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An Improved Method to Control the Speed and Flux of PM-BLDC Motors

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***Abstract*—Permanent Magnet Brushless DC (PM-BLDC) motors have become quite widespread and are utilized to serve for a variety of industrial purposes, because of their simple structure, high reliability and ease of control. Space Vectors theory is one of the most widely used methods which is implemented for controlling PM-BLDC. Supposing that each space vector refers to a unique arrangement of switch states, this theory calculates speed (or torque) error and stator flux error, compared to reference parameters. Consecutively, based on the aforementioned issues the most appropriate voltage vectors are attained to excite the stator phases. Ripples in speed and torque, are the main concerns, such methods try to deal with. In this paper, in addition to speed and flux errors, the speed variation slope is used as an auxiliary control parameter for a more precise speed control and decreasing speed ripples. The simulation results demonstrate a promising efficacy and accuracy of the proposed method.**

Keywords—PM-BLDC motors, Space Vectors Theory, Speed Control

I. INTRODUCTION

BLDC motor, as National Electrical Manufacturers Associations (NEMA) clearly defines, is "a rotating self-synchronous machine with a permanent magnet rotor and with known rotor shaft position for electronic commutation" [1]. These motors mostly have concentrated windings on their stators which are fed by a power electronic converter [2].

In recent years, regarding their specific advantages, PM-BLDC-equipped variable speed drives, have found multifarious usages in industry. Of these advantages, simple structure, ease of control, high efficiency, high power density and large torque-to-inertia ratio, can be enumerated. Aeronautics, Electric Vehicles, Servo Drives, military and domestic usages are the main industrial area that make use of PM-BLDC motors [3-5].

In literature, a variety of methods have been put into practice to control the speed and torque of PM-BLDC motors [6]. All of the proposed control methods have aimed to reach a ripple-free speed and torque besides flux control. Within the previous decades, conventional controllers such as P, PI and PID were mainly used for controlling PM-BLDC motors. Since such methods require real-time calculations and controllers with a high-speed response in order to track reference current, they have a perplexing implementation[2]. What's more, these methods are not capable of producing a high-speed torque response and the linearization process used in this mode used in them is not guaranteed to have the desired accuracy. In addition, the variations in motor parameters, which is inevitable due to ambient conditions, adversely affect the efficacy of the conventional control systems [7].

To overcome the above-mentioned deficiencies, in the past two decades, Space Vector Modulation-based control methods like Direct Torque Control (DTC) were introduced. At first stages, these methods were used for controlling the induction machines, later they were employed to control PM-BLDCs [6]. In these methods, a series of voltage vectors are introduced, so that each represent a specific arrangement of switch states. Each vector, dependent on the position of the rotor, leads to an increase or decrease in the torque and the flux. By making a comparison between the actual torque and reference torque, and by taking account the rotor position and the error of torque and flux into account, the appropriate voltage vector will be selected, so that torque and flux stay closest to their reference values [8]. Space vector based methods, such as DTC, switching frequencies are not equal in upper and lower switches of the same leg and the common mode voltage is usually high, which can get problematic in some cases [9]. Severe ripples in rotor speed and torque can be other disadvantages of aforementioned method.

In this paper an improved method is proposed to control PM-BLDC motors, which makes use of space vectors but mitigates the speed ripple problem. In addition to the parameters used in similar speed control methods, such as rotor speed and stator flux, this paper uses the slope of speed variations as an auxiliary control parameter to perform a more accurate speed control in the adjacency of reference speed and reduce speed ripples.

This paper is organized as follows: in section II the space vector theory is discussed in details; in section III the proposed method for speed control in PM-BLDC motor is presented; in section IV the efficiency of the proposed method is investigated and compared with conventional methods using real-time simulation in MATLAB software.

II. PRINCIPLES OF VOLTAGE SPACE VECTOR BASED CONTROL

The feature that makes voltage space vector based control stand out from other control methods, is its capability of direct and independent control of speed (or torque) and flux. In this method, regarding the deviations of speed (or torque) and stator flux from their reference values, the appropriate voltage vector is picked from switching table. Each vector represents a unique arrangement of power electronic converter switches being turned on or off. Fig. 1 obviously shows that the component of voltage which is perpendicular to flux vector, contributes to the production of positive or negative torque. Nevertheless, the component of voltage vector which is tangent to the flux vector results in the increase or decrease in stator flux. This control method, makes the speed stay close to its reference value so that flux varies within a circle band around the reference flux.

