(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
8 June 2006 (08.06.2006)

PCT

(10) International Publication Number
WO 2006/060537 A1

(51) International Patent Classification:
H02P 21/00 (2006.01)

(21) International Application Number:
PCT/US2005/043414

(22) International Filing Date:
30 November 2005 (30.11.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10/998,721 30 November 2004 (30.11.2004) US

(71) Applicant *(for all designated States except US)*: **HONEYWELL INTERNATIONAL INC.** [US/US]; 101 Columbia Road, P.O. Box 2245, Morristown, New Jersey 07960 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **WANG, Zheng** [CA/CA]; 5358 Quartermain Cres., Missisauga, Ontario (CA). **YOU, Zhou, George** [CA/CA]; 4879 Kimbermount Avenue, Suite 1504, Mississauga, Ontario (CA). **DAMING, Ma, Jack** [CA/CA]; 5550 Longford Drive, Mississauga, Ontario (CA).

(74) Agents: HOIRIIS, David et al.; Honeywell International INC., 101 Columbia Road, P.O. Box 2245, Morristown, New Jersey 07960 (US).

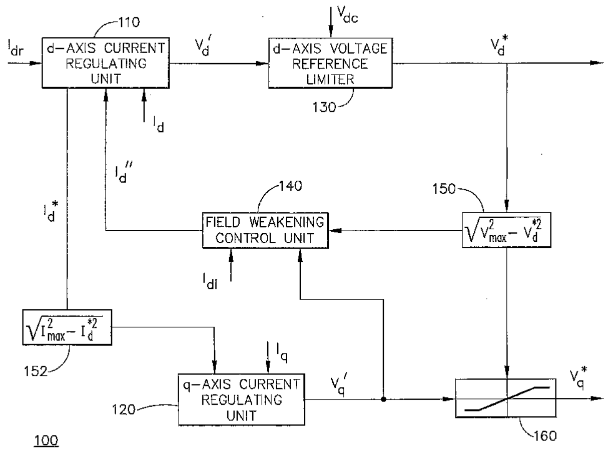
(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

[Continued on next page]

(54) Title: METHOD AND APPARATUS FOR FIELD WEAKENING CONTROL IN AN AC MOTOR DRIVE SYSTEM



(57) Abstract: A method and apparatus control a power converter (20) of an AC motor drive system (10). The method and apparatus: generate a field current regulating signal to control a field current component flowing from the power converter (20) to the AC motor (30), thereby achieving field current regulation; generate a torque current regulating signal to control a torque current component flowing from the power converter (20) to the AC motor (30), thereby achieving torque current regulation, the torque current regulation having lower priority than the field current regulation; and execute a close-loop field weakening control scheme, which generates a field weakening control command as a function of the difference between a torque current regulation voltage demand and voltage available for torque current regulation. The field current regulating signal is adjusted in accordance with the field weakening control signal to selectively reduce back EMF of the AC motor (30), thereby enabling the step of generating a toque current regulating signal to achieve a toque current component needed to drive the AC motor (30) at a desired speed despite a limitation on DC voltage available to the power converter (20).

WO 2006/060537 A1

METHOD AND APPARATUS FOR FIELD WEAKENING CONTROL IN AN AC MOTOR DRIVE SYSTEM

FIELD OF THE INVENTION

[0001] The present invention relates to inverter control in an AC motor drive system, and more particularly to a method and apparatus for controlling field weakening in an AC motor drive system.

BACKGROUND OF THE INVENTION

[0002] Voltage source inverter feed AC motor drives have become increasingly popular in general industrial applications, as well as in transportation vehicles such as electrical propulsion systems. In such applications, a wide operating speed range above the base speed (e.g., a high speed cruise) is often required. The recently emerging "more electrical" aircraft concept has also created more demand for AC motor drives in aerospace applications, such as for supplying engine starter, fan, and pump loads. Because of the limited DC bus voltage on aircraft and high output power rating requirement, some of these drive systems must be designed to operate at field weakening mode even at the rated operating point to achieve maximum voltage/current utilization and high efficiency operation. This makes field weakening control a critical part of the motor controller design.

[0003] When motor speed is lower than base speed, the inverter can provide enough voltage to support motor back EMF, so that field weakening is not required. When motor speed is higher than base speed, however, motor back EMF will exceed the inverter output voltage capability unless field weakening is applied. Thus, field weakening must be implemented to reduce the effective back EMF to achieve high-speed operation above base speed.

[0004] One basic field-weakening technique, such as the one applied in U.S. Pat. No. 6,407,531 issued to *Walters et al.* on Jun. 18, 2002, relies on a look up table. This kind of technique, however, requires that a large quantity of data be created off line and stored in the memory to achieve optimal field weakening control under any DC link voltage and any load conditions. Furthermore, sufficient margin must be factored in for parameter variation and the extra voltage needed during transition state. As such, the inverter output voltage capability cannot be fully utilized, which is a significant drawback for aerospace applications because it is directly related to the inverter size and weight.

[0005] Another approach to flux weakening is to calculate, on-line, the field weakening current from motor equations. Such an approach is described in U.S. Pat. No. 5,739,664 issued to *Deng et al.* on Apr. 14, 1998 and U.S. Pat. No. 6,504,329 issued to *Stancu et al.* on Jan. 7, 2003. These approaches, however, are very sensitive to uncertainties related to the system parameters and equations will be very complex for systems with an AC side output LC filter. A sufficient margin must be factored in to ensure stable system operation even with parameter variation. Thus, inverter output capability cannot be fully utilized.

