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Effect of different winding switching methods on regulating and energetic characteristics of synchronous motor with permanent magnet excitation

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Abstract

The article contains evaluation of effect of different winding switching methods for synchronous motor with permanent magnet excitation (SMPM) on energetic efficiency, possibility of enlarging the ranges of working speeds and torques, adaptation of regulating characteristics with the aim of using it in particular electric drive. The evaluation is performed at similar values of relative speed and relative inductance. The conditions, which make sensible the usage of 120-degree or 180-degree switching, meanwhile all considered SMPM characteristics are not worse than those under vector control, are defined. It is proved, that there is a possibility to minimize engine's energy consumption by regulating switching angle, as well as change it's mechanical characteristics. In particular, it is possible to get mechanical SMPM characteristic, typical for direct-current motor with series excitation, suitable for usage in electric traction drive.

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Keywords: Synchronous Motor with Permanent Magnet, windings switching methods, vector control, electromagnetic efficiency.

1. Introduction. Task statement.

When choosing type and principle of motor drive construction they mostly are guided by providing preset range of operation speeds, torques and minimizing of energy usage. For the purposes of getting the best energy indicators the most perspective are SMPM. There are various ways of switching the windings SMPM. For example, discrete

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switching, when stator field vector is rotating discretely through stator bore according to the signals of rotor position sensor (RPS). There is also a vector control, when field vector is rotating gradually. The mentioned above ways of motor power admit the changing of stator field vector magnitude and of it's angular position relative to the rotor field. This fact determines the possibility of the influence on the energy characteristics as well as on the adjusting properties of the drive.

Discrete switching the SMPM windings leaves open the possibility of cheap technical solutions in comparison with vector control, which is more expensive. Formation algorithms of stator field are resource-intensive (they can only be performed with process-specific microcontrollers). That is why arises the problem of comparative evaluation of different ways of switching the SMPM winding according to the energetic efficiency, the possibility to enlarge the range of working speeds and torques, and improvement of adjusting properties. The article describes the problem solution and gives recommendations, which give the possibility to choose SMPM power rationally on a certain electric drive.

2. Methods of SMPM characterization in steady-state

SMPM under vector control can be characterized as a synchronous motor, powered by harmonic voltage source with fixed value of torque angle (θ) [1,2], which is called switching angle in SMPM theory. Then to define electromagnetic and working power in steady-state we can use expressions, acknowledged in synchronous machine theory. Particularly, if we assume that SMPM stator is having permanent-magnet excitation and the difference of magnetic reactance along the axis d and q can be neglected, equations of relative values of electromagnetic (Pe) and working (Pw) powers can be written as [3]:

$$P_e = \frac{\nu\cdot(\cos(\theta)+\nu\cdot\xi\cdot\sin(\theta)-\nu)}{1+\xi^2}, \quad (1)$$

$$P_w = \frac{\nu\cdot(\xi\cdot\sin(\theta)-\cos(\theta))+1}{1+\xi^2}, \quad (2)$$

where $\nu = K\Phi\omega/U$ is relative motor speed, ω is instantaneous speed of armature rotation, Φ is instantaneous flux value, K is structural factor, which is defined by K=pN/2a, where p is a number of pairs of poles, N, a is respectively, number of active wires and number of parallel paths of armature winding; $\xi = \omega L/R$ is parameter defined by the SMPM construction, where L,R is magnetic and active reactance of winding.

Electromagnetic efficiency (η) will be defined by ratio of electromagnetic and working power

$$\eta = P_e/P_w\,. \quad (3)$$

Under discrete switching of three-phase SMPM there are two ways of switching: 180-degree and 120-degree [4,5]. In the first instance on every interswitching interval (ISI) there are three phase winding connected to power supply bus lines, in the second – just two phase windings. Electromagnetic processes, and thus the energy performance of the motor at various ways of switching the windings are different. Mathematical models that describe these processes, are now well-established [4,6–8]. For performance analysis of working characteristics, defining electromagnetic and working powers, as well as efficiency any of them can be chosen. We used the model described in the reference [6].

3. Comparative evaluation of switching methods in SMPM according to efficiency characteristics

Comparative evaluation of all SMPM switching methods, mentioned above was made at similar values of ξ and ν. Depending on the switching method, electromagnetic power and electromagnetic efficiency of SMPM were calculated either according to the expressions (1-3), or to the models, given in [4,6–8]. According to the calculations were built some ratios of those variables and switching angle θ at ξ = [0.5; 0.05] and ν = [0.5; 0.8], shown in Fig. 1.

