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A Novel Control Method Based on Common Framework of VC and DTC for IPMS Motor Drives

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ABSTRACT

A new modeling of interior permanent magnet synchronous (IPMS) motor is carried out that propose a new control method for high performance control of the motor. The proposed control method is the combination of vector control (VC) and direct torque control (DTC). This new control method is direct control of current components deviations with hysteresis controller and predetermined switching table. Hence simpler and faster control performances than DTC and VC has been achieved. Simulation results along with theoretical analysis of IPMS motor show the effectiveness of the proposed method in comparison with the common methods.

KEYWORDS*:* Direct Torque Control; Vector Control; Interior Permanent Magnet Motor; Stator flux component deviation; Torque deviation.

I. INTRODUCTION

High performance control of AC motor as the cornerstone of the modern industry is implemented by different advanced control methods like vector control (VC) and direct torque control (DTC) [1]-[2]. However, VC and DTC differ substantially in the way they are implemented. More importantly, the mathematical foundations and the principles of the two methods are far apart [1]-[3]. In contrary, the theoretical and practical discrepancies of the VC and DTC have over shadowed the performance similarities of the two methods [3]-[4]. This fact raises a new opportunity toward a common framework for analysis of VC and DTC methods of motor drives providing new principles for proposing novel AC motor control systems. The common framework has been reported in [4] for interior permanent magnet synchronous (IPMS) motor and the detailed behavior of the basis component of the VC and DTC was shown. On the other hand, [4] has focused on the comparison of VC and DTC by looking for their principle similarities and searching for a common basis of VC and DTC. Besides, this common framework and new control method has partially been investigated for induction motor in [5].

In this paper the new modeling of IPMS motor is carried out to lay down a new control method for high performance control of the motor. The principle of VC and DTC are investigated and then proposed control method will be concluded based on the common framework. Simulation results show the improvement of the proposed method for high performance control of the motor.

II. MACHINE MODELING

In this section a basis analysis of the IPMS motor is performed in order to achieve common basis for VC and DTC. The electromagnetic torque of the IPMS motor can be obtained by [2]:

$$T_e = kA\left|\vec{\psi}_s\right|\sin\delta - kB\left|\vec{\psi}_s\right|^2\sin 2\delta \tag{1}$$

where:

$$A = 2\psi_m L_q \quad , \quad B = \left(L_q - L_d\right) \quad , \quad k = \frac{3P}{2L_q L_d} \tag{2}$$

Where $\psi_m, L_q, L_d, and\ P$ are the permanent magnet flux, stator a-axis and d-axis leakage inductances and the number of pole pairs, respectively. Also $|\vec{\psi}_s|$ and δ are the amplitude of stator flux linkage vector and the angle between the stator flux linkage and the permanent magnet flux respectively.

Accordingly the torque equation of the motor in the stator flux rotating frame (x-y reference frame) can be written [4]:

$$T_e = \frac{3P}{2}\left|\vec{\psi}_s\right| i_y \tag{3}$$

The stator flux and current vectors and their components are shown in rotor and stator flux rotating reference frames in Fig.1. According to Fig. 1 by changing the stator flux vector at the switching period of the inverter, and after simple calculations have been proved in [4], torque deviation is obtained as:

$$\Delta T_e = k_1 \Delta\psi_T + k_2 \Delta\psi_F \tag{4}$$

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where:

$$k_1 = k\left[A\cos\delta - 2B|\vec{\psi}_s|\cos 2\delta\right]$$
$$k_2 = k\left[A\sin\delta - 2B|\vec{\psi}_s|\sin 2\delta\right] \quad (5)$$

The terms $\Delta\psi_T$ *and* $\Delta\psi_F$ in (4) are the perpendicular and radial components of the stator flux deviation vector in the x-y reference frame respectively, as illustrated in Fig.1.

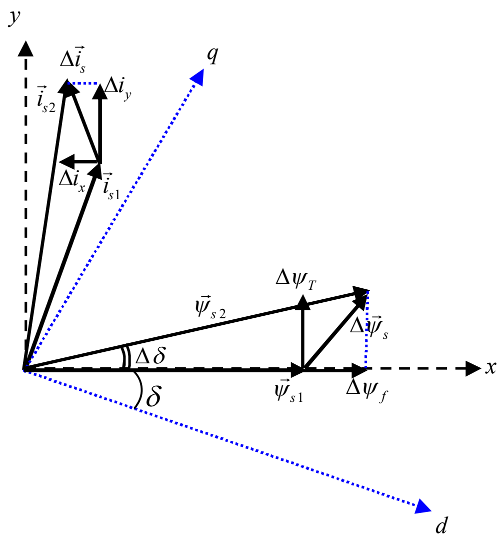

Fig. 1. Flux and current components deviation vectors in x-y reference frame.