[0006] A known field weakening control scheme is a close loop method, which does not use machine parameters for calculations in the field weakening operation. This control scheme should be able to adjust field-weakening current automatically during transient and steady state according to DC link voltage and load conditions. U.S. Pat. No. 5,168,204 issued to *Schauder* on Dec. 1, 1992, U.S. Pat. No. 6,288,515 issued to *Hiti et al.* on Sep. 11, 2001 and the paper authored by J. H. Song, J. M. Kim and S. K. Sul, entitled "A New Robust SPMSM Control to Parameter Variations in Flux Weakening Region," Proc. IECON'96, pp. 1193-1198, 1996, provide techniques that possess these features. These techniques adjust field-weakening current according to the inverter output voltage amplitude. There is no need for machine parameters but the choice of parameters in the field-weakening loop is still critical for the stability of the system. Because such techniques are close-loop based, during transition both d-axis and q-axis current loops lose control due to the shortage of voltage and over modulation will also occur, which will cause high frequency resonance for systems with AC side output LC filters. Unfortunately, many drive systems in aerospace applications require LC filters for the tough EMI requirements and the long cable between inverter and motor.

SUMMARY

[0007] According to one aspect, the present invention is a method of controlling a power converter of an AC motor drive system, the method comprising: generating a field current regulating signal to control a field current component flowing from the power converter to the AC motor, thereby achieving field current regulation; generating a torque current regulating signal to control a torque current component flowing from the power converter to the AC motor, thereby achieving torque current regulation, the torque current regulation having lower priority than the field current regulation; and executing a close-loop field weakening control scheme, which generates a field weakening control command as a function of the difference between a torque current regulation voltage demand and voltage available for torque current regulation, wherein the field current regulating signal is adjusted in accordance with the field weakening control signal to selectively reduce back EMF of the AC motor, thereby enabling the step of generating a toque current regulating signal to achieve a toque current component needed to drive the AC motor at a desired speed despite a limitation on DC voltage available to the power converter.

[0008] According to another aspect, the present invention is directed to a power converter controlling apparatus for controlling a power converter of an AC motor drive system, the controlling apparatus comprising: a field current controller for generating a field current regulating signal to control a field current component flowing from the power converter to the AC motor, thereby achieving field current regulation; a torque current controller for generating a torque current regulating signal to control a torque current component flowing from the power converter to the AC motor, thereby achieving torque current regulation, the torque current regulation having lower priority than the field current regulation; and a field weakening controller for executing a close-loop field weakening control scheme, which generates a field weakening control command as a function of the difference between a torque current regulation voltage demand and voltage available for torque current regulation, wherein the field current controller adjusts the field current regulating signal in accordance with the field weakening control signal to selectively reduce back EMF of the AC motor, thereby enabling the torque current controller to output a torque current regulating signal to achieve a torque current component needed to drive the AC motor at a desired speed despite a limitation on DC voltage available to the power converter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Further aspects of the present invention will become apparent from the following description taken in conjunction with the accompanying drawings, wherein:

[0010] FIG. 1 is a block diagram illustrating an AC motor drive system to which principles of the present invention may be applied;

[0011] FIG. 2 is a general block diagram illustrating functional components of an inverter control unit according to an embodiment of the present invention; and

[0012] FIG. 3 illustrates, in greater detail, elements of the inverter control unit of FIG. 2 in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

[0013] In one aspect, an embodiment of the present invention described below applies field weakening control in an AC motor drive system to maximize efficiency and power density by fully utilizing available DC bus voltage and minimizing the inverter current dynamically, and to ensure stable system operation when in a voltage limiting mode. In one embodiment, field weakening is initiated at a point that is adjusted, "on line," based on DC link voltage, which is typically not fixed in certain environments, such as on aircraft. In one implementation, transition to field weakening is achieved automatically and smoothly, without the need for a look-up table or knowledge of system parameters. In an embodiment of the present invention described below, a field weakening reference current is always maintained under the voltage limit condition, while a torque reference current is controlled with the limit of available DC bus voltage and the voltage that has already been used for generating the required field generating current. Thus, the field current demand has higher priority than the torque current under the limitations of both DC link voltage and inverter maximum current. In this way, a stable field is always guaranteed, which is a basic condition of a stable operation for a motor drive system.

[0014] FIG.1 illustrates an exemplary voltage source inverter feed vector controlled AC motor drive to which principles of the present invention may be applied. As illustrated, the AC motor drive system 10 includes: a DC link voltage input 15; a voltage source inverter 20 receiving DC power from the DC link voltage input 15; a pulse width modulation unit 35, which controls gating of the voltage source inverter 20 (e.g., utilizing a configuration of insulated-gate bipolar transistors (IGBTs)) so that the inverter 20 converts supplied DC voltage to multi-phase AC power; an AC motor 30, which is supplied multi-phase AC power via the inverter 20; and a control unit 100 for generating direct-, quadrature-axis inverter command reference voltages (V_d*, V_q*). An LC filter 25 may be included on the AC side of the inverter 20.

