each other. Moreover, a current lag will be introduced due to the inductive nature of the load (i.e. AC induction motor 28).

When the strapping machine 10 is at the tensioning phase of the strapping operation, the waveform PWM0 is set up for the required strap tension by adjusting its duty cycle from 0% to 100% that corresponds to the tension required. At other times, the waveform PWM0 is set to provide 100% duty cycle or any other desired value as the application may demand for the control of strap movement around the strap track or chute system of the strapping machine 10.

The frequency of the waveform PWM0 is optimal between 9 and 13 Hz, and is proportionally selected according to the mains frequency in use and to achieve asymmetry between the waveform PWM0 and the mains frequency. For example, a frequency of 10 Hz can be selected for the waveform PWM0 at 50 Hz mains frequency, whilst a frequency of 12 Hz can be selected for the waveform PWM0 at a 60 Hz mains frequency. The waveform PWM1 at a frequency of 100 Hz can be maintained at a 100% duty cycle during the tensioning phase to ensure that the clutch transmission acts with zero slip or in other words transmits full power.

It will be appreciated that each of the three TRIACs and associated zero cross circuits provide power control with the resolution or the complete mains half cycle. The net amount of time during which the TRIACs 52, 54 and 56 conduct is varied according to the duty cycle of the signal PWM0 so as to provide a proportionally greater number of complete positive and negative half cycles, without a break, that is statistically determined by the asynchronous firing of the zero cross circuits 58, 60 and 62 controlling operation of the TRIACs 52, 54 and 56. The gaps generated by missing half cycles shown in Figure 5 contributed to the power modulation required. In this example, the power modulation is one a reduction basis only.

Because the 10 Hz PWM0 waveform is not mains-locked, and the number of output pulses generated by the zero cross circuits 58, 60 and 62 will vary over a number of pulses in the PWM0 waveform, the duty cycle of the PWM 0 waveform can be set to control the average torque of the AC induction motor 28 over a number of consecutive PWM0 pulses. Although the number of half-cycles of current supplied to the AC induction motor 28 can vary each time the zero crossing circuits are activated, over time the number of half-cycles will average out to achieve the desired torque setting corresponding to the selected duty cycle of the signal PWM0.

By way of example, a 53% duty cycle set up on PWM0 would in practice be achieved in the above-described example in approximately 1-2 seconds with 53 half cycles being triggered in the first second and a further 53 cycles in the next second making a total of 106 half cycles from a total mains half cycle opportunity of 200 corresponding to 2 seconds of 50Hz source. This will relate to 10 to 20 PWM0 pulses being provided at 10 Hz.

Figures 6 and 7 illustrate torque-speed curves of different 3-phase AC induction motors. These curves illustrate that such 3-phase AC induction motors generate required torque at even very low angular velocity, which is essential to strap tensioning. The high currents needed for the operation of such induction motors are readily available for short duty from the 3-phase AC mains supply 44. Up to 7 x full-load current can be demanded periodically through the TRIACs 52, 54 and 56, allowing the induction motor 28 to provide its whole range of torque from 0 to its maximum as provided on its load curves which is significantly higher than its normal torque at locked rotor. Because of the intermittent power feed from the TRIACs 52, 54 and 56, the torque is pulsed through to provide a final average value. This torque pulsing also assists in the strap tensioning process.

The torque produced by the AC induction motor 28 would typically follow one of the torque curves of three-phase induction motors shown in these Figures, particularly at zero to very low rotational speeds where substantial torque is available from low impedance mains sources.

Embodiments of the invention provide simple and low cost torque control for AC induction motors using duty cycle regulation based PWM pulsed power control. Embodiments of the invention can be implemented with off-the-shelf components and retrofitted to a wide variety of existing industrial AC motor applications.

