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(54) **Title**: HARMONIC NOISE REDUCTION

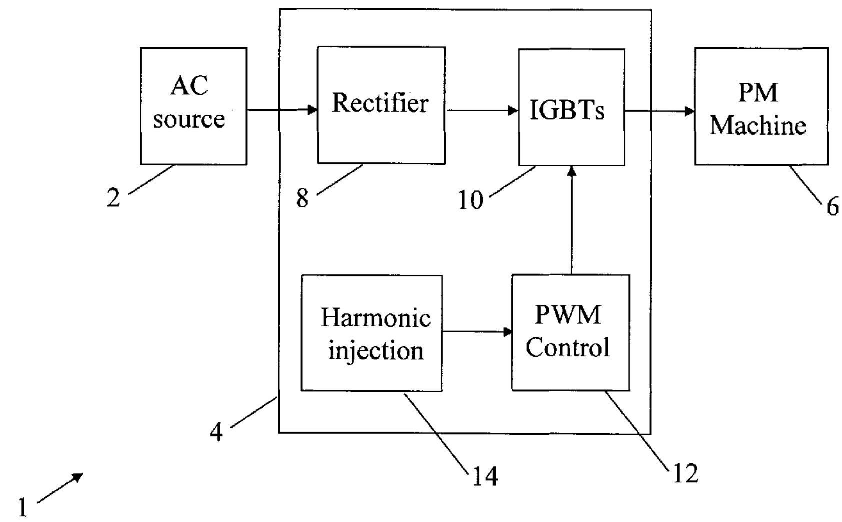

Fig. 1

(57) **Abstract**: The present invention relates to a method for regulating a set of first noise harmonics from a permanent magnet machine operatively connected to a power supply unit, the method comprising the step of injecting a second set of harmonics into a representation of a drive current provided to the electronic device in order to regulate at least part of the noise harmonics of the first set, wherein the harmonics of the second set is/are different from the noise harmonics of the first set. The invention further relates to a power supply unit for performing the method of the present invention.

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HARMONIC NOISE REDUCTION

FIELD OF THE INVENTION

The present invention relates to a method and a system for reducing harmonic noise from permanent magnet machine systems. In particular, the present invention relates to a method and a system for injecting additional current harmonics into a motor current in order to suppress other harmonics generated by the permanent magnet machine system.

BACKGROUND OF THE INVENTION

During recent years different permanent magnet (PM) machine designs have been introduced to the market. Trapezoidal and sinusoidal back electromotive force (EMF) are representations of two specific PM designs. However, new cost-effective PM designs blur the lines between these two specific PM designs, and future PM inverters must be able to handle these two extreme PM designs as well as any intermediate PM design.

Similarly, 'surface mount PM' vs 'interior PM' is a traditional description that was used to distinguish between non-salient and salient machines ($Ld=Lq$ and $Lq \neq Ld$). Here too, new advancements of powdered core segmented stator designs with low flux densities and softer saturation characteristics, inside out machine designs, and low cost needle point stator winding techniques are blurring the lines that previously segmented the market of PM inverters.

A square wave or a sinusoidal drive current provided to an intermediate machine solution will generate 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonic ripple currents and corresponding 6^{th} and 12^{th} harmonic ripple torques. These harmonics produce undesirable audible noise at 300 Hz to 600 Hz (assuming 50Hz operation).

Harmonic regulation/suppression has been used in conjunction with zero magnitude references to produce lower distortion fundamental current waveforms for active front ends and DC/AC inverters used as isolated power supplies. These power supplies are often referred to as inverters capable of supplying non-linear loads with low voltage total harmonic distortion (THD). Similarly, 3^{rd} harmonic voltage injection (or 9^{th},15^{th}, 21^{st} etc.) is regularly used to increase the fundamental voltage waveform magnitude given limited DC link voltages.

Examples of known methods are disclosed in US 6,777,907, US 7,034,493 and US 6,674,262.

It may be seen as an object of embodiments of the present invention to provide a simple way to suppress noise harmonics from permanent magnet machine systems, such as those using permanent magnet motors.

DESCRIPTION OF THE INVENTION

The above-mentioned object is complied with by providing, in a first aspect, a method for regulating a set of first noise harmonics from a permanent magnet machine operatively connected to a power supply unit, the method comprising the step of injecting a second set of harmonics into a representation of a drive current provided to the permanent magnet machine in order to regulate at least part of the set of first noise harmonics, wherein the harmonics of the second set is/are different from the noise harmonics of the first set. The noise harmonics of the first set typically includes the 5^{th} and 7^{th} harmonics and the harmonics of the second set typically includes the 6^{th} harmonic.

The present invention is of particular relevance in connection with non-optimized PM motors, such as "cheap" PM motors. In "cheap" PM motors, the sinusoidal back EMF voltage is sacrificed to save manufacturing costs. In "cheap" PM motors the back EMF voltage becomes non-sinusoidal. The torque generated by the product of a sinusoidal motor current and a non-sinusoidal voltage will not be smooth, and it will generate noise. Thus, the present invention aims at generating and injecting a non-sinusoidal motor current to minimize noise generated by ripple torque.

Thus, the method according to the first aspect of the present invention is of particular relevance in connection with control of PM machines, such as PM motors. It is an advantage of the present invention that the power supply unit in the form of a single motor inverter may be tailored to drive several different PM motor designs.

The individual harmonics of the second set may be weighted in accordance with an injection factor. In fact the individual harmonics of the second set may be weighted differently, and they may be weighted between -125% and 125%.