[0015] The system 10 includes a transforming unit 60 for transforming multi-phase line current values I_a, I_b, I_c to d-q reference frame quantities I_q, I_d (e.g., using well known Clark and Park transforms), which are input to the control unit 100. An additional transform unit transforms voltage reference signal V_d*, V_q* output by the control unit 100 to multi-phase voltage commands V_a, V_b, V_c or stationary stator frame voltage commands V_α, V_β. A speed sensor or speed estimator 50 determines rotor positioning/speed of the rotor of the AC motor 30.

[0016] Vector control or field-oriented control is one technique used in motor drives to control the speed and torque of AC motors. The control is conducted in a synchronous reference frame, i.e., the d-q frame. With this technique, motor stator current is resolved into a torque producing (q-axis) component of current, I_q, and a field producing (d-axis) component of current, I_d, where the q-axis leads the d-axis by 90 degrees in phase angle. The terminal voltage of the inverter is also resolved into the d-axis and q-axis components. As shown in FIG. 1, the phase angle of the synchronous reference frame can be from a speed/position sensor or from a speed estimator (i.e., for a speed sensorless controlled system). The q-axis current reference is typically output by a speed controller or a torque controller. The d-axis current reference is typically output from a field-weakening controller. The error signals between reference current and actually detected current are fed into a regulator to create inverter output voltage reference signal or modulation index.

[0017] In the system 10 illustrated in FIG. 1, it should be apparent to those of ordinary skill in the art that different PWM techniques may be used to generate PWM gatings. The DC link voltage input 15 may be from a DC power supply or battery unit. The torque current reference could be from a speed controller, a torque controller or a torque current profile. The current regulation performed by the control unit 100 could be applied with or without feedforward terms. The voltage source inverter 20 could be any topology inverter that converts DC voltage to variable frequency and amplitude AC voltage. The system 10 could be with or without the AC side output LC filter 25. The AC motor 30 could be permanent magnet, wound-field, synchronous reluctance motor or induction motor. The control unit 100 may be implemented using digital signal processing circuitry, analog circuitry, application specific integrated circuit(s) (ASIC), various combinations of hardware/software, etc.

[0018] The achievable output voltage and current of the inverter 20 are determined by the physical power ratings of the inverter 20 and the motor 30 and DC link voltage input 15. This relationship is illustrated mathematically as follows:

$$V_d^2 + V_q^2 \le V_{\max}^2, I_d^2 + I_q^2 \le I_{\max}^2$$

where $V_{\max}$ and $I_{\max}$ are maximum inverter voltage and current. As explained in detail below, embodiments of the present invention provide a voltage limit mechanism and a close-loop field weakening control loop. No lookup table and no system parameters are required in the field-weakening loop.

[0019] FIG. 2 is a general block diagram illustrating functional components of the control unit 100 in accordance with an embodiment of the present invention. As illustrated, the control unit 100 includes: a d-axis (field) current regulating unit 110; a q-axis (torque) current regulating unit 120; and a field weakening control unit 140. The control unit 100 further includes: a d-axis voltage reference limiter 130, which limits a d-axis current regulator output voltage (V_d') generated by the d-axis current regulating unit 110, thereby outputting the d-axis inverter command reference voltage (V_d^*); and a q-axis voltage reference limiter 160, which limits a q-axis regulator output voltage (V_q') output by the q-axis current regulating unit 120, thereby outputting the q-axis inverter command reference voltage (V_q^*). The control unit 100 further includes: a q-axis voltage limit calculator 150; and a q-axis current component limit calculator 152.

[0020] FIG. 3 is a block diagram illustrating, in greater detail, an arrangement for the control unit 100 according to an embodiment of the present invention. As illustrated, the d-axis current regulating unit 110 includes: a summing element 112 for summing a field weakening reference signal (I_d") output by the field weakening control unit 140 and the rated field current (I_{dr}), thereby generating a d-axis current reference signal (I_d*); a comparing element 114 for generating an error signal based on the difference between the d-axis current reference signal (I_d*) and the detected d-axis inverter output current (I_d); and a regulator 116 for generating the d-axis current regulator output signal (V_d') based on the error signal.

[0021] As illustrated, the q-axis current regulating unit 120 includes: a speed or torque control element 122 for generating a speed or torque control loop output signal (I_q'); a q-axis torque current reference signal limiter 124 for limiting I_q', thereby outputting the q-axis current reference signal (I_q*); a comparing element 126 for comparing the q-axis current reference signal (I_q*) with a detected q-axis inverter output current (I_q) to generate an error signal; and a regulator 128 for generating the q-axis current regulator output signal (V_q') based on the error signal.

[0022] The field weakening control unit 140 includes: an absolute value calculator 142 for calculating the amplitude of the q-axis current regulator output signal V_q'; a comparing element 144, which produces a q-axis voltage error signal as the difference between the output of absolute value calculator 142 and the output of the q-axis voltage limit calculator 150; a polarity calculator 145 for determining the polarity (sign) of the error signal generated by the comparing element 144; a regulator 146 for regulating a field weakening control signal based on the output of the polarity detector 145, thereby generating a field weakening current reference signal (I_d'); and a limiter 148 for limiting the field weakening current reference signal (I_d') based on a field weakening current limit (I_{dl}), thereby generating the field weakening reference signal (I_d") that is output to the d-axis current regulating unit 110.

