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FIVE PHASE HYBRID STEPPING MOTOR MICROSTEPPING CONTROL

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Abstract

Single stepping a motor results in jerky movements of the motor, especially at lower speeds. Microstepping is used to achieve increased step resolution and smoother transitions between steps. In most applications, microstepping increases system performance while limiting noise and resonance problems. The paper presents a method for calculation the values of the phase currents for microstepping control of a 5 – phase hybrid stepping motor. This method uses the standard control of the stepping motor with rated currents and only during the commutation the currents of the switched phases change their values in small steps so as the natural step is divided into several micro – steps. The authors have developed a mathematical model and computer programs for simulation of the motor operation under investigated microstepping control. The paper contains also the results from simulations and corresponding conclusions.

Keywords: hibrid stepping motor, simulation, microstepping control, PWM, phase currents waveforms, vernier control, vector-diagram1**.**

1. Introduction

Stepping motors are known as cost – effective, robust drives. They are used in a whole range of machines and devices and perform all kind of tasks from simple point - to – point positioning in handling and automation systems, fast, short – term movements in the textile industry to high – precision synchronized movements in printing applications. Stepping motors excel with a simple, sturdy construction(usually without feedback systems), they can be installed quickly and easily without requiring the user to set up complex control parameters (Acarnley, P.P.,1992, p.11-12).

Two – phase hybrid stepping motors are usually employed for simple applications, while the 5 – phase hybrid stepping motors have become the reliable solution for more demanding tasks. The advantages pf the 5 – phase stepping motors include the high natural resolution of 500 or 1000 steps per revolution, their low – noise and low – resonance operation. Their low detent torque makes them ideal for microstepping operation [3], [4]. One of the advantages of the microstepping operation of the stepping motor is much higher resolution of the motor shaft positioning. This is achieved without complex and expensive rotor position feedbacks or gear box. Another advantage is improved single – step response of the motor by substituting one big step for multiple micro-steps [5], [6]. Microstepping operation of the stepper motors is achieved by suitable changes of the values of the phase currents. There are two basic ways for microstepping control. The first way is to vary the currents in sinusoidal law. In this case the maximum static torque is constant and theoretically any step angle can be achieved [1], [2]. This method is used for stepping motors with permanent magnet rotors. The second way is to use the standard control with rated phase currents and only during the commutation in the new state the currents of the switched phases change their values in small steps so as the natural step is divided into several micro-steps – so called vernier control. The problem here is to find these current that ensure uniform microstepping angle.

The aim of the paper is to develop a method for calculating of the phase currents values for microstepping control of 5 – phase hybrid stepping motors and to investigate the motor operation under this type of control.

2. Structure of five – phase stepping motor

The five-phase hybrid stepper motor is developed with high resolution with no low speed resonance problems. The five-phase stepper can also be classified under permanent magnet hybrid stepper motor. The stator windings are energized in the proper sequencer to produce a rotating magnetic field which turns the rotor. The significant advantage of the five-phase stepper motor is its excellent torque retention capability at high operating speed. The motor used for implementation is a five-phase hybrid stepper motor and it is shown in Fig. 1 and Fig. 2. The figures above show two cross-sections of a 5-phase hybrid stepping motor. Hybrid stepping motors are composed primarily of two parts, the stator and the rotor. The rotor in turn is comprised of three components: rotor 1, rotor 2 and the permanent magnet. The rotors are magnetized in the axial direction, with rotor 1 polarized north and the rotor 2 polarized south. The stator contains 10 magnet poles with small teeth, each of which is wrapped in wire to form a coil. The coil is connected to the facing magnet pole and is wound so it becomes magnetized to the small pole when current is run through it. (Running a current through a given coil magnetizes the facing poles to the same magnetism, either North Pole or South Pole.). The two facing poles form a single phase. Since there are five phases, A trough E, the motor is called a 5 - phase stepping motor. There are 50 teeth on the outside of the rotor, with the teeth of rotor 1 and rotor 2 mechanically offset from each other by half a tooth pitch.