Also considering the current vector variations instead of the flux vector variations and using (3), the torque deviation is expressed as below [5]:

$$\Delta T_e = k_3\Delta i_y - k_4\Delta i_x \quad (6)$$

where:

$$k_3 = k'\left(\frac{A}{B}\frac{\sin\delta}{\sin 2\delta} - \frac{2L_qL_d}{2\psi_m\sin\delta - \left[(L_d+L_q)+(L_d-L_q)\cos 2\delta\right]}i_x\right)$$
$$k_4 = k'\left(\frac{2L_qL_d}{2\psi_m\sin\delta - \left[(L_d+L_q)+(L_d-L_q)\cos 2\delta\right]}i_y\right) \quad (7)$$

Comparing (4) with (6) results in that the deviation of i_y is related to the perpendicular component of flux deviation $\Delta\psi_T$ and the deviation of i_x is related to the radial component of flux deviation $\Delta\psi_F$ i.e.:

$$\begin{cases}\Delta i_y \propto \Delta\psi_T \\ \Delta i_x \propto \Delta\psi_F\end{cases} \quad (8)$$

As the Fig.1 shows, the current deviation component (Δi_y) and flux deviation component ($\Delta\psi_T$) are aligned with the y-axis and the current deviation Δi_x and flux deviation component $\Delta\psi_F$ are aligned with the x-axis.

Therefore, (8) is proved that the radial component of the stator flux linkage deviation is proportional to the x-axis component of the stator current vector deviation and both are responsible for providing the motor flux. Also, the perpendicular component of the stator flux linkage deviation is proportional to the y-axis component of the stator current vector deviation and these are responsible for motor torque development.

Equation (8) proves the analogy between VC and DTC by showing that the current and flux terms are proportional. It is important to notice that (4) and (6) were developed regardless of control methods. Therefore, taking (8) into account, both (4) and (6) are valid for description of the motor behavior under any control method including VC and DTC.

The above discussion shows that the principles of VC and DTC can be presented by the components of current and flux deviations instead of the component themselves.

III. Proposed Control Method

In this section the proposed control method based on the analogy between VC and DTC is shown. The derivation based analysis presented in last section, can be used to lay down a common framework for a novel interpretation of VC and DTC. The interpretation is presented based on current and flux component deviations instead of the components themselves.

It is known that (1) can be used to present the DTC based on the stator flux vector. Fig. 2 shows a block diagram of a DTC IPMS motor drive in which the torque and flux errors via hysteresis comparators provide corresponding flags to decide the best voltage vector from a switching table[2]. It is well understood that in DTC method, torque changes by selecting proper voltage vectors according to the amplitude and angle of the stator flux vector that provide a faster torque response due to a faster selection of the stator voltage vectors. This, is due to use of a predetermined switching table instead of a much more time consuming PWM. Also, using fast hysteresis controller providing the inputs of the switching table, result in DTC with faster dynamic response. On the other hand according to Fig. 2 the torque and flux estimation are necessary in this control method.

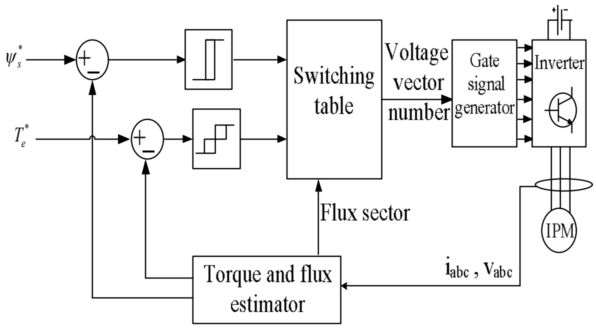

Fig. 2. DTC block diagram of the IPMS motor.

Equation (4) presents the new principles of DTC of IPMS motors by showing that the torque deviation is due to the deviations of the stator flux vector components instead of the component themselves [5].

Also (3) is used to present the principle of VC based on current components. In VC method the x-axis and y- axis components of the stator current vector are used in controlling the IPMS motor [1]. In other word in this control method the amplitude of stator flux linkage is kept constant by controlling i_x, and torque is controlled by controlling i_y. Fig. 3 shows a block diagram of a typical vector controlled IPMS motor drive. According to this figure proportional integral (PI) controller can control the stator current component and the appropriate voltage vectors are chosen by pulse width modulation (PWM) procedure. It should be mention that too much computational time is required in the PWM technique. Notice that in this control method, torque and flux estimation are no longer required.