[0023] In the embodiment illustrated in FIG. 3, the d-axis voltage reference limiter 130 includes a max voltage calculator 132 for calculating maximum voltage available to the inverter 20 as a ratio (K) of the DC link voltage (V_{dc}) from the DC link voltage input 15; and a limiter 134 for limiting the d-axis current regulator output signal (V_d') based on V_{max}, thereby outputting the d-axis inverter command reference voltage (V_d*). This embodiment assumes the DC link voltage V_{dc} changes dynamically. It should be recognized, however, the principles of the present invention are applicable to the simpler case in which V_{dc} is fixed. In such as case, it is not necessary to dynamically calculate V_{max}, which instead will be a constant value.

[0024] Although elements of the control unit 100 are shown as discrete elements, it should be recognized that this illustration is for ease of explanation and that functions of these elements may be combined in the same physical element, e.g., in the same microcontroller or in one or more application-specific integrated circuits (ASIC). Additional aspects of the operation of the elements illustrated in FIGs. 2 and 3 will become apparent from the following description.

[0025] The d-axis current regulating unit 110 generates the d-axis current reference signal I_d^* based on the result of the field weakening control loop implemented by the field weakening control unit 140. The q-axis current regulating unit 120 generates the q-axis current reference signal I_q^* from the speed or torque control loop output signal I_q' (from the speed or torque control unit 122) through the limiter 124, which applies a limit level ($\sqrt{I_{max}^2 - I_d^{*2}}$) calculated by the q-axis current component limit calculator 152. I_{max} is the maximum current the inverter 20 can provide. Both of the d-axis and q-axis current reference signals I_d^* and I_q^* are compared, by comparing elements 114, 126, respectively, with detected d-axis and q-axis inverter output current signals I_d and I_q to produce current error signals. The current error signals are fed into d-axis and q-axis current regulators 116, 128 to generate d-, q-axis current regulator output signals V_d' and V_q'. The d-axis current (field generating component of the stator current) regulator output signal V_d' is sent to the limiter 134, with limit level ±V_{max}, to create final d-axis inverter command reference voltage V_d^*. V_{max} is the maximum voltage the inverter 20 can create, which is proportional to the DC link voltage V_{dc}. The ratio K between V_{dc} and V_{max} depends on the PWM method adopted. Since V_d' is usually far away from V_{max}, d-axis current actually can be controlled without voltage limit. In this way the d-axis current is always under control, i.e., a solid air gap flux can be achieved in transient and steady state, which is advantageous to motor stable operation.

[0026] The q-axis current (torque generating component of the stator current) regulator output signal V_q' is sent to the limiter 160, with the limit level $\pm\sqrt{V_{\max}^2 - V_d^{*2}}$ calculated by the q-axis voltage limit calculator 150, to create the final q-axis inverter command reference voltage V_q^*. This limit mechanism 160 can ensure that there is no over modulation during transient and steady state, if required, which can prevent high frequency resonance for the drive systems with AC side output LC filters 25.

[0027] The field weakening control unit 140 is part of an outer q-axis voltage regulation loop to generate a field-weakening current reference signal. The goal of this loop is to output a signal that allows the d-axis current regulating unit 110 to adjust the d-axis current reference signal I_d^* to make the amplitude of the output signal of the q-axis current regulator $|V_q'|$ lower or equal than limit level $\sqrt{V_{\max}^2 - V_d^{*2}}$. In this way, there is $\sqrt{V_d'^2 + V_q'^2} \le V_{\max}$ i.e., d-axis and q-axis current loops can be fully controlled without voltage limit. To achieve this, the comparing element 144 of the field weakening control unit 140 compares the amplitude of the q-axis current regulator output signal $|V_q'|$ with $\sqrt{V_{\max}^2 - V_d^{*2}}$ to produce a q-axis voltage error signal. This error signal, or the sign of this error signal as determined by the polarity calculator 145 (optional), is fed into the regulator 146 to generate the field weakening current reference signal I_d'. I_d' is sent into the limiter 148 with limit level $-I_{dl}$ to 0 to create the field weakening reference signal I_d'' that is sent to the d-axis current regulating unit 110. I_{dl} is the field weakening current limit to prevent deep demagnetization of rotor permanent magnets. The sum of the field weakening reference signal I_d'' and the rated field current I_{dr}, as calculated by the summing element 112, is the final d-axis current reference signal I_d^*.

[0028] For an induction motor, the rotor magnetizing field is excited by stator current, I_{dr} is the rated field current. When motor speed is lower than base speed, I_d'' is zero and I_d^* will be I_{dr}. After motor speed is higher than base speed, I_d'' is a negative value and I_d^* will be lower than I_{dr}. Field will be weakened to lower down back EMF to achieve field weakening operation. For synchronous motors, rotor magnetizing field is excited by the rotor itself. I_{dr} is set to zero. When motor speed is lower than base speed, I_d'' is zero and I_d^* will be zero i.e., no field weakening is applied. After motor speed is higher than base speed, I_d'' is a negative value and I_d^* will also be negative, i.e., field weakening will be applied. If the error signal output by the comparing element 144 of the field weakening control unit 140 is used by the regulator 146 to generate field-weakening current, the field weakening control loop parameters will be important for the stability of the system. Better dynamic performance, however, can be achieved. For the system with lenient dynamic performance requirements, the sign of the error signal for field weakening current adjustment, as calculated by the polarity detector 145 of the field weakening control unit 140, is more preferable because the tuning of the field weakening control is simplified.