The noise harmonics of the first set may comprise the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics, whereas the harmonics of the second set may comprise the 6^{th} and 12^{th} harmonics.

Thus, it is an advantage of the present invention that the 5^{th}, 7^{th}, 11^{th} and 13^{th} noise harmonics generated by for example permanent magnet motors may be controlled by the injection and regulation of the 6^{th} and 12^{th} harmonics.

In a second aspect the present invention relates to a method for regulating a first noise harmonic from an electronic device operatively connected to a power supply unit, the method comprising the step of injecting at least one second harmonic into a representation of a drive current provided to the electronic device in order to suppress the first noise harmonic, wherein the second harmonic is different from the first noise harmonic.

Again, the method is of particular relevance in connection with control of PM machines, such as PM motors. It is an advantage of the present invention that a single motor inverter may be tailored to drive several different PM motor designs.

The first noise harmonic may be selected from the group consisting of the 5th, 7th, 11th and 13th harmonics, whereas the second harmonic may comprise the 6th and/or the 12th harmonics.

In a third aspect the present invention relates to a power supply for regulating a set of first noise harmonics from a permanent magnet machine operatively connected to a power supply unit, said power supply comprising means for generating and injecting a second set of harmonics into a representation of a drive current provided to the permanent magnet machine in order to regulate at least part of the set of first noise harmonics, wherein the harmonics of the second set is/are different from the noise harmonics of the first set. The noise harmonics of the first set typically includes the 5th and 7th harmonics and the harmonics of the second set typically includes the 6th harmonic.

The power supply of the present invention is of particular relevance in connection with control of PM machines, such as PM motors. It is an advantage that the power supply may be tailored to drive several different PM motor designs.

The means for generating and injecting the second set of harmonics may be adapted to weight individual harmonics of the second set in accordance with an injection factor. The individual harmonics of the second set may be weighted differently. The individual harmonics of the second set may be weighted between -125% and +125%.

The power supply may be adapted to regulate the 5th, 7th, 11th and 13th harmonics of the first set by injecting the 6th and/or the 12th harmonics into the representation of a drive current.

In a fourth aspect the present invention relates to a power supply for regulating a first noise harmonic from an electronic device operatively connected to a power supply unit, said power supply comprising means for generating and injecting a second harmonic into a representation of a drive current provided to the electronic device in order to suppress the first noise harmonic, wherein the second harmonic is different from the first noise harmonic.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will now be described in further details with reference to the accompanying figures, wherein:

Fig, 1 shows a motor drive system in accordance with an aspect of the present invention.

Fig. 2 shows various currents at injection factor 0%,

Fig. 3 shows various currents at injection factor 50%,

Fig. 4 shows various currents at injection factor 100%,

Fig. 5 shows various currents at injection factor 125%,

Fig. 6 shows various currents at injection factor -50%,

Fig. 7 shows various currents at injection factor -100%, and

Fig. 8 shows a series of plots demonstrating aspects of the present invention.

While the invention is susceptible to various modifications and alternative forms, specific embodiments have been shown by way of examples in the drawings and will be described in detail herein. It should be understood, however, that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE INVENTION

In general the present invention relates to a method and a system where noise harmonics generated by, for example, permanent magnet motors are controlled by the injection and regulation of particular harmonics in the stationary frame indirectly by injection and regulation of other harmonics in the commonly used dq reference frame.

In particular, the present invention addresses a method and a system involving injection and regulation of 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonics in the stationary frame indirectly by injection and regulation of only the 6^{th} and 12^{th} harmonics in the commonly used dq reference frame. The convolution of the 6^{th} and 12^{th} harmonics coordinate transformations with the fundamental coordinate transformation allows regulation of five separate harmonic frequencies with only two additional reference calculations.

The present invention relies on the fact that an identical convolution of frequencies occurs between the machine stator and rotor fluxes to produce 6^{th} and 12^{th} harmonic ripple torques. In relation to this the present invention takes advantage of the fact that the cylindrical symmetry will not be compromised in cost effective permanent magnet machines/motors.

Thus, according to the present invention the control of several harmonics is done by the injection of only two harmonics.

It is a huge advantage of the present invention that by varying the absolute and relative amplitudes of the injected harmonics the drive waveform can be tailored to match a given motor design. Moreover, the method and system of the present invention is not calculation intensive and, thus, requires minimal additional computational resources.

By injecting the 6^{th} and/or 12^{th} harmonic currents of a proper magnitude into the current references id and iq a sine wave current regulator can slowly be changed into a trapezoidal current regulator – cf. in particular Fig. 4. The ratios of the 6^{th} and 12^{th} harmonics may be tailored to match a given motor design by varying an injection factor.

Fig. 1 is a block diagram of a system, indicated generally by the reference numeral 1, in accordance with an aspect of the present invention. The system 1 comprises an AC source 2, a motor drive 4 and a permanent magnet machine 6.

As is well known in the art, the motor drive 4 includes a rectifier 8, a set of switches 10 (typically insulated gate bipolar transistors (IGBTs) as shown in Fig. 1) and a pulse width modulation (PWM) controller 12 for controlling the switches. The motor controller converts power received from the AC source first into a DC signal (using the rectifier 8) and then back into an AC signal (using the IGBTs). Importantly, the nature of the AC signal (such as the frequency of the signal) can be controlled using the PWM controller 12.