Embodiments of the invention are advantageous in precision applications like winding and/or tensioning machines, for example capstanbased tensioning machines, where an accurate and consistent level of applied force is critical. For example, embodiments of the invention can advantageously precise and repeatable tension control in strapping machines used in the packaging industry for positioning, tensioning and sealing straps around loads such as metals, piles of timber, newspapers, magazines, bales of hay and cotton, etc.

AC induction motors used in conventional strapping machines for the application of strap tension are normally engaged to rotatable winders through electromechanical clutches. This clutch function wears with time and is not repeatable or reliable. The clutch is employed because the motor torque can not be compensated without a very expensive servo motor control system with feedback due to the speed of response needed. Embodiments of the invention allow for the motor to directly control the tension value without the use of a clutch in slip duty. This has been made possible by the pulsed torque exhibited by the induction motor that is averaged in application, from virtually zero to its maximum rated value and in almost direct proportion to the duty cycle. The torque curves of the motor are responsible for the development of the variable torque experienced by the power pulse method of the invention.

Embodiments of the present invention therefore enable clutch controlled tensioning in conventional strapping machines to be converted or changed over to a power pulsed modulation scheme performed directly on the induction motor prime mover. This provides an improved strapping machine having an accurate and repeatable tensioning process with minimum maintenance. Such a strapping machine includes a single digital setpoint that is substantially invariable with age due to the elimination of wear factors when used in diverse industrial environments. The pulsed power torque control of the invention uses mains 50/60 Hz waveforms to provide controlled power in a statistical framework where probabilities are biased from 0 to 100T to provide an equivalent percentage variation for tension. Furthermore, the pulsed power torque control provides for pulsation in the winder that further improves the tensioning by the strapping machine.

Embodiments of the pulsed power torque control of the invention advantageously provide short duty modulated power into induction motors for a range of purposes, for example, strap tensioning, package compression, pallet squaring, and any purpose requiring less than maximum power in a controlled manner using AC induction motors for a short duty cycle.

Other advantages of embodiments of the invention include:

- more accurate control of tension or other required parameter;
- consistent and repeatable application of power for the control of tension or other parameter;
- drawing greater tension around corners of packages as it is an integrating process that has peaks that favour the application;
- increased opportunity for the deployment of standard strapping or other purpose machine in to a wider range of industry and product types;
- removal of variability between old and new strapping machines;
- reduction and substantial elimination of maintenance interventions due to controlled loading like strap tensioning through clutches and brakes;
- simplification of control circuits because tensioning clutch function has been modified to be digitally on or off only;
- reduction in tensioning clutch maintenance requirements because it operates in zero slip;
- increased reliability of the overall strapping machine.

The embodiments have been described by way of example only and modifications are possible with the scope of the invention disclosed.

CLAIMS:

1. A system for controlling the torque of a polyphase alternating current (AC) induction motor, including:

a triggerable bi-directional electronic switch for conducting an AC current, when the switch is triggered, to the AC induction motor;

a pulse width modulated (PWM) signal generator for generating a PWM signal; and

zero cross circuitry for detecting zero cross points of an AC power supply which occur during pulses of the PWM signal, the zero cross circuitry generating an output pulse for triggering the bi-directional electronic switch at each detected zero cross point,

wherein the duty cycle of the PWM signal is set to control the average torque of the AC induction motor.

2. A system according to claim 1, wherein the bi-directional electronic switch includes a bank of TRIACs, each TRIAC connecting each a single phase of the AC power supply to a single phase of the AC induction motor.

3. A system according to either one of claims 1 or 2, wherein the bi-directional electronic switch and zero cross circuitry are implemented in a solid state relay.

4. A system according to any one of the preceding claims, wherein the PWM generator is a programmable controller with a controllable PWM output function.

5. A system according to any one of the preceding claims, wherein the PWM generator is a programmable logic controller.

6. A system according to any one of the preceding claims, wherein the AC power supply is a low impedance direct AC mains supply.