On the other hand, (6) can presents the new principle of VC of IPMS motors by showing that the torque deviation is due to the deviation of current components i_x and i_y

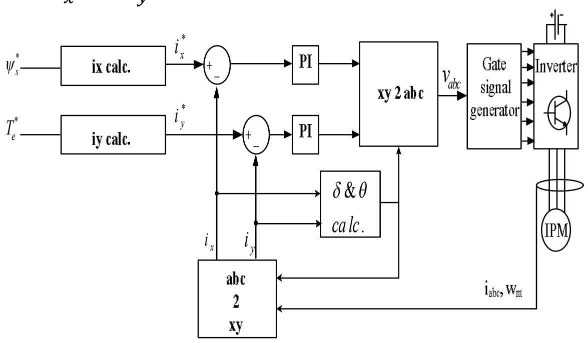

Fig. 3. VC block diagram of the IPMS motor.

According to the above concept the switching table with hysteresis controller and using the current components in motor controlling by neglecting the flux and torque estimation are the advantages of DTC and VC respectively.

Now a new control method based on the advantages of the above control methods will be investigated. In previous section a common behavior between VC and DTC is illustrated where the stator flux components in DTC have direct relationship with the stator currents components in VC. In other words due to (8) the switching table of DTC can be changed to Table 1 to achieve the mentioned advancement. In Table 1 for the hysteresis controllers' inputs, the corresponding x and y axis components of the stator current deviation vector is used with respect to (8) instead of flux and torque deviation.

So a new control method for IPMS is established which have the salient feature of two former methods. Also it eliminates some of these controller problems. The diagram of this new method is shown in Fig. 4. Hence by using current deviation in x-y reference frame and predetermined switching table, the proposed controller is simpler and faster than VC and DTC, respectively.

Table 1: The proposed control switching Table

Δi_x	Δi_y	region 1	2	3	4	5	6
↑	↑	$\vec{V}_2$	$\vec{V}_3$	$\vec{V}_4$	$\vec{V}_5$	$\vec{V}_6$	$\vec{V}_1$
	↓	$\vec{V}_6$	$\vec{V}_1$	$\vec{V}_2$	$\vec{V}_3$	$\vec{V}_4$	$\vec{V}_5$
↓	↑	$\vec{V}_3$	$\vec{V}_4$	$\vec{V}_5$	$\vec{V}_6$	$\vec{V}_1$	$\vec{V}_2$
	↓	$\vec{V}_5$	$\vec{V}_6$	$\vec{V}_1$	$\vec{V}_2$	$\vec{V}_3$	$\vec{V}_4$

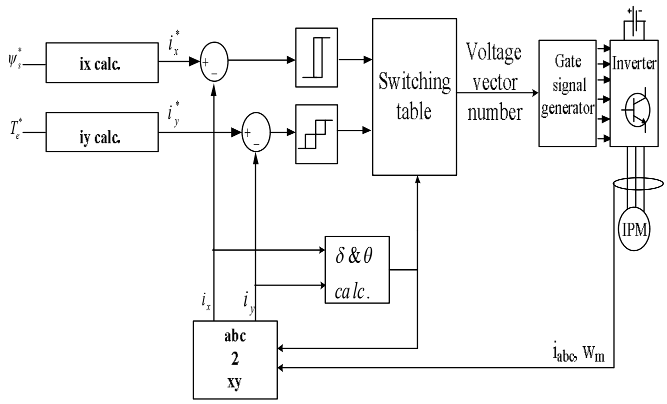

Fig. 7. The proposed control system of the IPMS motor.

IV. SIMULATION RESULTS

In this section the proposed control method is simulated to confirm it superiority over either VC or DTC. In order to have better comparison these three control methods are applied to the same IPMS motor. The motor parameters are given in the Appendix. Also, the same loading is used for all the control systems. After the motor speeds up to the commanded speed, a nominal load is applied to it at $t = 0.08\ sec$ and removed at $t = 0.15\ sec$.

Fig. 8 shows the motor speed under the three control systems. It is seen that the proposed control method has faster response than the VC to the speed command. Fig. 9 shows the motor developed torque under the three control systems. It is important that the torque development under the proposed method has less pulsation with respect to DTC and slightly more pulsations respect to VC. These are due to the indirect torque control and use the current hysteresis controller in the proposed control method respect to DTC and VC respectively. This results show the good behavior of the motor under the proposed control method as well as VC and DTC methods.