The motor drive 4 additionally includes a harmonic injection module 14. The harmonic injection module 14 is configured to provide harmonic injection into the PWM controller in order to add harmonics to the AC signal output to the permanent magnet machine 6 as described further below.

Figs. 2-4 show how the sine wave drive can be changed into a trapezoidal-shaped drive current by increasing an injection factor from 0 to 100% - in Fig. 2 the injection factor is 0%, in Fig. 3 the injection factor is 50%, and in Fig. 4 the injection factor is 100%.

Generally, the three phases of an inverter are denoted u,v,w. Thus, i_u and i_v denote drive currents from phase u and v, respectively. Abbreviations α and β represent two phase equivalents of the three phases u,v,w. Since a motor has three windings connected in a wye-connection, it is only a two variable problem.

The conversion from u,v,w to α , β is a well known conversion for a person skilled in the art. Abbreviations d and q denote rotating reference frame equivalents of α and β. The conversion from d and q to α and β is also well known to a person skilled in the art. Figs. 5-7 illustrate drive currents for injection factors of 125%, -50% and -100%, respectively.

By varying the injection factor between -125% and 125% the entire system can be tested and audible noise can be minimized at the installation site. Since PM motor designs of the future will not be ideal sine waves or ideal trapezoids, the ability to adjust 6^{th} and/or 12^{th} harmonic current injection will provide a unique solution where a single inverter may be configured for use with several different PM motor designs without sacrificing on audible noise levels. Moreover, it is of particular importance that this system level noise optimization experiment only has to be performed once for a given motor design.

Figure 8 shows a series of plots demonstrating aspects of the present invention. The first plot, indicated generally by the reference numeral 82, shows the back-emf induced in an exemplary “cheap” permanent magnet motor. The motor is a 3-phase motor, hence three voltage plots are shown. As can be seen in the plot, the back-emf is non-sinusoidal.

The second plot, indicated generally by the reference numeral 84, shows motor currents that may be injected into the IGBTs in accordance with the principles of the present invention. In this particular example, 6^{th} and 12^{th} harmonics are injected, with the 6^{th} harmonic having an injection factor of -65% and the 12^{th} harmonic having an injection factor of +50%.

The third plot, indicated generally by the reference numeral 86, shows torque. The ideal case would be a sinusoidal back emf and sinusoidal current, which would give a flat torque. In the event of the PM machine having back-emf shown in the first plot and no harmonic current injection (represented in Fig. 8 by a trapezoidal back emf and sinusoidal motor currents), the torque generated has a large ripple (shown in the torque plot). The injection of harmonic currents in accordance with the principles of the present invention (represented in Fig. 8 by a trapezoidal back emf and trapezoidal motor currents) significantly reduces the size of the torque ripples (as is also shown in the torque plot of Fig. 8).

The FFT plot of Fig. 8 (indicated generally by the reference numeral 88) provides FFT plots of the two examples shown in the torque plot (i.e. using a motor with a back emf as shown in Fig. 8, one with harmonic injection, one without). As shown in the FFT plot, when harmonic injection is not used (represented in Fig. 8 by a trapezoidal back emf and sinusoidal motor currents) a substantial torque ripple (7%) is generated at the 6th harmonic (300Hz) and a smaller, but still significant torque ripple is generated at the 12th harmonic (600Hz). Where harmonic injection as described above is used (represented in Fig. 8 by a trapezoidal back emf and trapezoidal motor currents), torque ripples still occur at the 6th and 12th harmonics, but the size is significantly reduced (to below 0.3% in the plot of Fig.8).

While the present invention has been illustrated and described with respect to a particular embodiment thereof, it should be appreciated by those of ordinary skill in the art that various modifications to this invention may be made without departing from the spirit and scope of the present invention.

WHAT IS CLAIMED IS:

1. A method for regulating a set of first noise harmonics from a permanent magnet machine operatively connected to a power supply unit, the method comprising the step of injecting a second set of harmonics into a representation of a drive current provided to the permanent magnet machine in order to regulate at least part of the set of first noise harmonics, wherein the harmonics of the second set is/are different from the noise harmonics of the first set and wherein the noise harmonics of the first set include the 5^{th} and 7^{th} harmonics and the harmonics of the second set include the 6^{th} harmonic.

2. The method according to claim 1, wherein individual harmonics of the second set are weighted in accordance with an injection factor.

3. The method according to claim 2, wherein the individual harmonics of the second set are weighted differently.

4. The method according to any one of claims 1 to 3, wherein the individual harmonics of the second set are weighted between -125% and 125%.

5. The method according to any preceding claim, wherein the noise harmonics of the first set comprise the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics.

6. The method according to any preceding claim, wherein the harmonics of the second set comprise the 6^{th} and 12^{th} harmonics.

7. A power supply for regulating a set of first noise harmonics from a permanent magnet machine operatively connected to a power supply unit, said power supply comprising means for generating and injecting a second set of harmonics into a representation of a drive current provided to the permanent

magnet machine in order to regulate at least part of the set of first noise harmonics, wherein the harmonics of the second set is/are different from the noise harmonics of the first set and wherein the noise harmonics of the first set include the 5th and 7th harmonics and the harmonics of the second set include the 6th harmonic.

8. The power supply according to claim 7, wherein the means for generating and injecting the second set of harmonics is adapted to weight individual harmonics of the second set in accordance with an injection factor.

9. The power supply according to claim 8, wherein the individual harmonics of the second set are weighted differently.

10. The power supply according to any one of claims 7 to 9, wherein the individual harmonics of the second set are weighted between -125% and 125%.