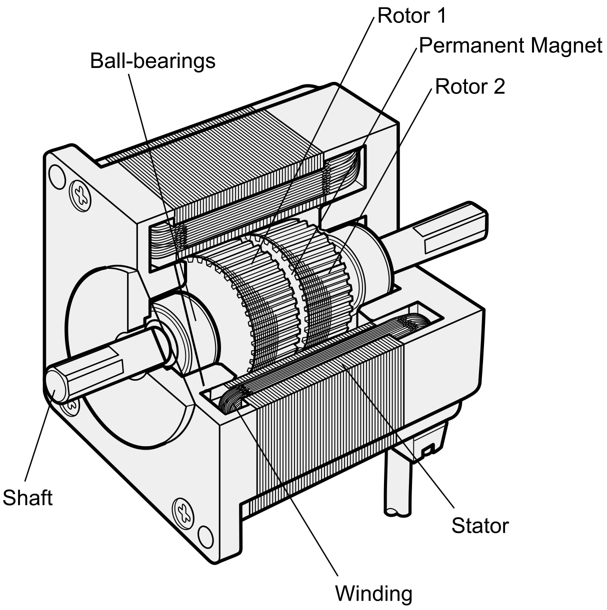

Fig. 1: 5 Phase Stepping Motor Cross-Section Parallel to Shaft

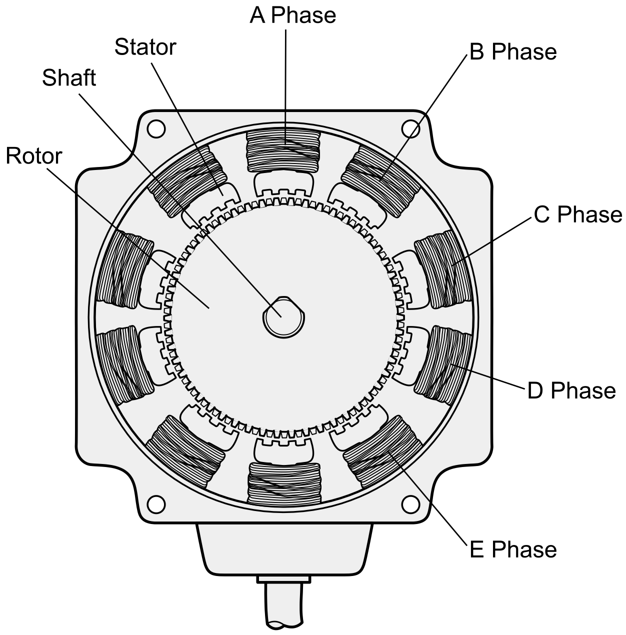

Fig. 2: 5 Phase Stepping Motor Cross-Section Perpendicular to Shaft

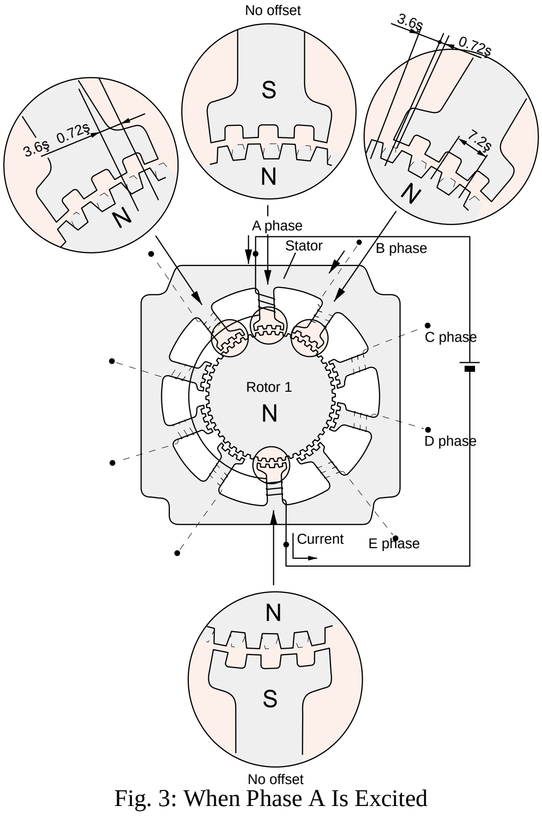

Fig. 3: When Phase A Is Excited

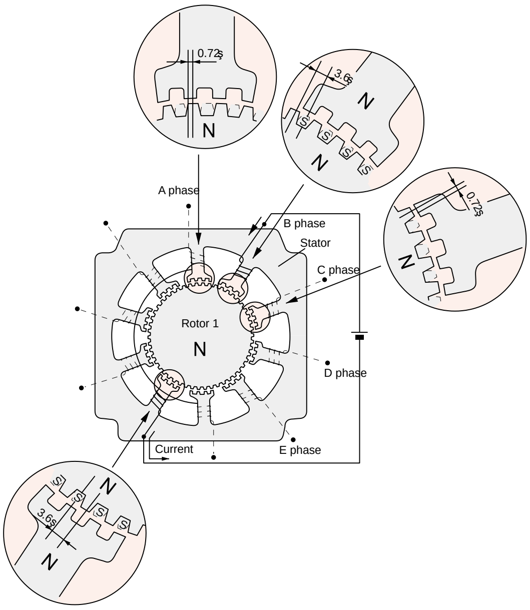

Fig. 4: When phase B is excited

Fig. 3 and Fig. 4 help to describe the relationship on the positions of the stator and rotor teeth when magnetized. When phase A is excited, its poles are polarized south. This attracts the teeth of rotor cup 1, which are polarized north, while repelling the teeth of rotor cup 2, which are polarized south. Therefore, the forces on the entire unit in equilibrium hold the rotor stationary. At this time, the teeth of the phase B poles, which are not excited, are misaligned with the south-polarized teeth of rotor 2 so that they are offset at 0.72°. When excitation switches from phase A to B shown in figure 4, the phase B poles are polarized north, attracting the south polarity of rotor 2 and repelling the north polarity of rotor cup 1. In other words, when excitation switches from phase A to B, the rotor rotates by 0.72°. As excitation shifts from phase A to phases B, C, D and E, then back around to phase A, the stepping motor rotates precisely in 0.72° steps. To rotate in reverse, the excitation sequence is reversed as phase A, E, D, C, B, then back to phase A. High resolution of 0.72° is inherent in the mechanical offset between the stator and rotor, accounting for the achievement of precise positioning without the use of an encoder or other sensors [18], [19].

3. Static torque of a 5 – phase hybrid stepping motor

The following study is made for 5 – phase hybrid stepping motor with 500 steps per revolution. The natural step angle of this type of motor is θ_{st} = 36° electrical or 0,72^o mechanical which is achieved at bipolar phase supply with 4 energized phases at time (Kuo, B. C., J. Tal.,1993 p.125). The idealized waveforms of the phase currents at low speeds are shown in Fig. 5 [11],[12],[13].

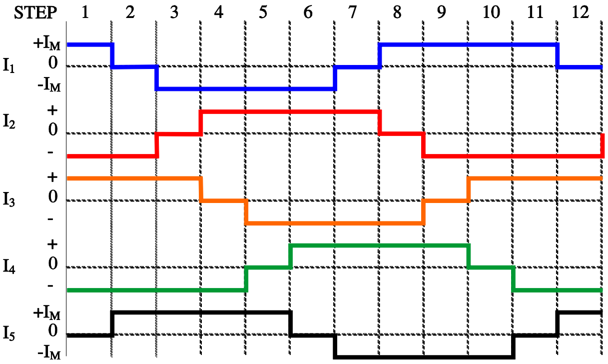

Fig. 5: Idealized phase currents waveforms of 5-phase hybrid stepping motor

Here the author uses the model for the electromagnetic torque of the hybrid stepping motor without taking into account the non – linearity of the magnetic circuit and the magnetic permeance of the air gap. Under these circumstances the static torque curves of the phases and of the motor are sinusoidal and the relation between the current and the torque is linear. This allows for using vector diagrams for summing the torques of the phases [5], [6]. Let's consider the state 1 from Fig. 5 where the phase currents values are the following:

$$I_1 = I_M \quad I_2 = -I_M \quad I_3 = I_M \quad I_4 = -I_M \quad I_5 = 0$$

Here I_M is the rated current value when the phase is supplied. The rated current is the value the stepping motor can operate with for an infinite long time in static mode without overheating. Of course the motor can operate also with currents different from the rated value – for example in static mode or in dynamic modes like acceleration, deceleration, entering resonant regions etc. For the 5 – phase hybrid stepping motors the static torque create by each phase is proportional to the phase current[ ]. Taking into account the values of the currents in state 1 in Fig. 5 we have the following expression for the static torques:

$$T_1 = k_M \cdot I_M \cdot sin\Theta \tag{1}$$

$$T_2 = -k_M \cdot I_M \cdot sin(\Theta - 144°) \tag{2}$$

$$T_3 = k_M \cdot I_M \cdot sin(\Theta + 72°) \tag{3}$$

$$T_4 = -k_M \cdot I_M \cdot sin(\Theta - 72°) \tag{4}$$

$$T_5 = k_M \cdot 0 \cdot sin(\Theta + 144°) = 0 \tag{5}$$

where k_M is a factor with constant value for a given motor, I_M is the phase current, Θ is the angle of rotation of the rotor in electrical angle. The phase shift between the adjacent phases is 216° el. and the origin is the center of the stator tooth of the phase number 1. The magnitudes of the torque vectors correspond to T_m , where T_m = k_M . I_M is the amplitude of the static torque sinusoidal curve created by one phase supplied by a current I_M. The total torque of the motor T_E is a sum of the torques of five phases. After summing the expression for the torque (1) to (5) and corresponding rearrangements the total torque will be:

$$\begin{aligned} T_E &= 4 \cdot k_M \cdot I_M \cdot cos72° \cdot cos36° \cdot sin(\Theta + 54°) = \\ &= 3{,}078 \cdot k_M \cdot I_M \cdot sin(\Theta + 54°) = \\ &3{,}078 \cdot T_m \cdot sin(\Theta + 54°) \end{aligned} \tag{6}$$

4. Calculating of the current values for microstepping control of hybrid stepping motor

In order to obtain division of the natural step it is necessary to have the total torque vector turn by one micro-step at each change of the values of the phase currents. The micro-step angle is defined by defining the angle position of the total torque vector.