7. A method for controlling the torque of a polyphase alternating current (AC) induction motor, including:

generating a pulse width modulated (PWM) signal;

detecting zero cross points of an AC power supply which occur during pulses of the PWM signal;

triggering a bi-directional electronic switch for supplying an AC current to the AC induction motor at each detected zero cross point; and

setting the duty cycle of the PWM signal is set to control the average torque of the AC induction motor.

8. A winding machine having a rotatable winder driven by a polyphase alternating current (AC) induction motor, including a system according to any one of claims 1 to 6 for controlling the torque of the motor.

9. A winding machine according to claim 8, wherein the winding machine is a strapping machine.

10. A method for controlling tension in a strapping machine having a rotatable winder driven by a polyphase AC induction motor via a variable torque electromagnetic clutch, the method including:

directly transmitting torque from the motor to the winder without clutch slip; and

controlling the tension in a strap mounted on the winder by controlling the torque to the motor by a method according to claims 1 to 7.

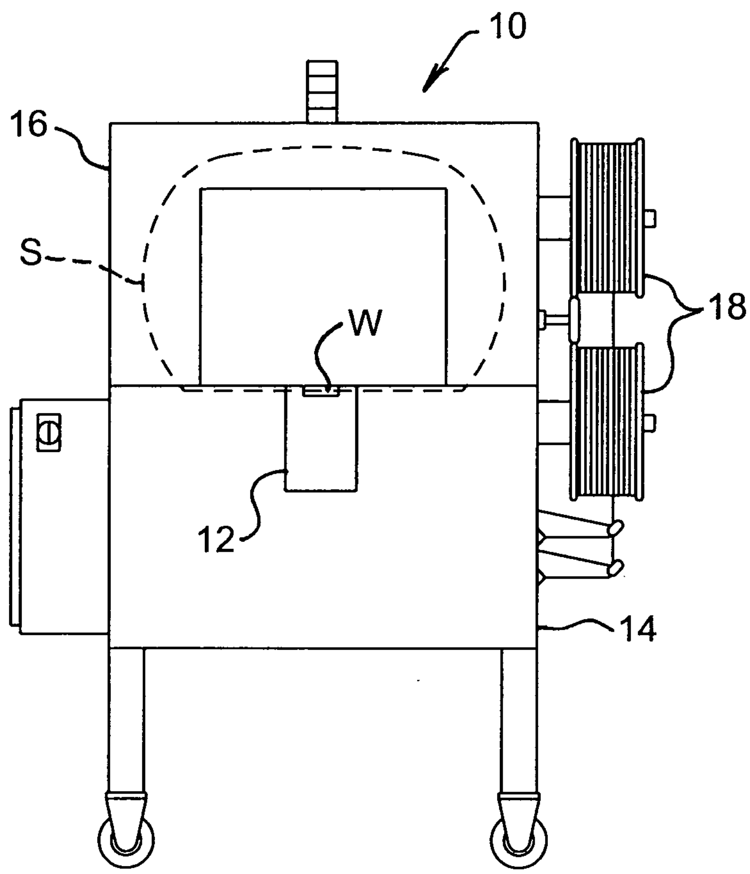
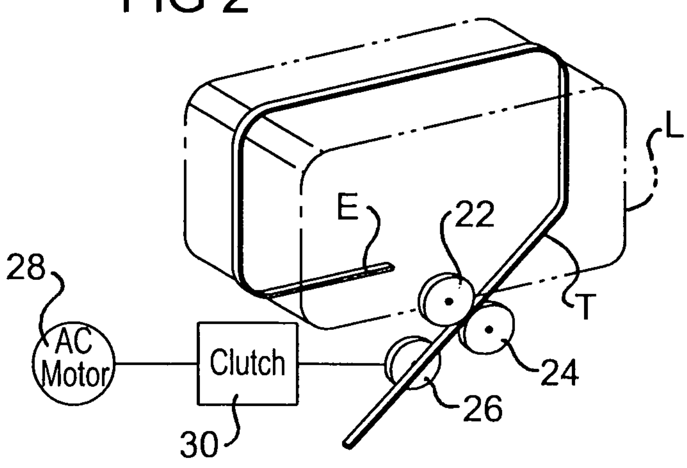