There are several types of switching methods such as two phase, three phase and combined two and three phase switching which are used for controlling PM-BLDC motors. A brief description of these methods is presented in the following subsections.

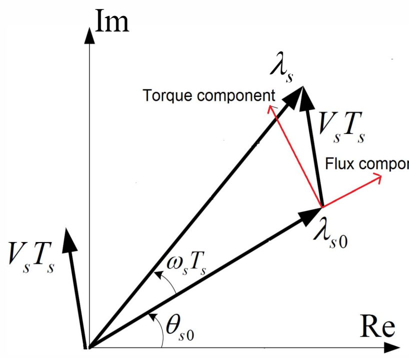


Figure 1. Flux and Torque component of voltage vector

A. Non-Zero Voltage Space Vector of Three Phase Conduction Mode

This switching method, makes use of six voltage space vectors, which divide the $\alpha\beta$ plane into six equal areas, referred to as Sectors, shown in Fig.2. Suppose that the state of the switches is encoded by binary numbers, so that for voltages V_1, V_2, V_3, V_4, V_5 and V_6 in Fig.2, we can present the switch states by following arrays: (100101), (101001), (011001), (011010), (010110) and (100110). Each of these binary codes consist of 3 pairs of binary digits, which respectively show the state of the upper and lower switches of the phases A, B and C, where 0 indicates the Off state and 1 indicates the On state for the pertaining switch[10].

The vectors presented above, can be utilized in specific occasions, dependent on the rotor position, rotor speed and flux magnitude. When the stator flux vector is situated in Sector 1, while the rotor is rotating counter-clockwise, vector V_3 will increase the torque. Using this vector in Sector 1, it should be noted that in the first half of the sector, along with the increase in torque, the flux will deplete; on the contrary, in the second half of the Sector 1, it will increase the flux; as for the middle of the sector, it does not alter the flux in any directions.

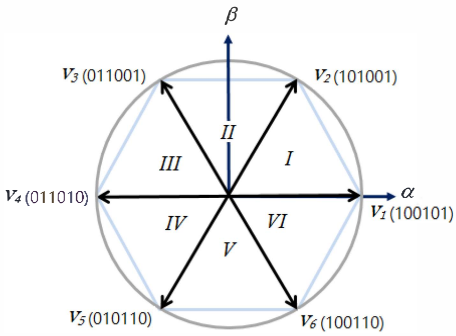


Figure 2. Non-zero voltage vectors for three-phase conduction mode.

Table 1.Voltage vector selection for three phase conduction without flux control

Speed	Sector					
	I	II	III	IV	V	VI
Increasing	V_3	V_4	V_5	V_6	V_1	V_2
Decreasing	V_6	V_1	V_2	V_3	V_4	V_5

Some voltage vector based control methods tend not to have any control on the flux, thus they use the vectors which have the least effect on the stator flux. Such vectors, shown in Table 1, are chosen, regarding the rotor position, speed (or torque) error[10].

B. Non-Zero Voltage Space Vector of Two Phase Conduction Mode

Alike the method presented above, non-zero voltage space vector of two phase conduction mode consists of six voltage vectors and six sectors. In this method, the voltage vectors V_1, V_2, V_3, V_4, V_5 and V_6 are defined by the following arrays: (100001), (001001), (011000), (010010), (000110) and (100100), where only two phases are permitted to be switched. Fig. 3 demonstrates the non-zero voltage space vectors for two phase conduction mode. The effect of each vector on the flux and the torque, regarding the rotor position, is shown in Table 2.