The current waveforms shown in Fig. 5 are the basis for the definition of the proposed microstepping control. Let’s consider the transition from state 1 to state 2 in Fig. 5. Here the current I_1 falls from I_M to 0, while the current I_5 rises from 0 to I_M . During this change of the state the rotor of the hybrid stepping motor is rotated in CCW direction by one natural step angle Θ_M = 36° el. The principle of the microstepping control is illustrated in Fig. 6. In order to perform this control from the time t_1 the current I_1 begins to fall and the current I_5 –to rise. Here both currents have discrete pre-defined values. For each state (set of current values) the rotor turns by one micro-step angle Θ_μ in CCW direction:

$$\Theta_\mu = \frac{\Theta st}{n} \tag{7}$$

where n is a whole number, by which the natural step of the motor is divided. This is also the number of different states of the currents between the times t_1 and t_2 shown in the Fig. 6, Morar, A.,2007p. 263).

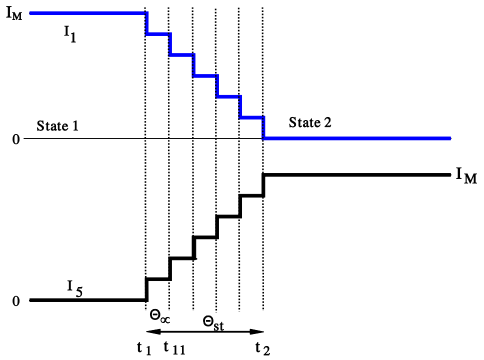

Fig. 6: Principe of the microstepping control

The process shown in Fig. 6 have to be done at each change of excitation state from Fig. 5 in order to divide each natural step of the motor. In Fig. 7 it is shown the torque – vector diagram for the first two states between the moments t_1 and t_2 from Fig. 6 when diving the natural step by 4.

The T_{11} and T_{12} are the torques of the phase number 1, T_{51} and T_{52} – these of the phase 5 and T_E, T_{E1}, T_{E2} – the vectors of the total torque of the motor when changing the currents I_1 and I_5.

The problem for calculating the reference values of the phase currents can be solved at some limiting conditions. The following limiting conditions are formulated:

- the amplitude of the sinusoidal curve of the total static torque is constant, i. e. the vector magnitude is constant and equal to those when 4 phases of the motor are energized with current I_M;
- the vector of the total torque rotates by angle equal to one micro-step Θ_μ at each subsequent state.

The vector-diagram shown in Fig. 7 is drawn on the basis of these statements.

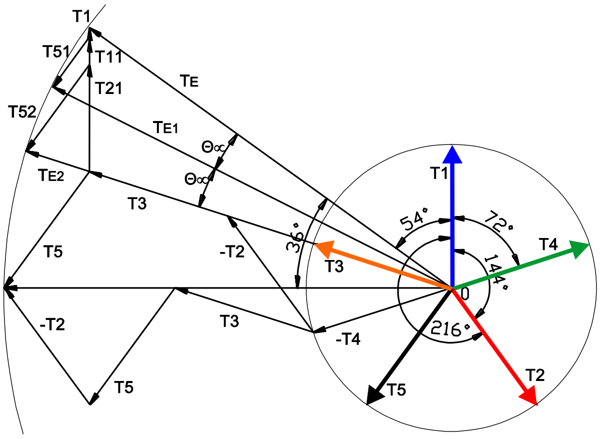

Fig. 7: Torque – vector diagram when dividing the natural step by 4

Here one can see the variations of the torques when the currents in the two commutating phases change their values. The torque of the phase 1 decreases while this of the phase 5 – increases. As a result the total torque vector turns in CCW direction by one micro-step angle at each subsequent state. The locus of the total motor torque is a circle because his magnitude is constant. In the formulated problem the unknown quantities are the magnitude of the torques $T_{11} \div T_{13}$ and $T_{51} \div T_{53}$. Considering that the relation between the static torque and the phase current is linear (expression (1) to (5), the expressions for the torque can be converted in such for the currents. After that these currents can be determined through of some trigonometric calculations.