FIG 1

FIG 2



Substitute Sheet
(Rule 26) RO/AU

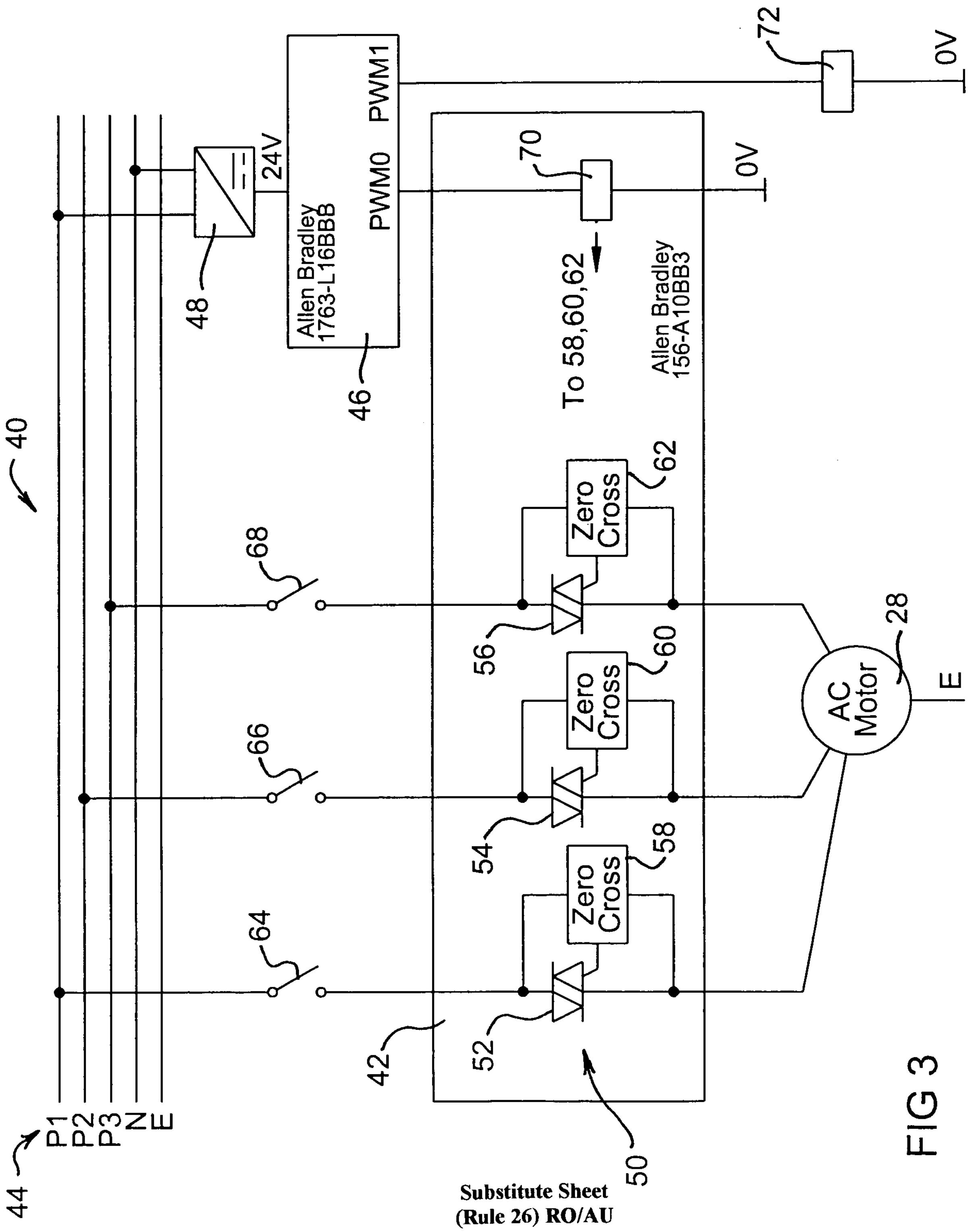

40
44
P1
P2
P3
N
E
48
24V
Allen Bradley
1763-L16BBB
46
PWM0
PWM1
72
0V
70
0V
To 58,60,62
Allen Bradley
156-A10BB3
68
66
64
Zero Cross