[0029] In the above-described embodiment, the field weakening reference current is always maintained under the voltage limit condition, while the torque reference current is controlled with the limit of available DC bus voltage and the voltage that has already been used for generating the required field current. Thus, the field current demand has higher priority than the torque current under the limitations of both DC link voltage and inverter maximum current. In this way, a stable field is always guaranteed, which is a basic condition of a stable operation for a motor drive system. The above-described embodiment achieves this effect by applying the following logic:

[0030] 1) First, the field weakening I_d^* is only limited by I_{dl}, which is maximum allowable field weakening defined by the system.

[0031] 2) Second, V_d^* required by I_d^* is only limited by V_{max}, which is defined by the system (max. available DC bus).

[0032] 3) Then, the torque Iq^* is limited by $\sqrt{I_{\max}^2 - I_d^{*2}}$, where I_{max} is defined by the inverter capability.

[0033] 4) Fourth, V_q^* required by I_q^* is limited by $\sqrt{V_{\max}^2 - V_d^{*2}}$.

[0034] 5) Field weakening close loop control is applied.

[0035] As described above, the embodiment illustrated in FIG. 3 assumes that the DC link voltage V_{dc} changes dynamically. It should be recognized, however, the principles of the present application are applicable to the simpler case in which V_{dc} is fixed. In such as case, it is not necessary to dynamically calculate V_{max}, which instead will be a constant value, and there is no need for DC link voltage detection. In such an implementation, a maximum modulation index (d_{max}) for the inverter can be adopted for control, instead of the dynamically changing V_{max}. In this scheme, the output signals of the d-axis and q-axis current regulating units, 110, 120, are inverter modulation index signals d_d' and d_q', instead of V_d' and V_q'. The limits imposed on d_d' and d_q' are d_{max} and $\sqrt{d_{\max}^2 - d_d^2}$, respectively, instead of V_{max} and $\sqrt{V_{\max}^2 - V_d^{*2}}$. The field weakening control error signal is $\sqrt{d_{\max}^2 - d_d^2}$ $-|d_q'|$ instead of $\sqrt{V_{\max}^2 - V_d^{*2}}$ $-|V_q'|$. Other aspects remain the same. This simplified embodiment may be applied, for example, to a battery fed system.

WE CLAIM:

1. A method of controlling a power converter (20) of an AC motor drive system (10), said method comprising:

generating a field current regulating signal to control a field current component flowing from said power converter (20) to the AC motor (30), thereby achieving field current regulation;

generating a torque current regulating signal to control a torque current component flowing from said power converter (20) to the AC motor (30), thereby achieving torque current regulation, said torque current regulation having lower priority than said field current regulation; and

executing a close-loop field weakening control scheme, which generates a field weakening control command as a function of the difference between a torque current regulation voltage demand and voltage available for torque current regulation,

wherein said field current regulating signal is adjusted in accordance with said field weakening control signal to selectively reduce back EMF of said AC motor (30), thereby enabling said step of generating a toque current regulating signal to achieve a toque current component needed to drive the AC motor (30) at a desired speed despite a limitation on DC voltage available to said power converter (20).

2. The method according to claim 1, wherein

said DC voltage available to said power converter (20) is constant; and

said step of generating a field current regulating signal and said step of generating a torque current regulating signal generate modulation index signals for said power converter (20).

3. The method according to claim 1, wherein said field current regulating signal is a d-axis voltage reference signal, which is limited based on DC voltage available to said power converter (20), and said torque current regulating signal is a q-axis voltage reference signal, which is limited based on the DC voltage

available to said power converter (20) and the level of said d-axis voltage reference signal.

4. The method according to claim 3, wherein said field weakening control scheme generates said field weakening control signal based on a polarity of voltage saturation, which indicates a saturation condition for said q-axis voltage reference signal or an error amplitude, calculated as the difference between $\sqrt{V_{\max}^2 - V_d^{*2}}$ and $|V_q'|$, where V_q' is a q-axis current regulation output signal.

5. The method according to claim 1, wherein

said step of generating the field current regulating signal limits a field component of current as a function of maximum allowable field weakening; and

said step of generating the torque current regulating signal limits a torque component of current based on $\sqrt{I_{\max}^2 - I_d^{*2}}$, where $I_{\max}$ is maximum current said power converter (20) can provide and I^*_d is a d-axis reference current.

6. A power converter controlling apparatus (100) for controlling a power converter (20) of an AC motor drive system (10), said controlling apparatus comprising:

a field current controller (110) for generating a field current regulating signal to control a field current component flowing from said power converter (20) to the AC motor (30), thereby achieving field current regulation;

a torque current controller (120) for generating a torque current regulating signal to control a torque current component flowing from said power converter (20) to the AC motor (30), thereby achieving torque current regulation, said torque current regulation having lower priority than said field current regulation; and

a field weakening controller (140) for executing a close-loop field weakening control scheme, which generates a field weakening control command as a function of the difference between a torque current regulation voltage demand and voltage available for torque current regulation,

wherein said field current controller (110) adjusts said field current regulating signal in accordance with said field weakening control signal to selectively reduce back EMF of said AC motor (30), thereby enabling said torque current controller (120) to output a torque current regulating signal to achieve a torque current component needed to drive the AC motor (30) at a desired speed despite a limitation on DC voltage available to said power converter (20).