For the state, shown in Fig. 6 and taking into account the currents’ signs from Fig. 5 and on the basis of the expressions (1) ÷ (5), the total static torque of the hybrid stepping motor can be expressed as follows:

$$T_E = T_1 - T_2 + T_3 - T_4 + T_5 = k_M \begin{bmatrix} I_1 sin\Theta - I_M\ sin(\Theta - 144°) + I_M\ sin(\Theta + 72°) \\ - I_M\, sin(\Theta - 72°) + I_5 sin(\Theta + 144°) \end{bmatrix} \quad (8)$$

Here the currents I_1 and I_2 are unknown and change their values while the rest of the phases are energized by current I_M . After some transformations the expression (8) becomes:

$$T_E = k_M [I_1\, sin\Theta + 2,62 I_M\ sin(\Theta + 72°) + \\ + I_5 sin(\Theta + 144°)] \quad (9)$$

In order to fulfill the condition for keeping the magnitude of the static torque vector constant and taking into account the expressions (6) and (9), the following equation can be written:

$$k_M [I_1\ sin\Theta + 2,62 IM\ sin(\Theta + 72°) + \\ + I_5 sin(\Theta + 144°)] = \\ = 3,078 \cdot k_M \cdot I_M sin(\Theta + 54° + p\Theta\mu) \quad (10)$$

Here p is the number of the consecutive micro-step. After dividing the both sides of (10) by k_M and applying a phase shift of -54° to all terms in the equation we obtain:

$$I_1 sin(\Theta - 54°) + 2,62 \cdot I_M\ sin(\Theta + 18°) + \\ + I_5\, sin(\Theta + 90°) = 3,078 \cdot I_M sin(\Theta + p\Theta\mu) \quad (11)$$

This equation has to be solved for the currents I_1 and I_5. After rearrangements this yields:

$$I_1 sin(\Theta - 54°) + I_5 cos(\Theta + 90°) = \\ = 3,078 \cdot I_M sin(\Theta + p\Theta\mu) - 2,62 \cdot I_M sin(\Theta + 18°) \quad (12)$$

$$I_1 sin\Theta \cdot cos 54° + (I_5 - I_1 . sin 54°) cos\Theta = \\ = I_M \begin{bmatrix} sin\Theta(3,078 cos\ p\Theta\mu - 2,62 cos 18°) + \\ + cos\Theta(3,078 sin\ p\Theta\mu - 2,62 sin 18°) \end{bmatrix} \quad (13)$$

And finally we obtain the following from of the equation (13):

$$0,59 \cdot I_1 sin\Theta + (I5 - 0,81 \cdot I1) cos\Theta = \\ I_M (3,078 cos\ p\Theta\mu - 2,49) sin\Theta + \\ + I_M (3,078 sin\ p\Theta\mu - 0,81) cos\Theta \quad (14)$$

It can be presented as following set of equations for the currents I_1 and I_5:

$$\left| \begin{matrix} 0,59 \cdot I_1 = I_M (3,078 cos\ p\Theta\mu - 2,49) \\ I_5 - 0,81 \cdot I_1 = 3,078 sin\ p\Theta\mu - 0,81 \end{matrix} \right. \quad (15)$$

The solution of above set of equations for the currents I_1 and I_5 is as follows:

$$\left| \begin{matrix} I_1 = I_M (5,235 cos\ p\Theta\mu - 4,235) \\ I_5 = I_M (3,078 sin\ p\Theta\mu + 4,235 cos\ p\Theta\mu - 4,235) \end{matrix} \right. \quad (16)$$

Thus by using the expressions(16) we can calculate the values of the phase currents I_1 and I_5 that makes the p-th consecutive micro-step after the state t_1 from Fig. 6 and Fig. 7. The same from of the solution will be obtained for commutation of any another two currents, say I_1 and I_2, at the transition from the state 7 to 8 on Fig. 5. On the basis of the obtained solution the results for two particular cases are presented here. The study is done for above mentioned 5- phase hybrid stepping motor with 500 steps per revolution and natural step of Θ_{st} = 36° el. The following angle for the micro-step is obtained when this natural step is divided by 4:

$$\Theta\mu = \frac{\Theta st}{n} = \frac{36°}{4} = 9° \quad (17)$$

The values of the currents I_1 and I_5 are calculate by using the expression (16) in order to operate the motor with micro-step of 9°. The results are shown in Table1. These results are in units relative to the current I_M:

$$I_1^* = I_1 / I_M \ ; \qquad I_5^* = I_5 / I_M \quad (18)$$

Table1

Θ, deg	0	9	18	27	36
I_1^*	1	0,9358	0,7439	0,4293	0
I_5^*	0	0,4293	0,7439	0,9358	1

with assumption that n = 8 (dividing of the natural step by 8) the micro-step angle becomes:

$$\Theta_\mu = \frac{\Theta st}{10} = 4,5° \quad (19)$$

And the motor does 4000 micro-steps per revolution. Again by using (16) and (18) the values for the currents I_1 and I_5 are calculated and are presented in the Table 2.

The current values for the natural step, divided by arbitrary whole number, can be calculated using above approach. The waveforms of the currents I_1 and I_5 during the operation of the motor are shown in the next chapter.