11. The power supply according to any one of claims 7 to 10, said power supply being adapted to regulate the 5th, 7th, 11th and 13th harmonics of the first set.

12. The power supply according to any one of claims 7 to 11, said power supply being adapted to inject the 6th and 12th harmonics into the representation of a drive current.

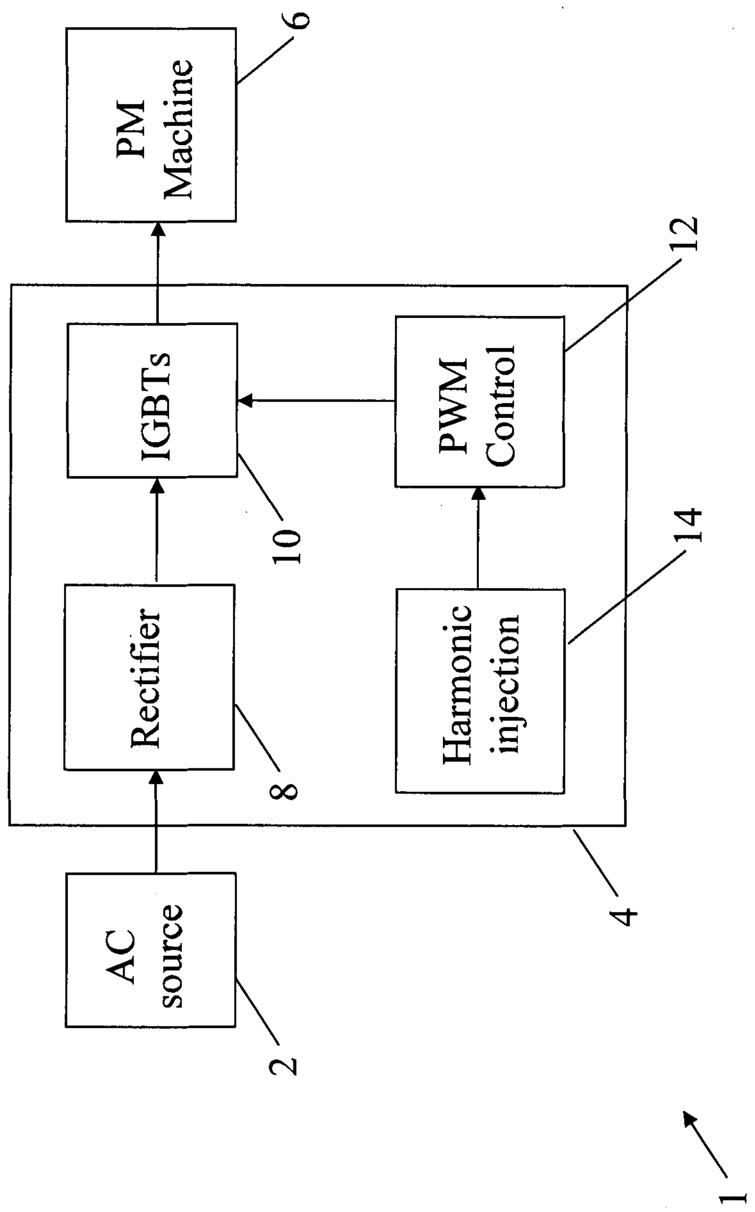

PM Machine
6
IGBTs
10
PWM Control
12
Rectifier
8
Harmonic injection
14
AC source
2
4
1