7. The apparatus according to claim 6, wherein

said DC voltage available to said power converter (20) is constant; and

said field current controller (110) and said torque current controller (130) generate modulation index signals for said power converter (20).

8. The apparatus according to claim 6, wherein said field current regulating signal is a d-axis voltage reference signal, which is limited based on DC voltage available to said power converter (20), and said torque current regulating signal is a q-axis voltage reference signal, which is limited based on the DC voltage available to said power converter and the level of said d-axis voltage reference signal.

9. The apparatus according to claim 8, wherein said field weakening controller (140) generates said field weakening control signal based on a polarity of voltage saturation, which indicates a saturation condition for said q-axis voltage reference signal or an error amplitude, calculated as the difference between $\sqrt{V_{\max}^2 - V_d^{*2}}$ and $|V_q'|$, where V_q' is a q-axis current regulation output signal.

10. The apparatus according to claim 6, wherein

said field current controller (140) limits a field component of current as a function of maximum allowable field weakening; and

said torque current controller (130) limits a torque component of current based on $\sqrt{I_{\max}^2 - I_d^{*2}}$, where $I_{\max}$ is maximum current said power converter (20) can provide and I^*_d is a d-axis reference current.

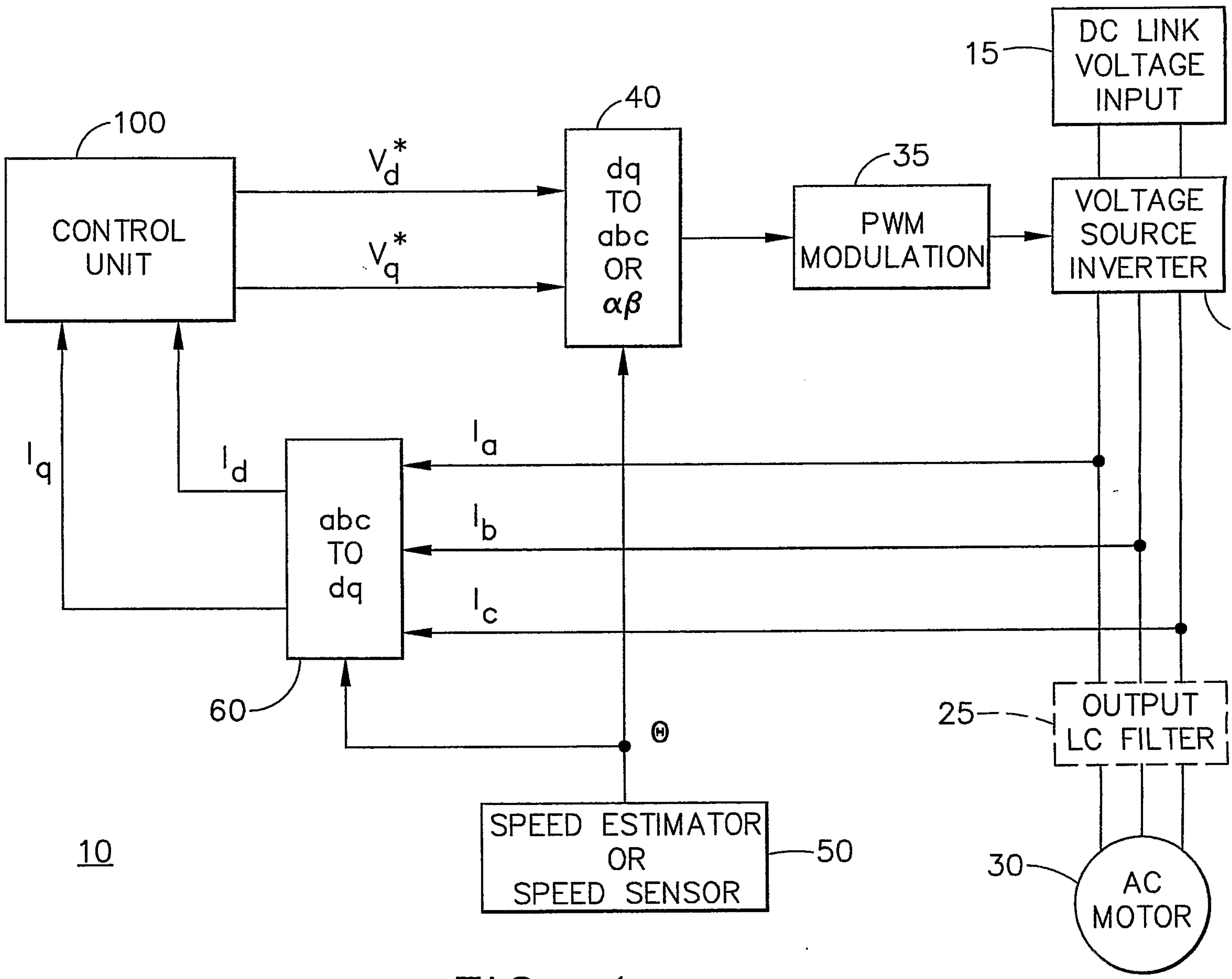
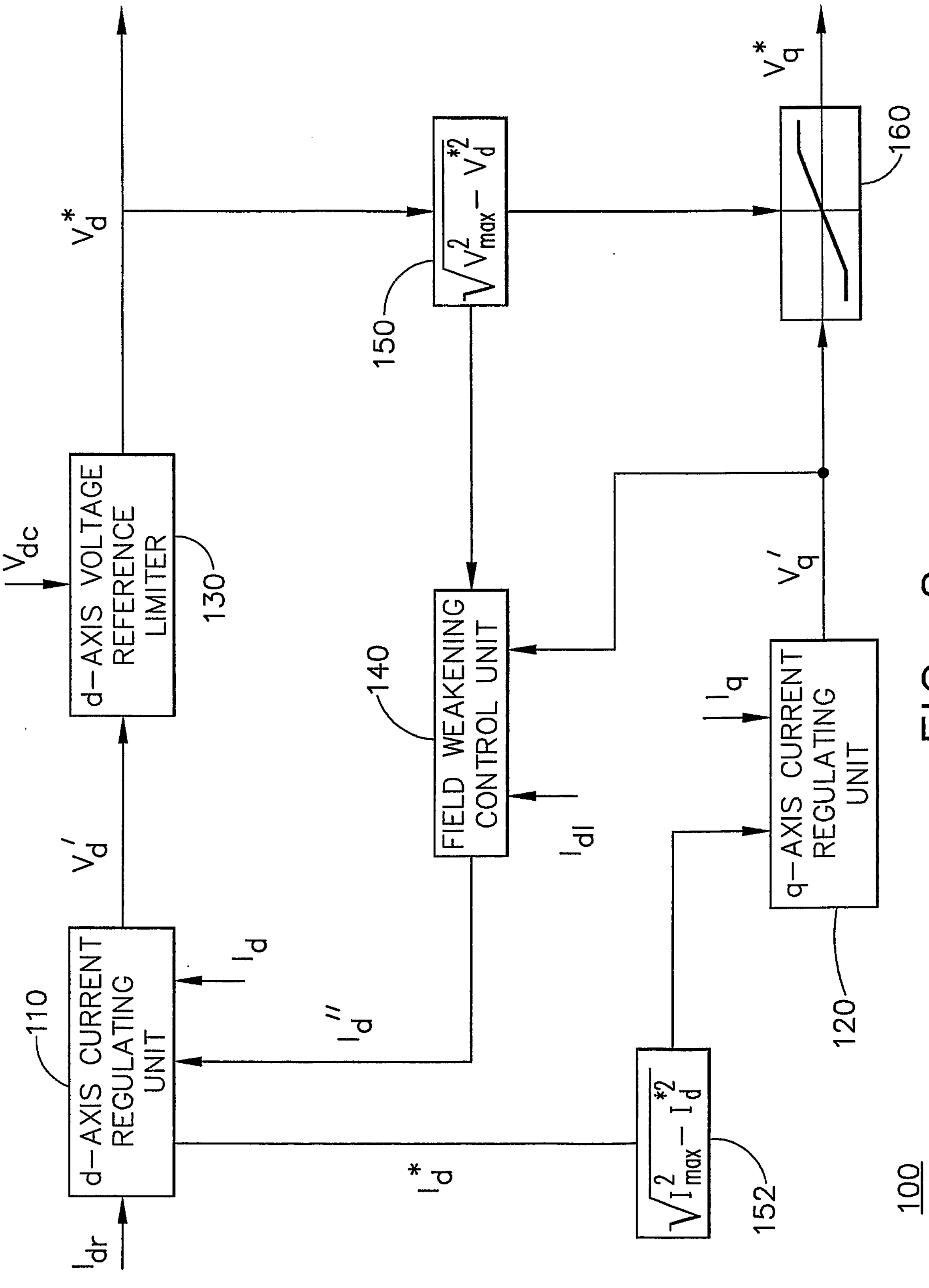
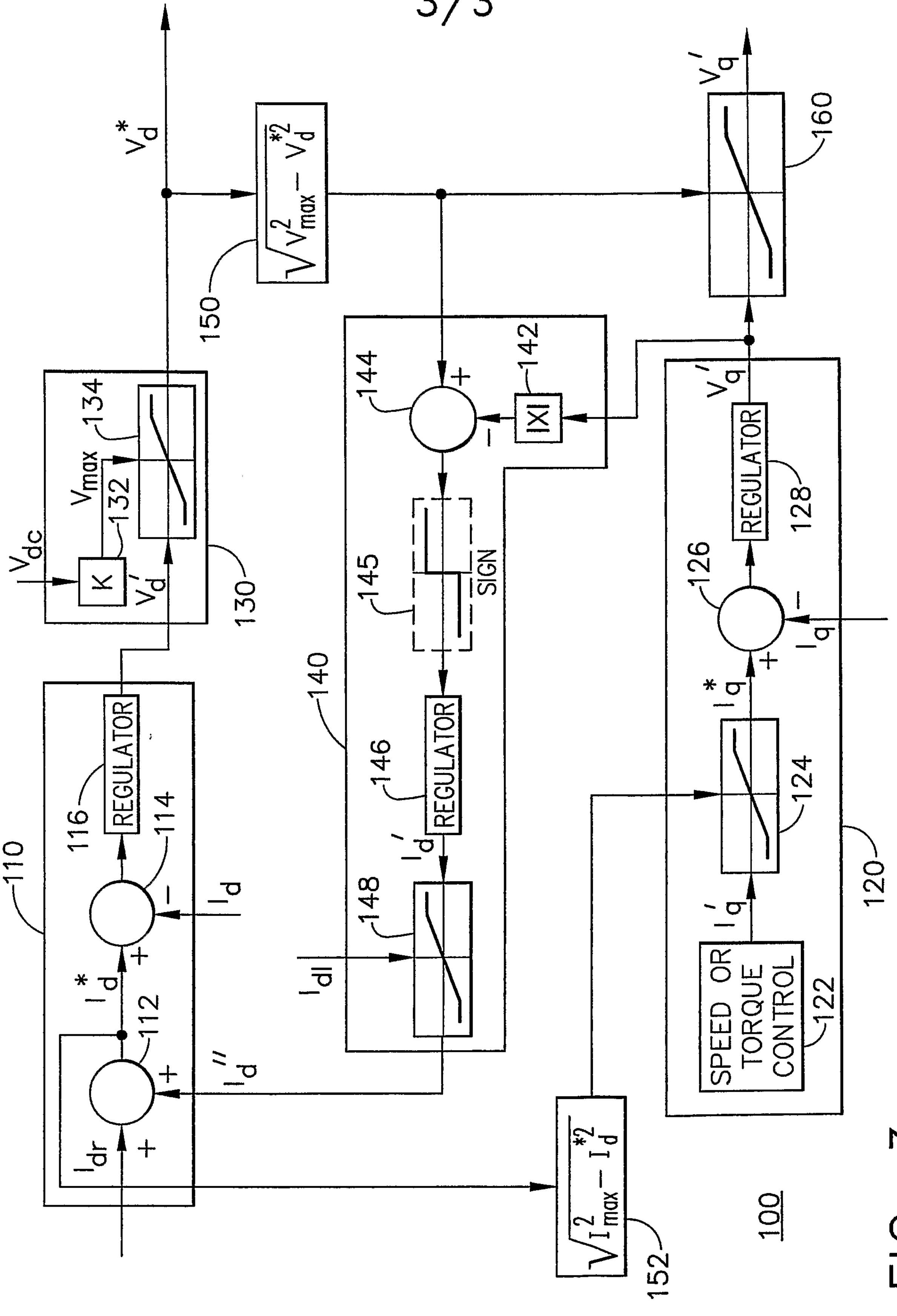