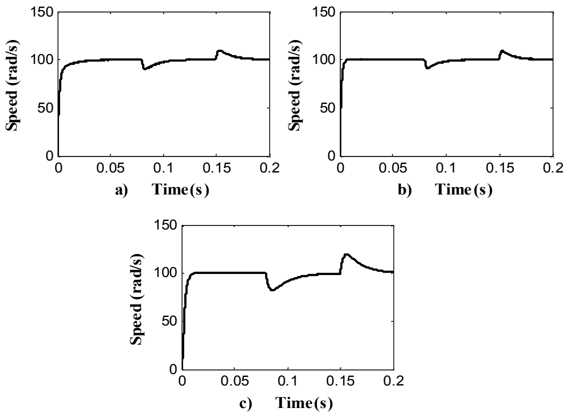

Fig. 8. The motor speed variation response under the three control methods: a) VC, b) DTC, c) proposed method.

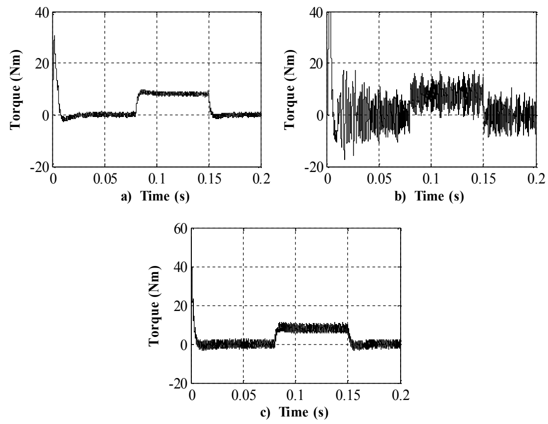

Fig. 9. The motor torque response under the three control methods: a) VC, b) DTC, c) proposed method.

Fig. 10 shows the stator phase current under these three control systems. It is seen that the current ripples under the proposed control method are less than those under DTC. This results in less torque pulsations as reported in Fig 9.

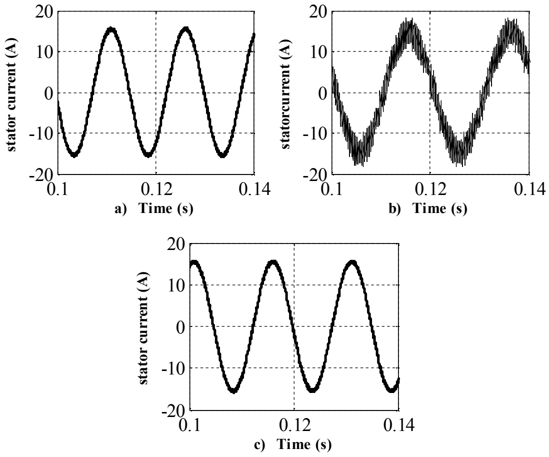

Fig. 10. The stator current under the three control methods: a) VC, b) DTC, c) proposed method.

Fig. 11 shows the stator flux variation under three control methods. It is evident that in the proposed control method the flux ripples are less than those under DTC and slightly similar to ones under VC. This is due to the direct control of the stator flux in DTC and indirect control of the stator flux in the proposed control and VC. Notice that according to the orientation of the stator flux vector in either VC or proposed control methods, it has fast dynamic as well as DTC.

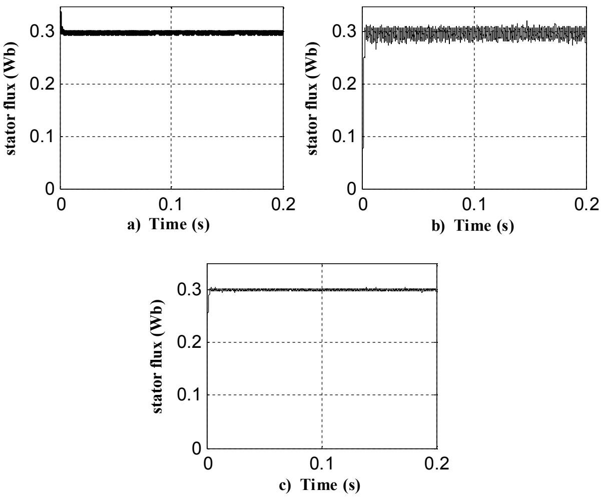

Fig. 11. The stator flux amplitude under the three control methods: a) VC, b) DTC, c) proposed method.

Fig. 12 and 13 show the x- and y- axis components of the stator current vector under three control methods. These current components in the proposed control method have more pulsation than VC and less pulsation than DTC. This fact is due to use the current hysteresis controller for the current components in the proposed control method.