Fig. 1

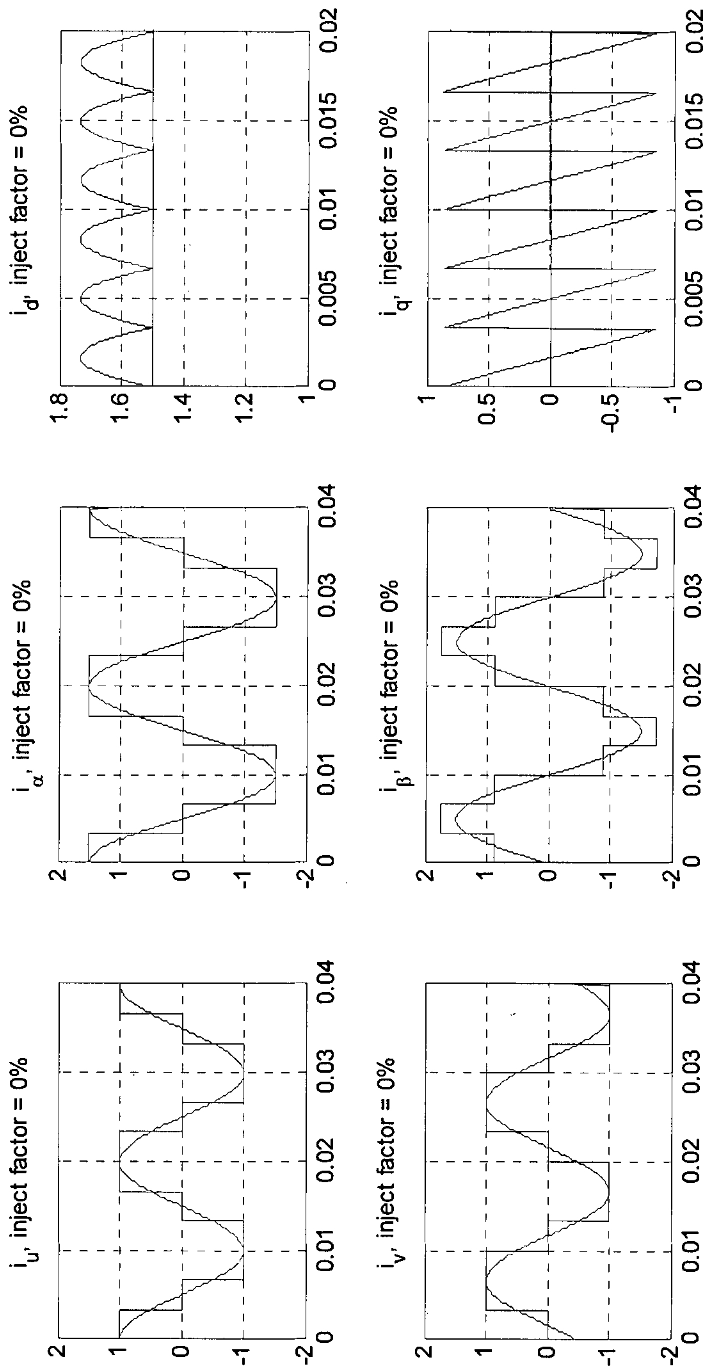

iu, inject factor = 0%
iα, inject factor = 0%
id, inject factor = 0%
iv, inject factor = 0%
iβ, inject factor = 0%
iq, inject factor = 0%

Fig. 2

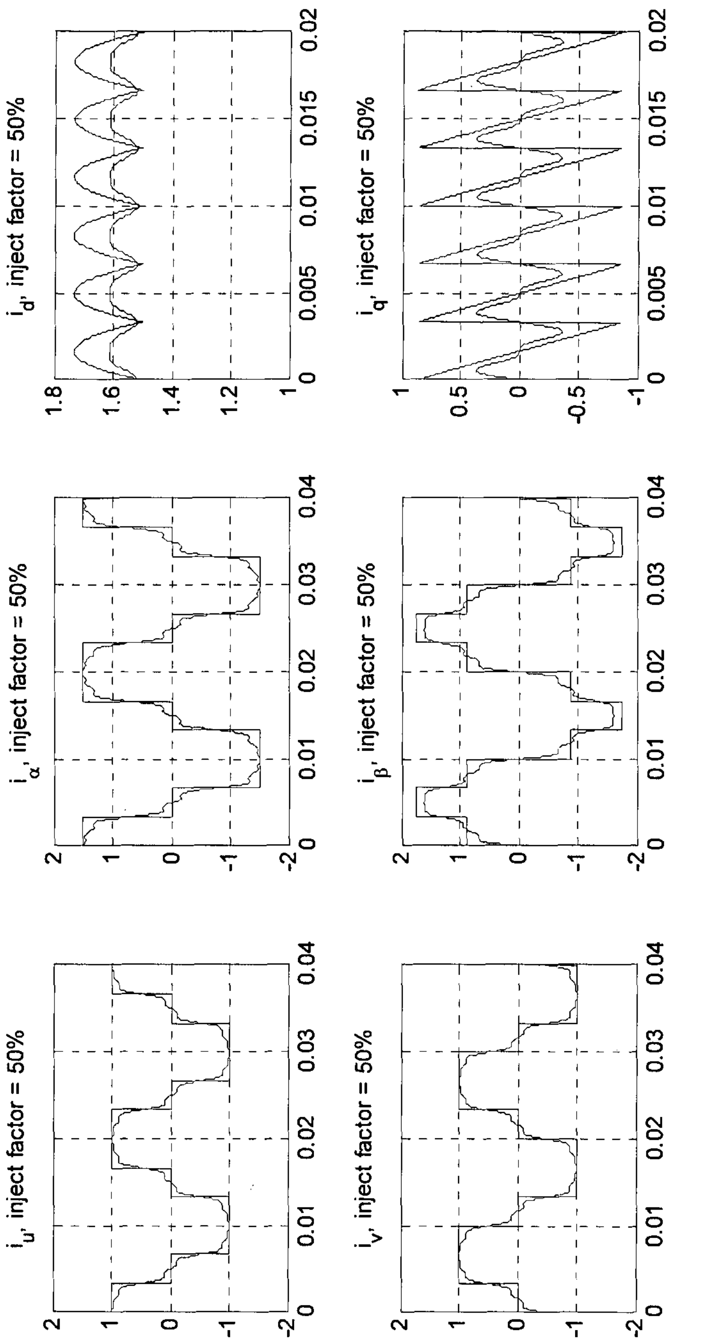

i_u, inject factor = 50%
i_v, inject factor = 50%
i_α, inject factor = 50%
i_β, inject factor = 50%
i_d, inject factor = 50%
i_q, inject factor = 50%

