Time response analysis for two-phase PMSM with two-sectional phase windings

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Abstract. A new approach to investigation of two-phase PMSM control methods on the level of phase windings sections is presented. For two-phase PMSM with two-sectional windings all control methods are considered from a unified position. Section and phase usage variants implementable at all possible section connection schemes are determined and classified; armature magnetic induction vector amplitudes and angle positions are calculated. The vectors are grouped by graphical representation, phase usage variant and section connection scheme into sets, number of which leading to non-zero vectors and the zero vector is determined. A simulation is carried out, speed time response curves are calculated and compared; the affecting of section connection scheme and phase usage variant on speed transition time and idle speed is ascertained; groups are discovered, section connection schemes can be attributed to. The obtained results can be used in demand by drive developers to select the most suitable PMSM control method.

1. Introduction
Nowadays a transition process is going on to the new technological order which is grounded on new hardware basis and characterized with digital intelligent control methods. Qualitative changes in production, control and usage of electric motors have been occurred and a great variety of electric motors and control methods has appeared.

This fact has led to application of polyphase permanent magnet synchronous machine (PMSM) in modern drives and expansion of drives’ application area. The most often three-phase motors are in use, two-[1–3] and single-phase [4] motors find application. Research investigations of motors with five phases and more [5–7] are being carried out.

Motor characteristics depend on phase number, winding connection scheme and control method. The motor’s phase windings consisting of sections bring in additional control methods. For two-phase PMSM with two-sectional winding questions about effecting of section connection scheme and control method on static and dynamic characteristics are remaining not fully explored. It needs to make sophisticated investigations to select the most suitable method for a certain problem solving.

2. Theory and vector forming methods
2.1. Terms and definitions
Corresponding to the sectional approach proposed in [8], following terms and definitions are introduced: sectional vector (SV)—armature magnetic induction vector formed by one section; unit sectional vector—armature magnetic induction vector forming by one section when full supply voltage is applied to it and full current flows; phase vector (PV)—total vector of all sections belonging to
the same phase; base vector (BV)—resulting vector of all phase ones. It is acting between adjacent phase switchings; base vector set—a set of all base vectors at a certain motor control method.

2.2. Section and phase designation

A through designation system of phases, sections and their leads is introduced and presented in table 1. It is an improved version of the system presented in [9]. In rows phases are placed, in columns—sections. The columns are divided into two parts section leads are shown in. The phases are designated with letters: capital ones—when a whole phase is under consideration, and lowercase ones point to the phase the section belongs to.

| Table 1. Designation of phases, sections and their leads. |
|----------------------------------------------------------|
| Phases | Sections 1 | Sections 2 |
|--------|------------|------------|
| A      | $a_{11}$   | $a_{12}$   |
|        | $a_{21}$   | $a_{22}$   |
| B      | $b_{11}$   | $b_{12}$   |
|        | $b_{21}$   | $b_{22}$   |
| C      | $c_{11}$   | $c_{12}$   |
|        | $c_{21}$   | $c_{22}$   |
| ...    | ...        | ...        |
| P      | $p_{11}$   | $p_{12}$   |
|        | $p_{21}$   | $p_{22}$   |

The first index points to section number, the second one—to its lead number. For example, $a_{12}$—the second lead of the first section of the A phase. When a section is considered as a whole unit, the first index only is specified. If needed, number of phases and sections can be increased.

2.3. Equivalent circuit

In accordance with the sectional approach, an equivalent circuit has been composed (figure 1). It is allocated on a complex plane. Due to the phases’ perpendicularity, values of sectional vectors’ projections on collinear axis are equal to the same values, and on perpendicular axis—to zero.

![Figure 1. Equivalent circuit of the armature winding of the two-phase BLDC motor.](image-url)
By vector calculation following assumptions are made:
1) resistances and inductances of all sections are equal;
2) back-EMF of each section is considered as equal to zero;
3) mutual inductance of sections is equal to zero.

Since position of each section in the complex plane is independent on section connection scheme or phase participation variant in BV forming, the equivalent circuit makes it possible to consider all available motor control methods as different compositions of the same sections in use.

3. Base vector forming

Base vectors are depending on section connection scheme and phase usage variant. There are six section connection schemes for a two-phase PMSM with two-sectional windings (figure 2): with unconnected sections (a), parallel (b), serial (c), two radial ones: “star” with common point connected either to the supply bus or to the ground (d) and “star” with neutral point (e), and, finally, the closed scheme “square” (f).

![Figure 2. Section connection schemes.](image)

The introduced designation and sections' position on the complex plane are kept on the connection schemes; owing to this, it is simple to determine the participation of each section in the vector forming along an appropriated axis at a certain section connection scheme.

In table 2 possible participation variants of two sections belonging to an arbitrary phase (designated with P letter) in forming of PV, are shown. They are hereinafter referred to as
“section usage variants”. In one-phase motor PV coincides with BV, as PV is single. A PV amplitude is derived as a sum of SV ones and depends on variant choice. Their total number is 9, 3 of them correspond to the zero vector.

**Table 2.** Section usage variants.

| Designation | Name                          | Phase Vector                                      | Number of PVs |
|-------------|-------------------------------|---------------------------------------------------|---------------|
| $P$         | active phase                  | is equal to sum of co-directional sectional vectors | 2             |
| $\overline{P}$ | passive phase             | is equal to zero, as all sectional vectors are equal to zero | 1             |
| $\overline{p}$ | phase with a passive section | corresponds to one non-zero sectional vector       | 4             |
| $p^*$       | phase with opposite active sections | is equal to zero                                   | 2             |

In a two-phase PMSM with two-sectional windings there are $A$ and $B$ phases, combinations of their section usage variants for BV forming are named “phase usage variants”. Total number of them is 81. This number is a particular case of an $n$-phase motor with two-sectional windings (at $n = 2$), where BV forming variant number is $3^{2n}$. The value 3 in the degree’s base represents possible SV direction number along the real or the imaginary axis: positive, negative and zero. When only number of sections participating in PV forming is considered and not, which section of the two ones produces an SV, we have 16 phase usage variants (figure 3), 4 variants of them lead to zero BV (designated by grey background). The number of zero BV equals to $2^n$.