62
60
58
56
54
52
42
50
AC Motor
28
E

FIG 3

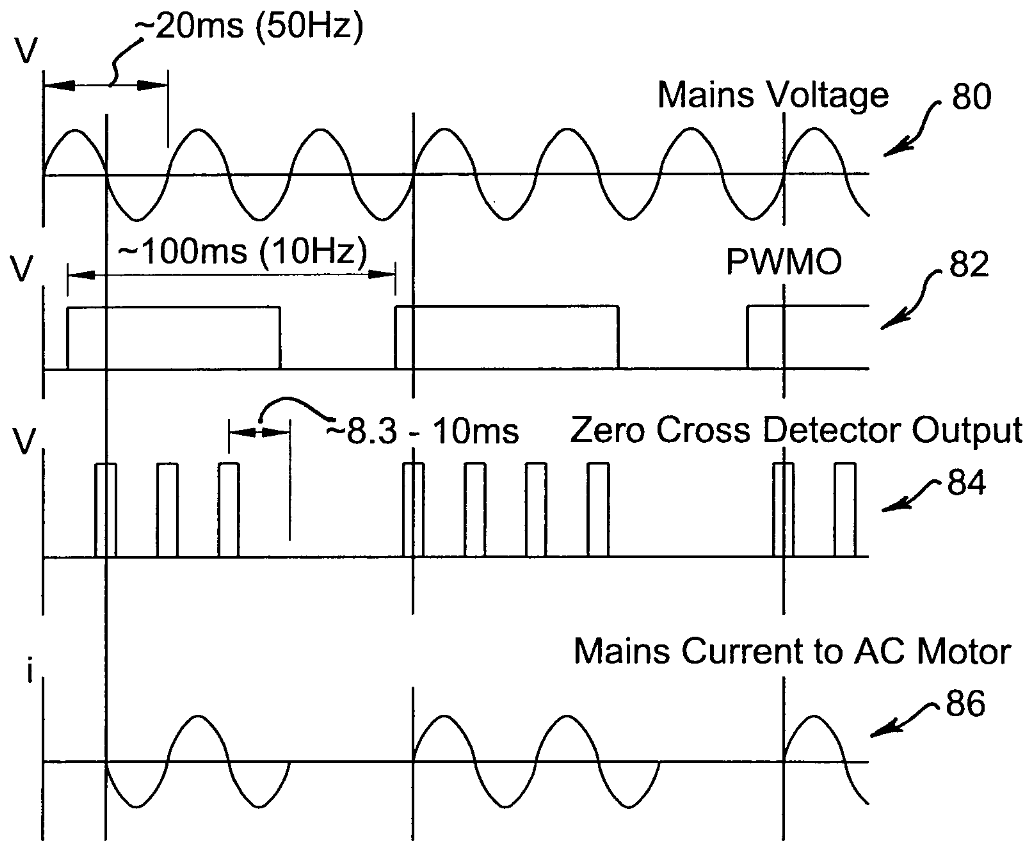

V
~20ms (50Hz)
Mains Voltage
80
V
~100ms (10Hz)
PWMO
82
V
~8.3 - 10ms
Zero Cross Detector Output
84
i
Mains Current to AC Motor
86