Fig. 3

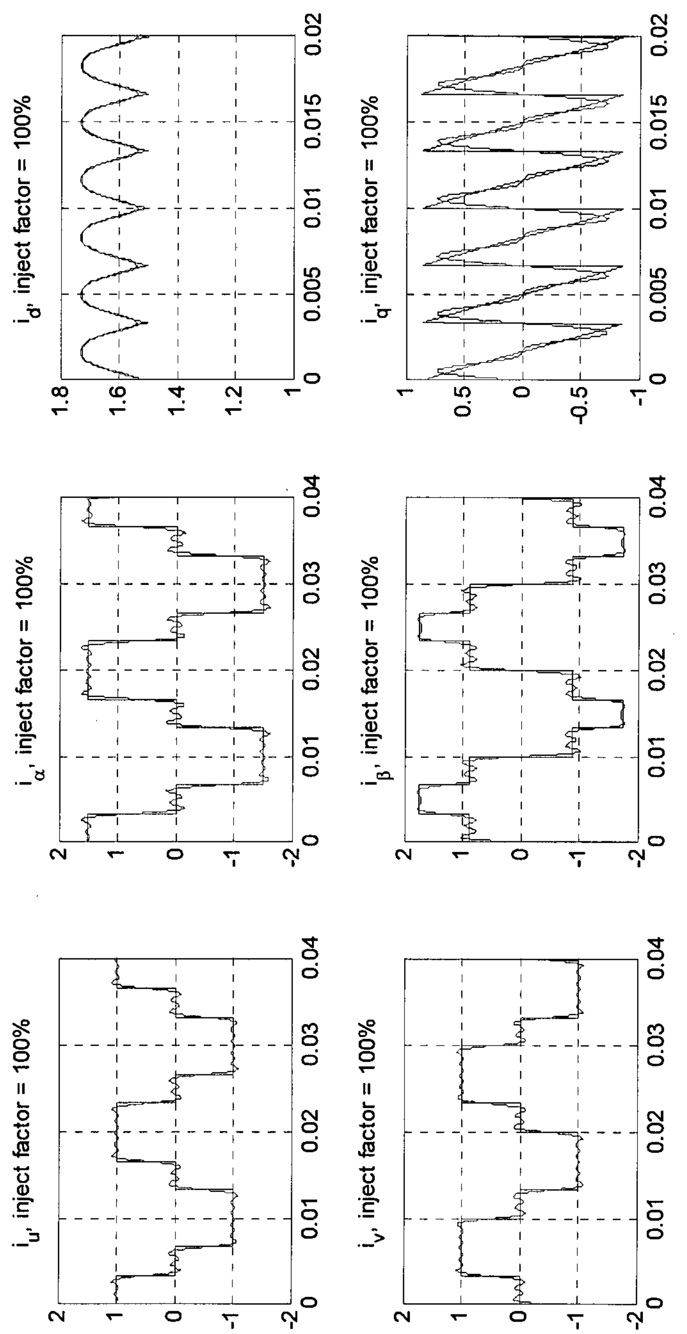
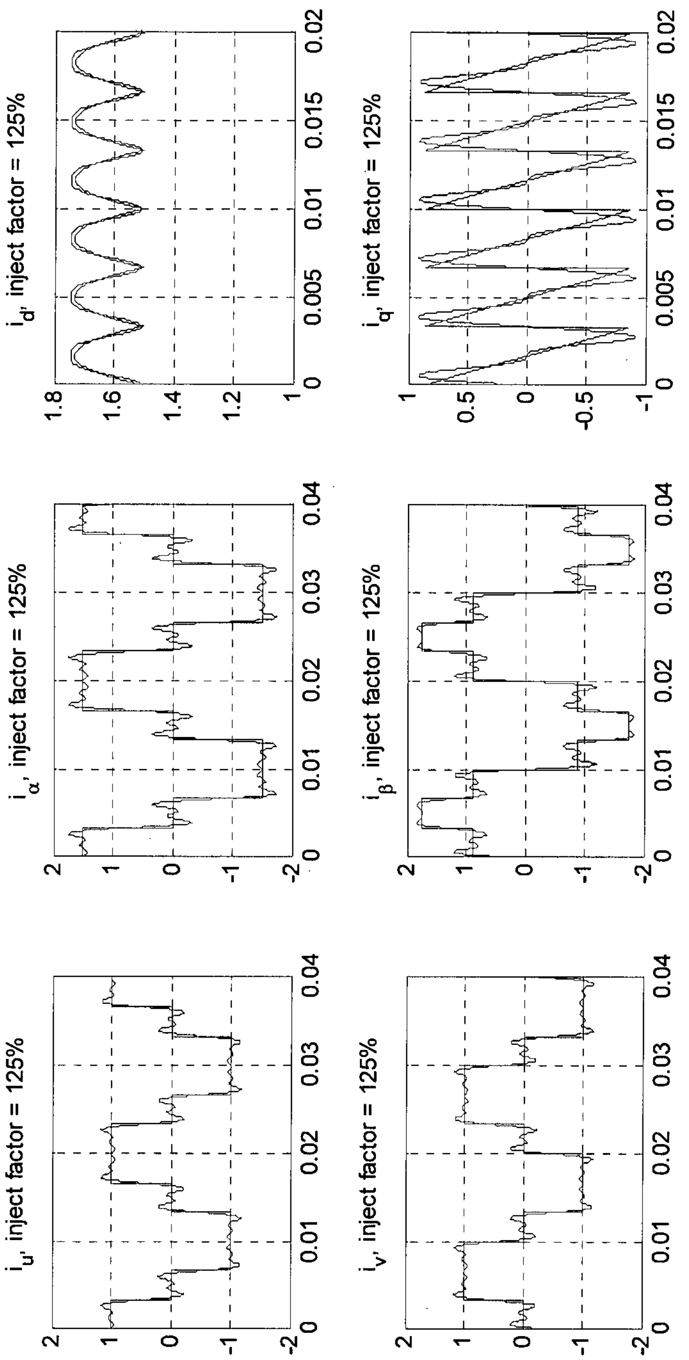

i_u, inject factor = 100%
i_v, inject factor = 100%
i_α, inject factor = 100%
i_β, inject factor = 100%
i_d, inject factor = 100%
i_q, inject factor = 100%