C. Non-Zero Voltage Space Vector of Combined Two and Three Phase Conduction Mode

This method makes use of both two-phase and three-phase vectors, hence it will consist of twelve vectors and twelve sectors, each sector spanning 30 degrees[11]. In Fig.4 sector divisions along with two phase and three phase vectors are shown. An example might help to elaborate on method. In Sector 1, vector V_4 produces the maximum positive torque; V_2 and V_6 produce the minimum torque; while V_3 and V_5 result in a medium torque. In another view, V_2 and V_3 increase the flux while V_5 and V_6 decrease it. Having all this in mind, if we aim to reduce the speed, we can utilize vectors V_8, V_9, V_{10}, V_{11} and V_{12}. In this case, V_{10} will produce maximum negative torque; V_{12} and V_8 will produce minimum negative torque; while V_{11} and V_9 will result in a medium negative torque. It is obvious that V_{11} and V_{12} increase the flux, while V_9 and V_{11} decrease it.

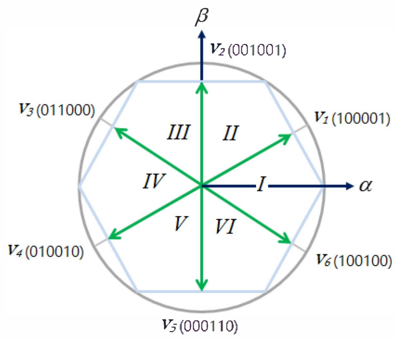
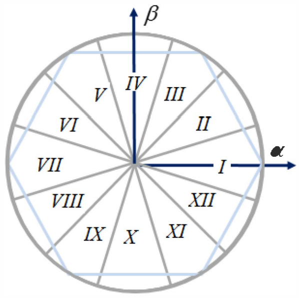


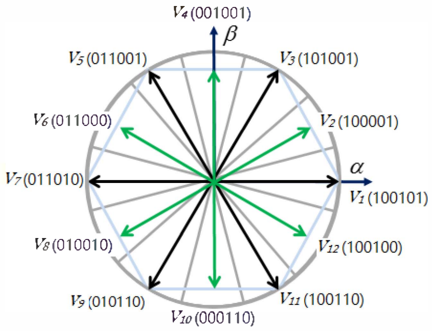
Figure 3. Non-zero voltage vectors for two-phase conduction mode.

Table 2. Voltage vector selection for two phase conduction mode

φ	τ	SECTOR					
		I	II	III	IV	V	VI
1	1	V_1	V_2	V_3	V_4	V_5	V_6
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_2	V_3	V_4	V_5	V_6	V_1
	-1	V_5	V_6	V_1	V_2	V_3	V_4
-1	1	V_3	V_4	V_5	V_6	V_1	V_2
	-1	V_4	V_5	V_6	V_1	V_2	V_3



(a)

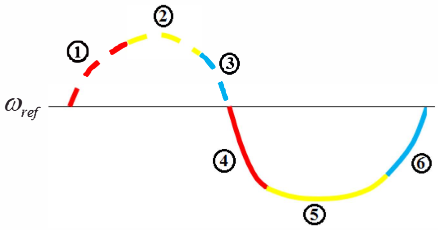


(b)

Figure 4. Twelve sectors (a), and 12 voltage space vectors (b) of combined two and three phase conduction mode.

III. Proposed Method

As discussed in section I, speed ripple is one the major concerns in controlling PM-BLDC motors. In this paper, speed variations' slope is used as an auxiliary control parameter to mitigate this problem. Fig.5 (a) shows the pattern of putting this auxiliary parameter into effect. In this method, combined two-phase and three phase switching is implemented.



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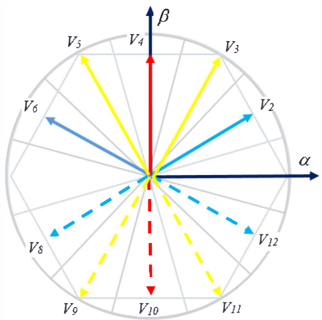


(b)

Figure 5. Six different states of speed variation slope (a) and appropriate voltage vectors assigned to each in sector I (b)

Table 3. Voltage vector selection for proposed method in sector 1

speed	Type of speed variation	$\lambda_s > \lambda_{ref}$	$\lambda_s < \lambda_{ref}$
$\omega > \omega_{ref}$	Increase with high slope	V_{10}	V_{10}
	Variation with low slope	V_9	V_{11}
	Decrease with high slope	V_8	V_{12}
$\omega < \omega_{ref}$	Increase with high slope	V_6	V_2
	Variation with low slope	V_5	V_3
	Decrease with high slope	V_4	V_4

Adding speed variations' slope to the control parameters results in the constraints enumerated below:

1. If the rotor speed is higher than reference speed and its rising slope is high (red dash line in the curve), the voltage vector that produces the maximum negative torque will be chosen.