Fig. 14 shows the flux trajectory under different control methods. According to this figure the flux response in proposed control method is as fast as other control methods.

The simulation results prove that the proposed control method can provide a desirable high performance control of the IPMS motor where illustrated the usefulness of the control system in demanding applications. Also, the proposed control system is presented here with a conventional switching table as in DTC. It is expected that the motor performance can be further improved by the proposed control method if an optimized switching table is used.

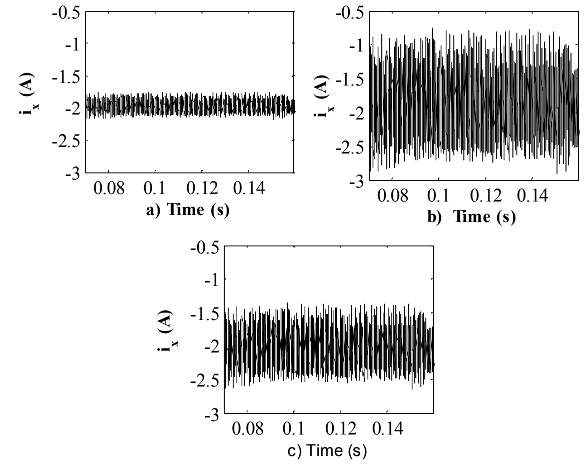

Fig. 12. X- axis component of the stator current under the three control methods: a) VC, b) DTC, c) proposed method.

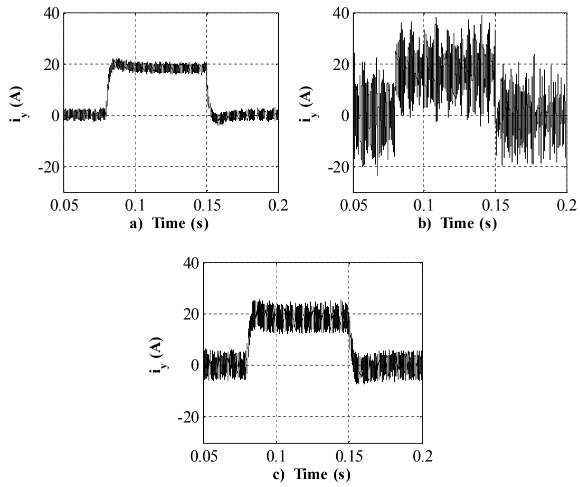

Fig. 13. y- axis component of the stator current under the three control methods: a) VC, b) DTC, c) proposed method.

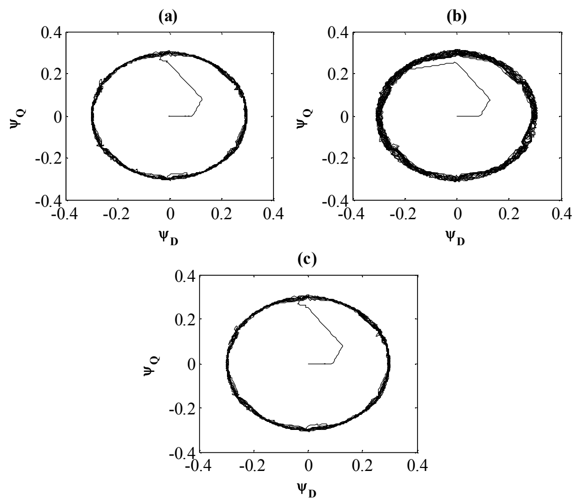

Fig. 14.Stator flux trajectory under the three control methods: a) VC, b) DTC, c) proposed method.

V. Conclusion

In this paper a new control method based on the combination of VC and DTC methods for high performance control of the motor is performed. Actually, this new control method is direct control of current components deviations with hysteresis controller and switching table.

It is shown that the radial component of the stator flux linkage deviations is proportional to the x-axis component of the stator current vector deviation hence both are responsible for providing the motor flux. Also, the perpendicular component of the stator flux linkage deviation is proportional to the y-axis component of the stator current vector deviation and these are responsible for motor torque development. Through this fact similar behavior for fundamental components of VC and DTC can be seen. Consequently, the new proposed method is implemented by using DTC along with VC component.

Simulation results indicate that the proposed control has simpler and faster control than VC and less system variable pulsations than those under DTC. Also it is proved that the proposed control method can provide a desirable high performance control of the IPMS motor.

APPENDIX

Motor Parameters:
Number of pole pairs = 3,
Stator resistance = 1.4 Ω,
Stator d-axis leakage inductance = 0.0511 H,
Stator q-axis leakage inductance = 0.066 H,
Magnet flux = 0.154 Wb.

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