Fig. 4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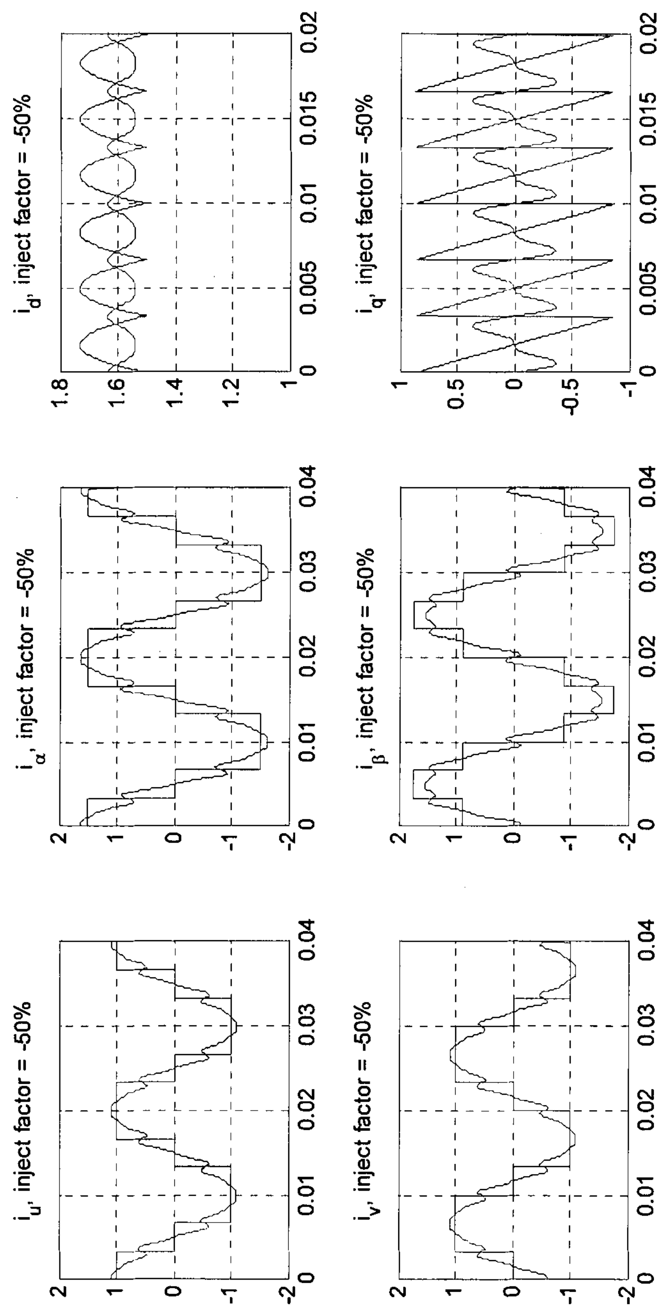
i_q, inject factor = 125%
i_α, inject factor = 125%
i_β, inject factor = 125%
i_u, inject factor = 125%
i_v, inject factor = 125%
0
0.005
0.01
0.015
0.02
0.03
0.04
1.8
1.6
1.4
1.2
1
0.5
-0.5
-1
2
-2

Fig. 5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i_v, inject factor = -50%
i_α, inject factor = -50%
i_β, inject factor = -50%
i_d, inject factor = -50%
i_q, inject factor = -50%

Fig. 6

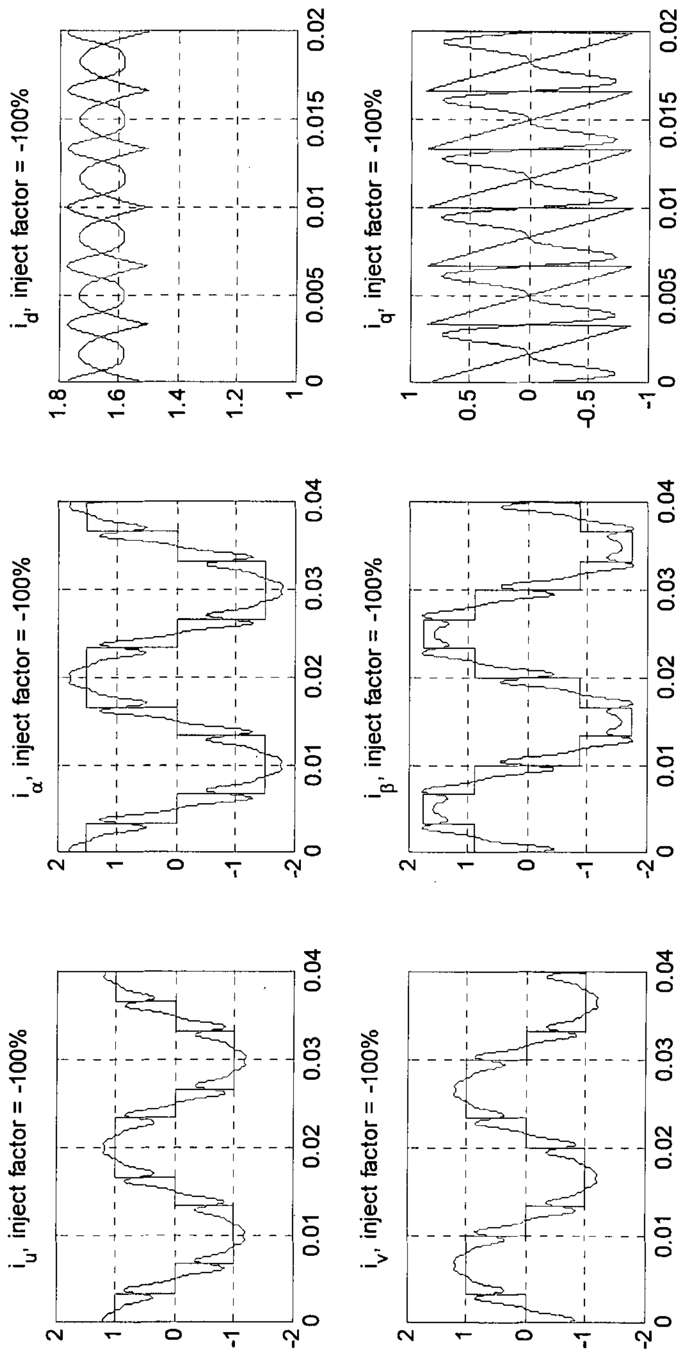
i_d, inject factor = -100%
i_q, inject factor = -100%
i_α, inject factor = -100%
i_β, inject factor = -100%
i_u, inject factor = -100%
i_v, inject factor = -100%