Table2

Θ, deg	0	4,5	9	13,5	18	22,5
I_1^*	1	0,984	0,936	0,855	0,744	0,602
I_5^*	0	0,229	0,429	0,602	0,744	0,855
Θ, deg	27	31,5	36			
I_1^*	0,429	0,229	0			
I_5^*	0,936	0,984	1			

5. Simulation of the hybrid stepping motor operation with microstepping control

The motor operation with above described microstepping control is simulated by a computer. The used mathematical model of the motor in conjunction with the current regulator is described in details in [5]. The model includes the voltage equations, the equation of motion of the rotor and the expression for the electromagnetic torque of the motor. The voltage equations are written on the basis of the equivalent circuit of one motor phase shown in Fig. 8.

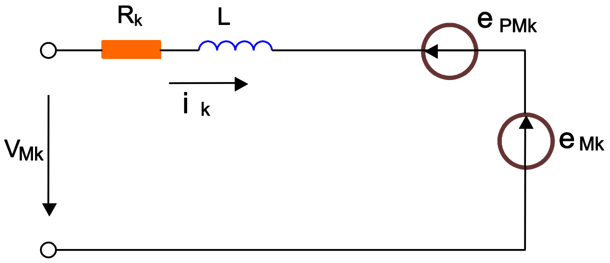

Fig. 8: Equivalent circuit of one motor phase

Hence the voltage equation for the phase number *k* is:

$$V_M = R_k i_k(t) + L\frac{di_k}{dt} \pm \sum_{j=1,\, j\neq k}^{5} M_{kj}\frac{di_j}{dt} + e_{PMk} \qquad (20)$$

where $e_{PMk} = \dfrac{d\Psi_{PMk}}{dt}$ and $e_{Mk} = \pm \sum\limits_{j=1,\, j\neq k}^{5} M_{kj}\dfrac{di_j}{dt}$

The following notations are used here:

R_k – total resistance in the phase circuit (this includes the resistances of: the phase coil, the transistors, the current sensing resistor, the connecting wires);

L – phase inductance;

M_{kj} – mutual inductance between phases *k* and *j*;

e_{PMk} – EMF of the permanent magnet in the rotor;

e_{Mk} – EMF due to mutual inductances;

V_{Mk} – voltage applied to the phase;

i_k – phase current;

Ψ_{PMk} – phase flux linkage from the permanent magnet in the rotor.

The equations for all 5 phases have the same form, the parameter Ψ_{PMk} being offset at (6π/5) (see expression (1) to (5). The expression (20) is modified each time according to the current regulator state. This is a part from the algorithm simulating the work of the current regulator. The following set of differential equations represents the five phases of the motor:

$$\begin{vmatrix} L_1 & -M_{12} & -M_{13} & -M_{14} & -M_{15} \\ -M_{21} & L_2 & -M_{23} & -M_{24} & -M_{25} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ -M_{51} & -M_{52} & -M_{53} & -M_{54} & L_5 \end{vmatrix} \times \begin{vmatrix} di_1/dt \\ di_2/dt \\ \cdot \\ di_5/dt \end{vmatrix} = \qquad (21)$$

$$= \begin{vmatrix} V_1 - R_1 i_1 - e_{PM1} \\ V_2 - R_2 i_2 - e_{PM2} \\ \ldots\ldots \\ V_5 - R_5 i_5 - e_{PM5} \end{vmatrix}$$

The equation of the rotor motion expressed in the form suitable for numerical integration is also added:

$$\left| \begin{aligned} &\dot{\Theta} = \omega \\ &\dot{\omega} = z\left(T_E \;\; t \;\; - T_L \;\; - k_D \frac{\omega}{z} \right) / J \end{aligned} \right. \qquad (22)$$

where:

J – moment of inertia of the rotor;

k_D – damping coefficient;

$T_E(t)$ - total electromagnetic torque of the motor;

T_L – load torque;

ω - electrical angular velocity of the rotor;

Θ – angle of rotation of the rotor in electrical angle;

z – number of the rotor teeth.

The relationship between the voltage equation (21) and the motion equation (22) is the expression for the electromagnetic torque $T_E(t)$ known from:

$$T_E(t) = -z\Psi_m \sum_{k=1}^{5} i_k(t) sin(\Theta + \varphi_k) \qquad (23)$$

Where Ψ_m – maximal flux linkage of the phase from the permanent magnet, φ_k – phase shift angle according to expressions (1) to (5). The equations (21), (22) and the expression (23) form a set of differential equations describing the motor commutations in conjunction with the current regulator. The authors developed also an algorithm describing the work of the current regulator embedded in the programs for numerical integration of the differential equations. Accordingly to the described mathematical model the authors developed a computer program in MATLAB for simulation of the 5-phase hybrid stepping motor. The operation of the 5 - phase hybrid stepping motor in microstepping mode is simulated by means of the developed programs. The following parameters are used during the simulations: L = 5.03mH, Ψ_m = 8mWb, M = 0, 4L, $M1$ = 0,15L, R_k = 1 or 5,5Ω in dependence of the current regulator state, phase supplying current I_M =4A, supplying voltage for the regulator and the motor V_M = 140V, J = 0,002 kg.m^2, T_L = 0. It is important to mention that the motor parameters L, M, $M1$, Ψ_m, R_k are the real parameters measured from the motor and they are not obtained by theoretical way.