2. If the rotor speed is varying with a mild slope in a speed higher than reference speed (yellow dash line in the curve), the voltage vector that produces the medium negative torque, will be chosen.

3. If the rotor speed is higher than the reference speed and moves towards the reference speed with a very high slope (blue dash line in the curve), the voltage vector which produces the minimum negative torque, will be chosen.

4. If the rotor speed is lower than reference speed and is decreasing with a notable slope (red line in the curve), the voltage vector that produces the maximum positive torque, will be chosen.

5. If the rotor speed is lower than the reference speed and it varies with a mild slope (yellow line in the curve), the voltage vector which produces medium positive torque, will be chosen.

6. If the rotor speed is lower than the reference speed and is moving towards the reference speed with a high slope (blue line in the curve), the voltage vector that produces the minimum positive torque will be chosen.

The constraints of speed variations' slope is considered in such a way that the speed deviations around its reference value decreases to its minimum possible value. It should be noted that in all steps pinpointed above, the constraints of flux error is considered as well. Regarding the number of possible choices for voltage vector, between the two possible vectors for each state, the voltage vector that makes the stator flux closer to the reference flux, will be picked. In order to fulfil this purpose, one comparator will be used to compare the amount of stator flux with its reference value. In each instant of time, the components of stator flux are calculated as indicated in equations (1), (2):

$$\varphi_{s\alpha} = \int (V_{s\alpha} - R_s\, i_{s\alpha})dt \tag{1}$$

$$\varphi_{s\beta} = \int (V_{s\beta} - R_s\, i_{s\beta})dt \tag{2}$$

Where R_s is phase resistance. $V_{s\alpha}, V_{s\beta}, i_{s\alpha}$ and $i_{s\beta}$ are the components of phase voltage and current in $\alpha\beta$ coordinate.

Table 4. Voltage vector selection for proposed control method

	T	+		++		+++	---	--		-	
	φ	+1	-1	+1	-1	0	0	+1	-1	+1	-1
SECTOR	I	V_2	V_6	V_3	V_5	V_4	V_{10}	V_{11}	V_9	V_{12}	V_8
	II	V_3	V_7	V_4	V_6	V_5	V_{11}	V_{12}	V_{10}	V_1	V_9
	III	V_4	V_8	V_5	V_7	V_6	V_{12}	V_1	V_{11}	V_2	V_{10}
	IV	V_5	V_9	V_6	V_8	V_7	V_1	V_2	V_{12}	V_3	V_{11}
	V	V_6	V_{10}	V_7	V_9	V_8	V_2	V_3	V_1	V_4	V_{12}
	VI	V_7	V_{11}	V_8	V_{10}	V_9	V_3	V_4	V_2	V_5	V_1
	VII	V_8	V_{12}	V_9	V_{11}	V_{10}	V_4	V_5	V_3	V_6	V_2
	VIII	V_9	V_1	V_{10}	V_{12}	V_{11}	V_5	V_6	V_4	V_7	V_3
	IX	V_{10}	V_2	V_{11}	V_1	V_{12}	V_6	V_7	V_5	V_8	V_4
	X	V_{11}	V_3	V_{12}	V_2	V_1	V_7	V_8	V_6	V_9	V_5
	XI	V_{12}	V_4	V_1	V_3	V_2	V_8	V_9	V_7	V_{10}	V_6
	XII	V_1	V_5	V_2	V_4	V_3	V_9	V_{10}	V_8	V_{11}	V_7

In Fig. 5 (b) the appropriate vectors for controlling the speed in each of the parts shown in Fig. 5 (a) is presented for sector1. For example, if the stator flux position is situated in Sector 1 and the speed curve is sharply increasing from a point below the reference speed (the red dash line in Fig.4), the voltage vectors V_2 or V_6, which produce the minimum positive torque will be used. The criterion which is used for choosing one of these vectors, is the stator flux error. So if the stator flux is lower than the reference flux, vector V_2 will be used, otherwise V_6 will be more suitable. The order of picking voltage vectors is summarized in Table 3 for Sector 1 and in Table 4 for all sectors. The block diagram of proposed method is shown in fig. 6.