100
CONTROL UNIT
V_d^*
V_q^*
40
dq TO abc OR αβ
35
PWM MODULATION
15
DC LINK VOLTAGE INPUT
VOLTAGE SOURCE INVERTER
20
I_q
I_d
abc TO dq
I_a
I_b
I_c
60
Θ
25
OUTPUT LC FILTER
SPEED ESTIMATOR OR SPEED SENSOR
50
30
AC MOTOR
10

FIG. 1



I_{dr}
d–AXIS CURRENT REGULATING UNIT
110
I_d
I_d''
V_d'
V_{dc}
d–AXIS VOLTAGE REFERENCE LIMITER
130
V_d^*
I_d^*
$\sqrt{I_{max}^2 - I_d^{*2}}$
152
FIELD WEAKENING CONTROL UNIT
140
I_{dl}
$\sqrt{V_{max}^2 - V_d^{*2}}$
150
q–AXIS CURRENT REGULATING UNIT
120
I_q
V_q'
160
V_q^*
100

FIG. 2



100
110
112
114
116
REGULATOR
I_{dr}
I_d^*
I_d
I_d''
+
−
120
122
SPEED OR TORQUE CONTROL
124
126
128
REGULATOR
I_q'
I_q^*
I_q
V_q'
130
132
134
K
V_{dc}
V_{max}
V_d'
V_d^*
140
142
|X|
144
145
SIGN
146
REGULATOR
148
I_d'
I_{dl}
150
$\sqrt{V_{max}^2 - V_d^{*2}}$
152
$\sqrt{I_{max}^2 - I_d^{*2}}$
160

FIG. 3

INTERNATIONAL SEARCH REPORT

International application No
[illegible]CT/US2005/043414

A. CLASSIFICATION OF SUBJECT MATTER
H02P21/00

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 B60L

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 practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 884 834 A (SIEMENS AKTIENGESELLSCHAFT) 16 December 1998 (1998-12-16)	1,2,4-7, 9,10
A	column 10,, line 17 - line 53	3,8
X	US 5 168 204 A (SCHAUDER ET AL) 1 December 1992 (1992-12-01) cited in the application	1,2,4-7, 9,10
A	column 5, line 32 - column 6, line 56	3,8
A	US 5 659 235 A (YAMADA ET AL) 19 August 1997 (1997-08-19) column 4, line 47 - line 55	1-10
A	US 5 467 000 A (BAUER ET AL) 14 November 1995 (1995-11-14) column 6, line 41 - line 57	1-10

☐ 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 document 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)

"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 30 March 2006	Date of mailing of the international search report 07/04/2006
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Authorized officer Frapporti, M

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2005/043414

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0884834 A	16-12-1998	DE 19725136 A1	24-12-1998
US 5168204 A	01-12-1992	DE 69327264 D1	20-01-2000
		DE 69327264 T2	31-05-2000
		EP 0566322 A2	20-10-1993
		JP 3390045 B2	24-03-2003
		JP 6054577 A	25-02-1994
US 5659235 A	19-08-1997	JP 3262253 B2	04-03-2002
		JP 8228404 A	03-09-1996
US 5467000 A	14-11-1995	CA 2127728 A1	10-01-1995
		DE 59300691 D1	02-11-1995
		EP 0633653 A1	11-01-1995