The simulation model allows for investigating the motor behavior in different modes of operation – static, steady state and transient modes. Some results of these investigations are presented henceforward. Fig. 9 shows the rotor motion at microstepping control when the natural step is divided by 4. Here are used the current references shown in Table1 multiplied by the value of I_M = 4A. It can be clearly seen that the rotor turns by 9° at each micro-step (according to the expression (17)). The stepping rate is 15 steps per second. The waveforms of the currents I_1 and I_5 obtained at the same conditions are shown in Fig.10.

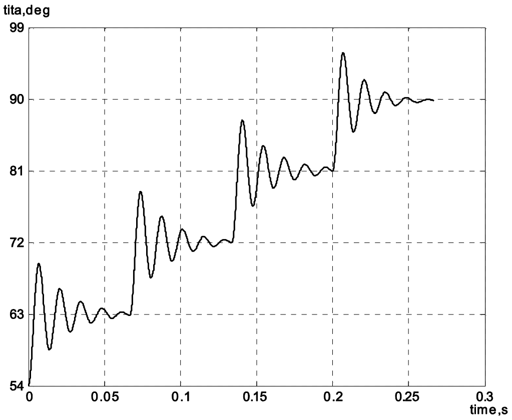

Fig. 9: Rotor motion when the step is divide by 4 and step rate 15 step per second

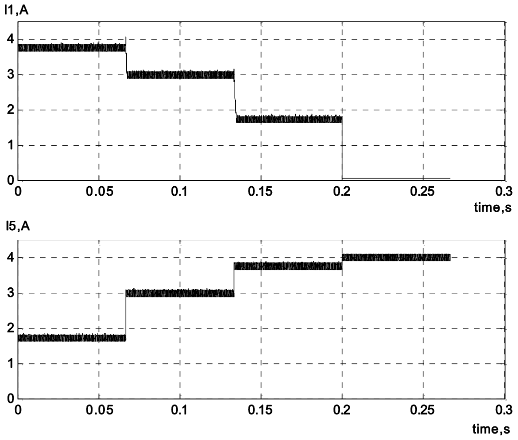

Fig. 10: The waveform of the currents I_1 and I_5 when the step is divided by 4

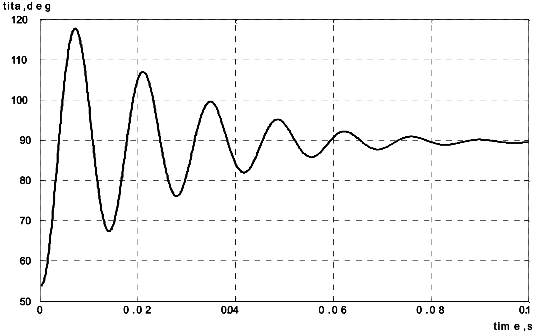

Fig. 11: Rotor motion when the motor does one natural step of 36°

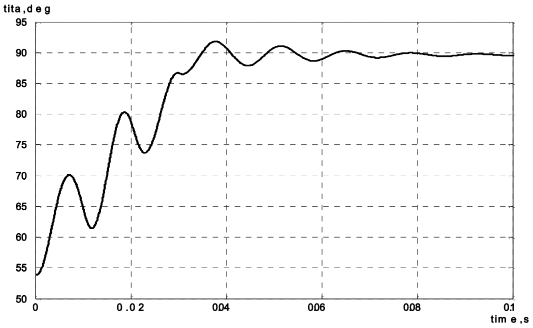

Fig. 12: Rotor motion when step is divided by 4 and step rate 100 step per second

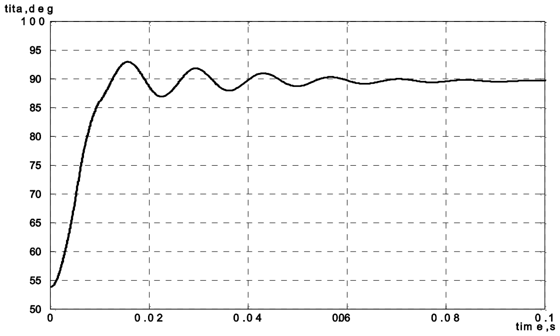

Fig. 13: Rotor motion when step is divided by 4 and step rate 300 step per second