IV. SIMULATION RESULTS

To validate the efficiency of the improved switching method, presented above, the control system shown in Fig. 6 is simulated in MATLAB software. Additionally, the same simulation is performed with two phase and three phase switching methods, so that the results can be compared with each other. Parameters of the studied PM-BLDC motor are presented in Table. 5. The reference speed is considered to be 2000 rpm, in all the stages of simulation. Fig. 7 illustrates the speed variation trends, resulting from implementation of the aforementioned switching methods. As it can be easily inferred from Fig. 7 the rotor speed ripple, when using the two phase and three phase switching method, is 40 rpm and 32 rpm respectively. But, when the proposed switching method is put into practice, the speed ripple value will decrease to 6.5 rpm, which means 83.75 % and 79.69 % reduction in speed ripple compared to two phase switching method and three phase switching method respectively.

The electromagnetic torque of the PM-BLDC motor in each of the three simulated switching methods is presented in Fig. 8 Apparently, the proposed method presents a lower torque ripple compared with the two other switching methods.

In Fig. 9 the stator flux variations are illustrated in $\alpha\beta$ plane. As expected, the stator flux is varying within a circle band. Note that, since the switching frequency is significantly higher than the conventional switching methods, it is recommended that the permitted band for flux variations be extended, so that the switching frequency decreases. Finally the current of the phase A of the PM-BLDC motor, when using the proposed switching method is presented Fig. 10.

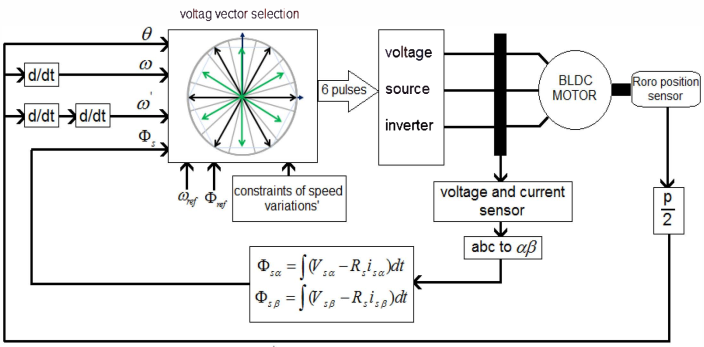
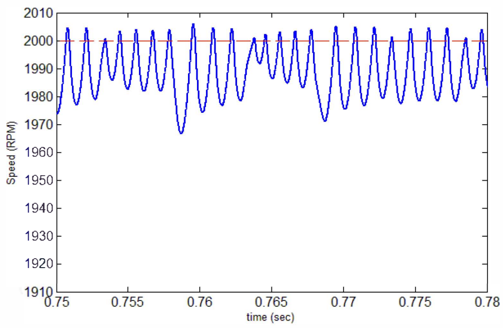
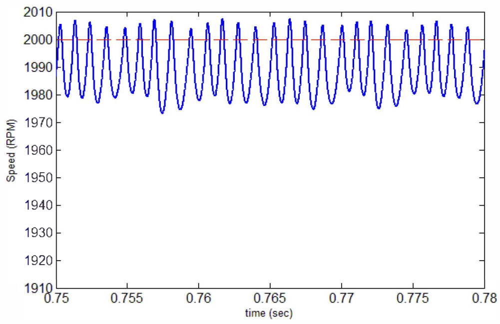


Figure 6. Block diagram of the proposed method



(a)