FIG 4

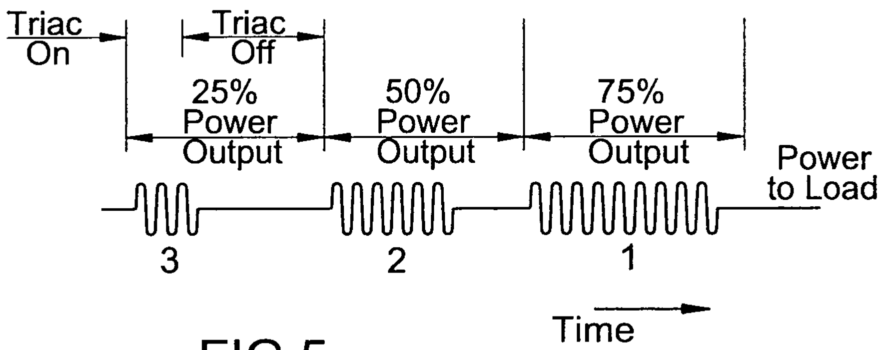


FIG 5

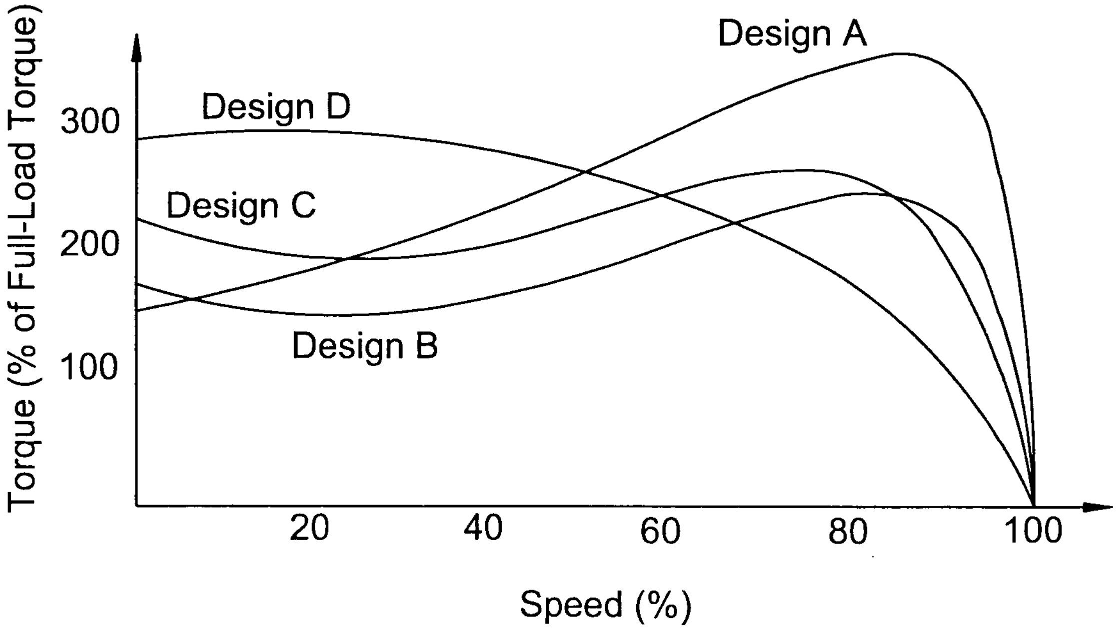


FIG 6

Substitute Sheet
(Rule 26) RO/AU

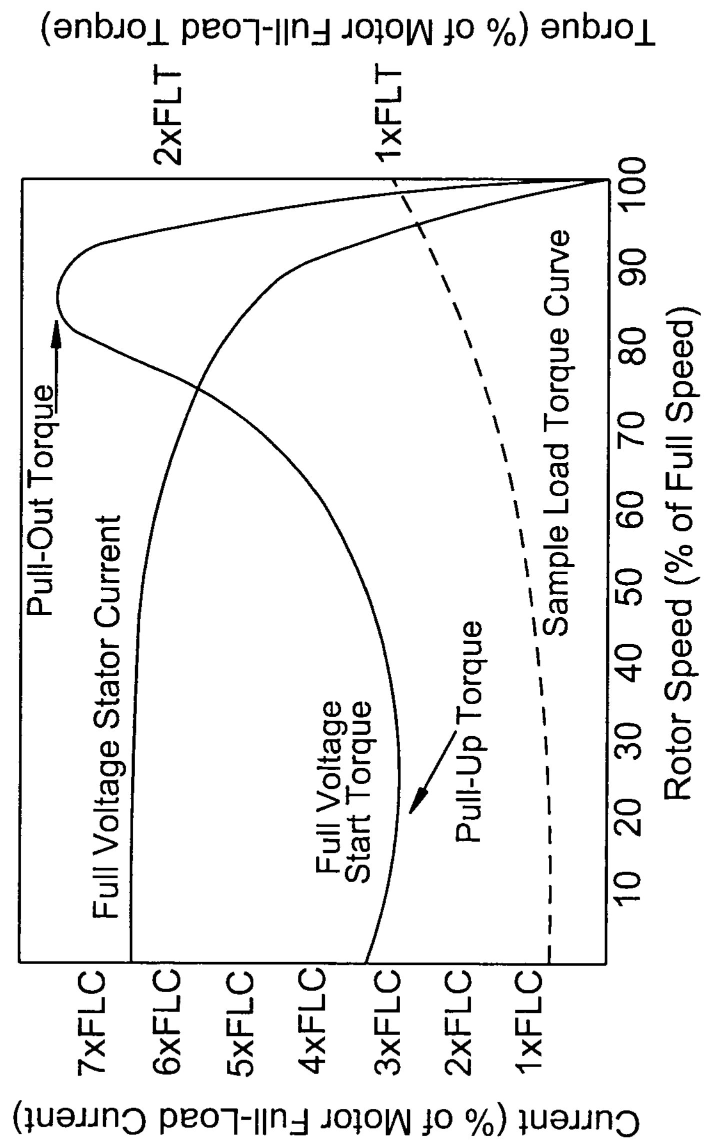

Torque (% of Motor Full-Load Torque)
2xFLT
1xFLT
Pull-Out Torque
Full Voltage Stator Current
Full Voltage
Start Torque
Pull-Up Torque
Sample Load Torque Curve
7xFLC
6xFLC
5xFLC
4xFLC
3xFLC
2xFLC
1xFLC
10
20
30
40
50
60
70
80
90
100
Rotor Speed (% of Full Speed)
Current (% of Motor Full-Load Current)

FIG 5

INTERNATIONAL SEARCH REPORT	International application No. PCT/AU2008/000807

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

H02P 6/08 (2006.01) ***H02P 27/06*** (2006.01)

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)

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)
EPODOC, WPI and Full text English databases searched with keywords: torque, control+, ac, induction motor?, pwm, switch+, zero_cross, trigger and similar keywords.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 3,855,509 A (WRIGHT) 17 December 1974 See whole document	1 – 10
A	Patent Abstracts of Japan: JP 07-025552 A (HITACHI LTD) 27 January 1995 See whole abstract	1 – 10
A	Patent Abstracts of Japan: JP 08-101722 A (DAIKIN IND LTD) 16 April 1996 See whole abstract	1 – 10

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 July 2008	04 AUG 2008
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. +61 2 6283 7999	Authorized officer **Shreyas Kumar** AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6222 3674

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2008/000807

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Patent Abstracts of Japan: JP 10-023765 A (MATSUSHITA REFRIG CO LTD) 23 January 1998 See whole abstract	1 – 10

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member
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JP	7025552	NONE
JP	8101722	NONE
JP	10023765	NONE

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END OF ANNEX