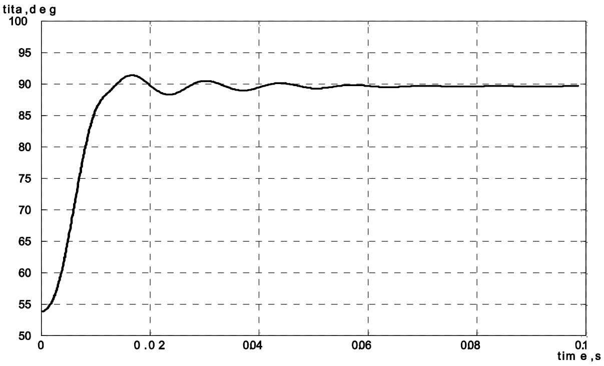

Fig. 14: Rotor motion when step is divided by 8 and step rate 600 step per second

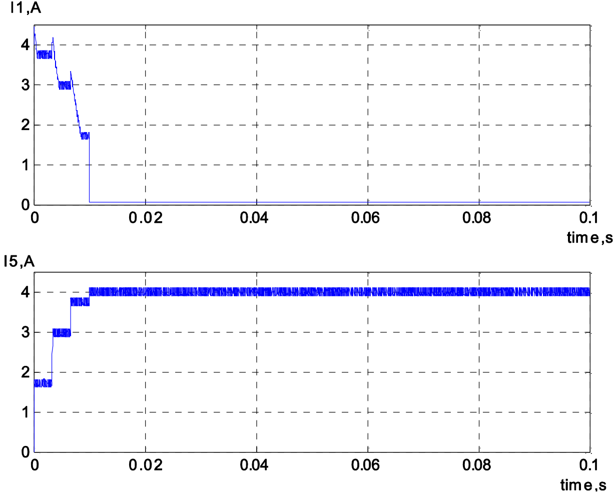

Fig. 15: Waveforms of the currents I_1 and I_5 when the step is divided by 4 and step rate 300 step per second

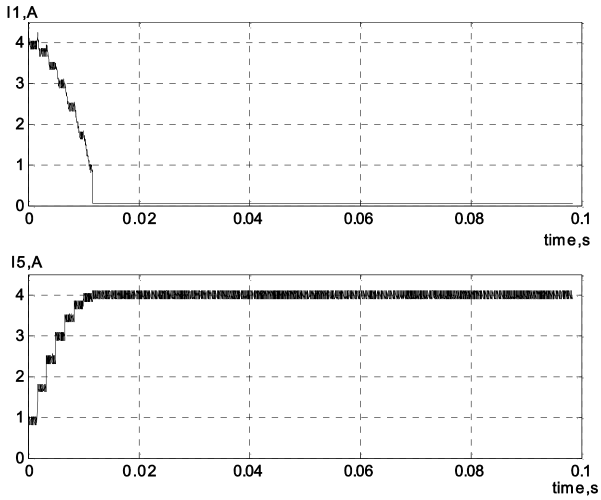

Fig. 16: Waveforms of the currents I1 and I5 when the step is divided by 84 and step rate 600 step per second

Fig. 12, 13 and 14 show the rotor movement by angle of 36° that is exactly one natural step of the motor. In Fig. 12 and 13 this is done when the natural step is divided by 4. Respectively Fig. 14 shows the motion of the rotor when the natural step is divided by 8. These results show that the quality of the rotor motion improves when one natural step is substituted for multiple micro-step. Fig. 11 shows one-step response when the motor does one natural step of 36°. The rotor movement is much smoother and with smaller resonance oscillations. The time to settle in the new position is also decreased. In the same time by means of the developed programs can be calculated also another quantities characterizing the hybrid stepping motor operation. Fig.15 shows the waveforms of the currents I_1 and I_2 at same condition like these on Fig.14. It can be clearly seen how the currents accept the values calculated theoretically and shown in table 1 and table 2. The current regulator sustains the reference value of the current with some pulsation due to his chopper mode of operation.

6. Conclusion

The presented in the paper microstepping control can be used effectively only for stepping motors with 3 and more simultaneously energized phases. These are the 3 – and 5 – phase hybrid stepping motors and also 4 – and 5 – phase switched reluctance stepping motors as well motors with greater number of phases.

The developed method for calculation the phase currents for microstepping control gives the opportunity to divide the natural step of the motor by any whole number. With this mode of operation the phase currents have values always smaller than the rated (I_M). So this leads to more uniform distribution of the losses in the motor phase windings and in the current regulators compared to the micro-step control with sinusoidal current waveforms (especially in static modes). In the same time the static torque of the motor is preserved.

Using the presented mathematical model of the motor in conjunction with the current regulator the operation of the hybrid stepping motors can be simulated in different modes of operation. The obtained results show that the method for calculating of the reference values of the currents gives correct results. It can be concluded also that the proposed microstepping control leads to much better quality of the rotor motion – smoother and faster. The further improvement of the model requires taking into account the saturation of the magnetic circuit of the motor in the model for the calculation of the reference currents as well as in the model describing the motor operation.

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