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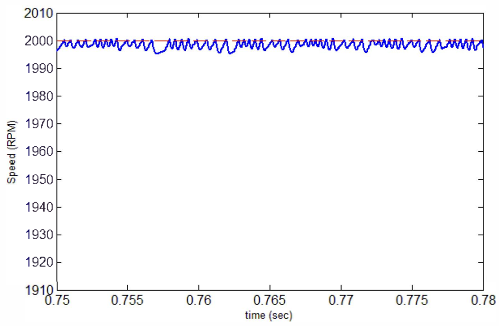
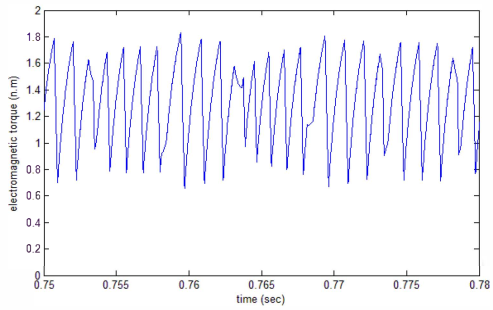


(c)

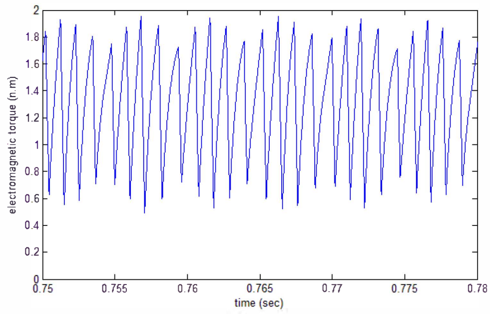
Figure 7. Speed waveform of two phase switching (a), three phase switching (b) and Proposed method switching with flux control (c)

Table 5. PM-BLDC motor specification

Parameter	Value	Unit
Terminal voltage	120	Volt
Torque constant	0.095	Nm/Amp
Stator resistance	2	Ohm
Stator Inductance	2	mH
Rotor inertia	0.00006	Kg-m^2
Load Torque	1	Nm
Poles number	2	-



(a)



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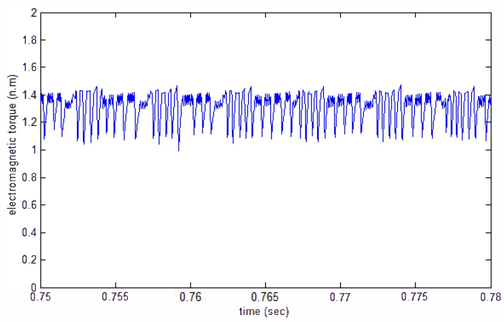

(c)

Figure 8. Torque waveform of two phase switching (a), three phase switching (b) and proposed method switching with flux control(c)

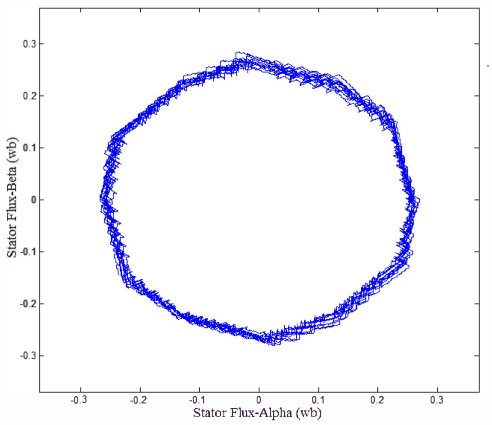

Figure 9. Stator flux linkage locus

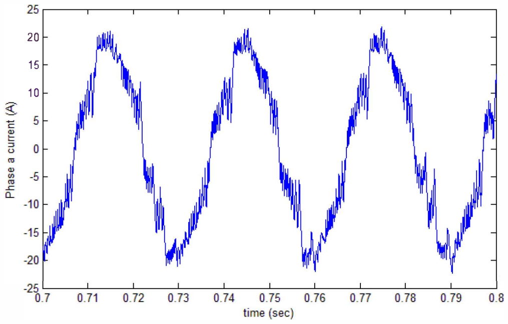

Figure 10. Current waveform (i_a)

V. CONCLUSION

In this paper a novel method was introduced for controlling PM-BLDC motors. This method is based on space vectors theory and utilize speed variations' slope as an auxiliary control parameter, to efficiently control the rotor speed and reduce the speed ripple. The conventional speed control methods used for PM-BLDC motors, along with the proposed method, are presented. Finally, two-phase and three-phase switching methods as well as the presented method, are implemented in simulation and the results are compared. As the results reveal, by using the proposed method for speed control, the speed ripple decreases significantly by more than 75 percent.

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