![Figure 3. Usage variants of A and B phases.](image-url)

In case of three-phase machine with two section windings there are 64 variants and 8 ones with zero vector. Total BV forming variant number for three-phase machine with two-sectional windings is 729.
4. Base vector sets
BV are united into base vector sets (BV sets). For a two-phase PMSM with two-sectional windings six section connection schemes and ten various BV sets are possible: \(A, B, D, E, F, G, H, K, L, O\). The set \(O = \{0\}\) contains a single element corresponding to the zero BV. BV amplitudes are derived as sums of PVs. Stall torque developed by the motor is proportional to them. To achieve a set, three copies of the calculated BV are created and placed by angles multiple of 90°.

Their descriptions are given in the exponential form in table 3. They are grouped by graphical representation, inside of it—by section connection scheme, and finally—by phase usage variant. BV amplitudes are specified in relative units (relatively to the unit sectional vector).

In two-phase PMSM with two-sectional windings, grounding on the six section connection schemes, 45 base vectors can be formed, 44 of which are non-zero and one is zero. There are ten base vector amplitude values: 0, \(2/3\), \(1/\sqrt{2}\), \(\sqrt{10}/3\), \(4/3\), \(\sqrt{5}/2\), \(2\), \(2\sqrt{2}\) and sixteen angle values, 4 for each quadrant of the complex plane (for the first quadrant they are: \(\text{atan}(0)\), \(\text{atan}(1/3)\), \(\text{atan}(1)\) and \(\text{atan}(3)\).

5. Simulation results
A simulation for all possible section connection schemes and phase usage variants is carried out, for it a model based on [10] is created. Numerical values of transient time and \(\Omega_{\text{idle}}\) corresponding to specified rows are given in table 3.

As calculation input data, parameters of DBM50-0.04-3-2 motor were used. In figure 4 speed time response curves for all cases are shown. The speed transient time values are presented in relative units. Unit values are the transient time and the idle speed at unconnected sections and the separate section usage method. Their absolute values are 0.056 sec and 393.1 rad/sec respectively.

![Figure 4](image)

**Figure 4.** Comparison of transient process curve shapes at all section connection schemes.

It can be seen that the calculated curves can be conditionally divided into three groups by idle speed. The first group occupies values from 1 to 1.16 and belongs to high values. They are achieved at parallel and unconnected sections (lines 1–4).

The second group has an intermediate position (0.58–0.82, lines 5–10 but 9) and is actual at the closed connection (“square”).
Table 3. Base vector sets.

| BV forming method | Base vector set in the complex plane | Setting time, rel. | \( \Omega_{idle} \), rel. | Line number in figure 5 | Graphical representation |
|-------------------|------------------------------------|-------------------|--------------------------|-------------------------|--------------------------|
| “square” connection | \( \mathbf{AB} \) \( \mathbf{E} \) \( k = 2m + 1 \land m \in \mathbb{N}_0 \land m < 4 \) | 0.15 | 0.82 | 5 | ![Graphical representation](image) |
| “star” connection | \( \mathbf{AB} \) \( \mathbf{E} \) \( k = 2m + 1 \land m \in \mathbb{N}_0 \land m < 4 \) | 0.2 | 0.7 | 8 | ![Graphical representation](image) |
| “star” with common point | \( \mathbf{AB} \) \( \mathbf{E} \) \( k = 2m + 1 \land m \in \mathbb{N}_0 \land m < 4 \) | 0.34 | 0.58 | 9 | ![Graphical representation](image) |
| “star” with neutral point | \( \mathbf{AB} \) \( \mathbf{E} \) \( k = 2m + 1 \land m \in \mathbb{N}_0 \land m < 4 \) | 0.36 | 0.41 | 18 | ![Graphical representation](image) |
| parallel connection | \( \mathbf{AB} \) \( \mathbf{E} \) \( k = 2m + 1 \land m \in \mathbb{N}_0 \land m < 4 \) | 0.38 | 1.16 | 1 | ![Graphical representation](image) |

The third group occupies little values (0.41–0.58, lines 9–20 but 10) which take place at serial and radial (“star”) connection schemes with common and neutral point.

However, at high idle speed values, setting time has also high values. In the first group it has values 0.53–1, in the second group they are 0.15–0.2 and 0.16–0.44 in the third group.
6. Conclusion
A development of PMSM control theory is carried out: cases have been covered when motor’s phase windings are divided into sections.

A principle of PMSM phase section usage variant forming has been developed, which enables to determine either general number of variants or number of ones leading to zero base vector for an arbitrary phase number.

For the possible section connection schemes in two-phase BLDC motor base vector sets and their mathematical descriptions are obtained. Connection schemes and base vector forming methods enabling to obtain maximum \( (2\sqrt{2}) \) and minimum \( (2/3) \) stall torque values are determined.

A comparative analysis of speed transient process curve shapes at all possible section connection schemes and phase usage methods has been fulfilled. It is determined that the maximal idle speed value is achieved at unconnected and parallel sections, the minimal one—at the “star” with common and neutral point. However, at unconnected and parallel sections the transient time has maximal value, at the “square”—minimal one and at the “star”—intermediate one.

The obtained base vector descriptions can be used for Hall sensor placement, forming of mathematical description of digital control signals, and also by development of combined phase usage methods destined to minimize torque ripples.

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