Fig. 7

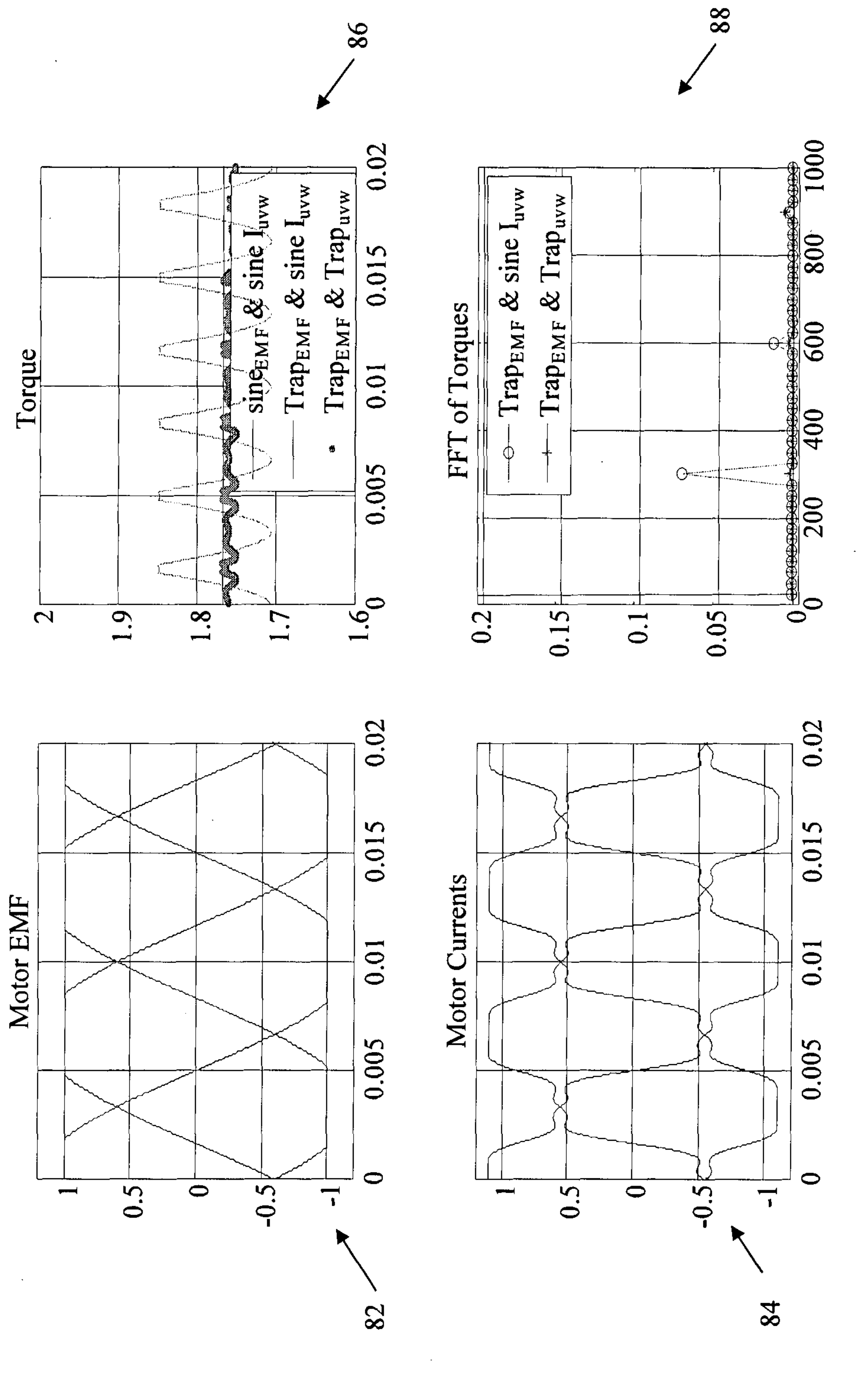
Motor EMF
Motor Currents
Torque
sine$_{EMF}$ & sine I$_{uvw}$
Trap$_{EMF}$ & sine I$_{uvw}$
Trap$_{EMF}$ & Trap$_{uvw}$
FFT of Torques
Trap$_{EMF}$ & sine I$_{uvw}$
Trap$_{EMF}$ & Trap$_{uvw}$
82
84
86
88

Fig. 8