From comparison of the given ratios we can deduce:

1. The highest efficiency for motors with relatively low inductance of winding (ξ < 1) we get at 120-degree

switching. Vector control is slightly inferior. The worst variant is 180-degree switching.
2. At ξ > 1 ratios of η(θ) and Pe(θ) for SMPM with vector control and 180-degree switching are practically the same and have their maximum in electromagnetic power and efficiency.

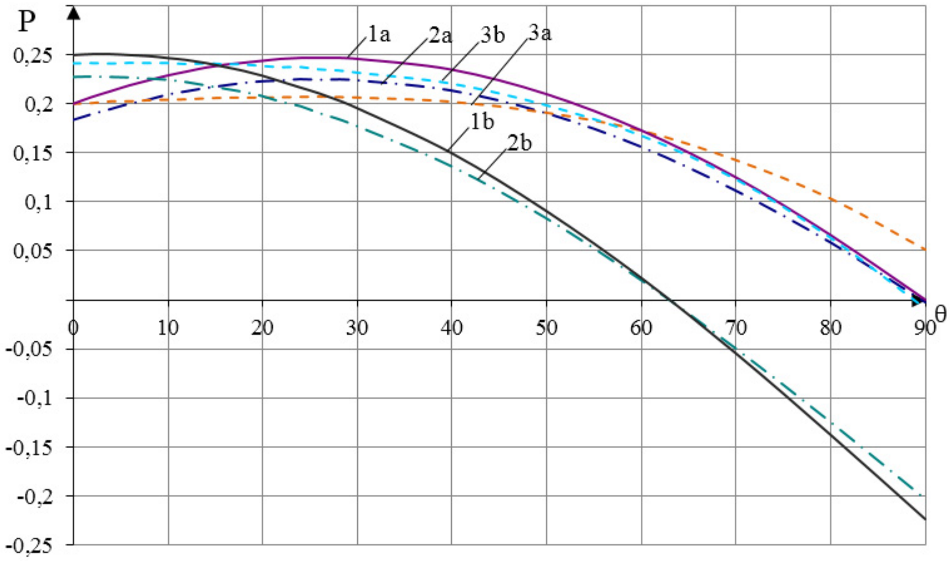

Fig. 1. Ratio of electromagnetic power Pe and switching angle θ at ν = 0.5 for ξ= [0.5; 0.05], where 1a – Pe under vector control for ξ= 0.5; 1b – for ξ= 0.05; 2a – Pe at 180-degree switching for ξ= 0.5;2b – for ξ= 0.05; 3a – Pe at 120-degree switching for ξ= 0.5; 3b – for ξ= 0.05

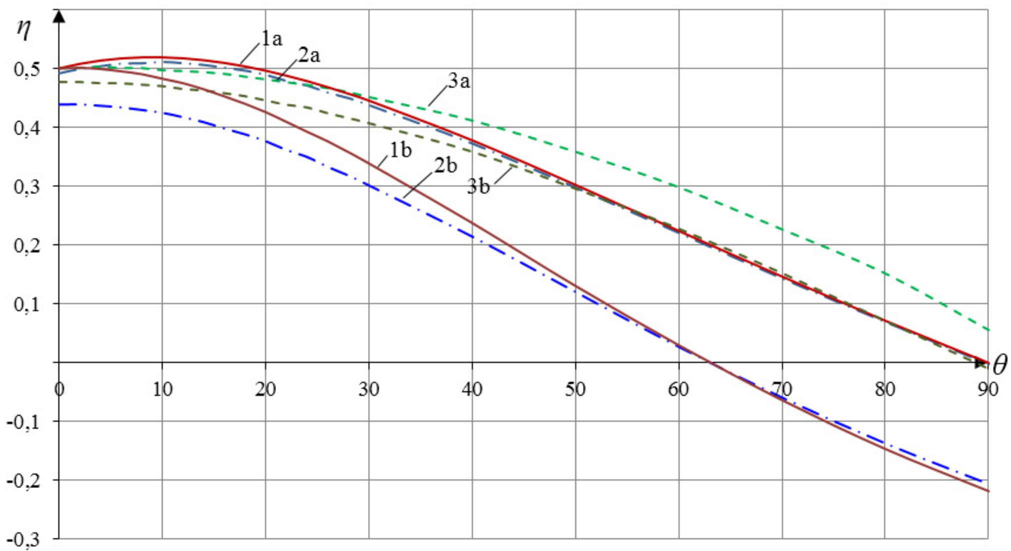

Fig. 2. Ratio of electromagnetic efficiency and switching angle θ at ν = 0.5 for ξ= [0.5; 0.05], where 1a – efficiency under vector control for ξ= 0.5; 1b – for ξ= 0.05; 2a – efficiency at 180-degree switching for ξ= 0.5; 2b – for ξ= 0.05; 3a – efficiency at 120-degree switching for ξ= 0.5; 3b – for ξ= 0.05

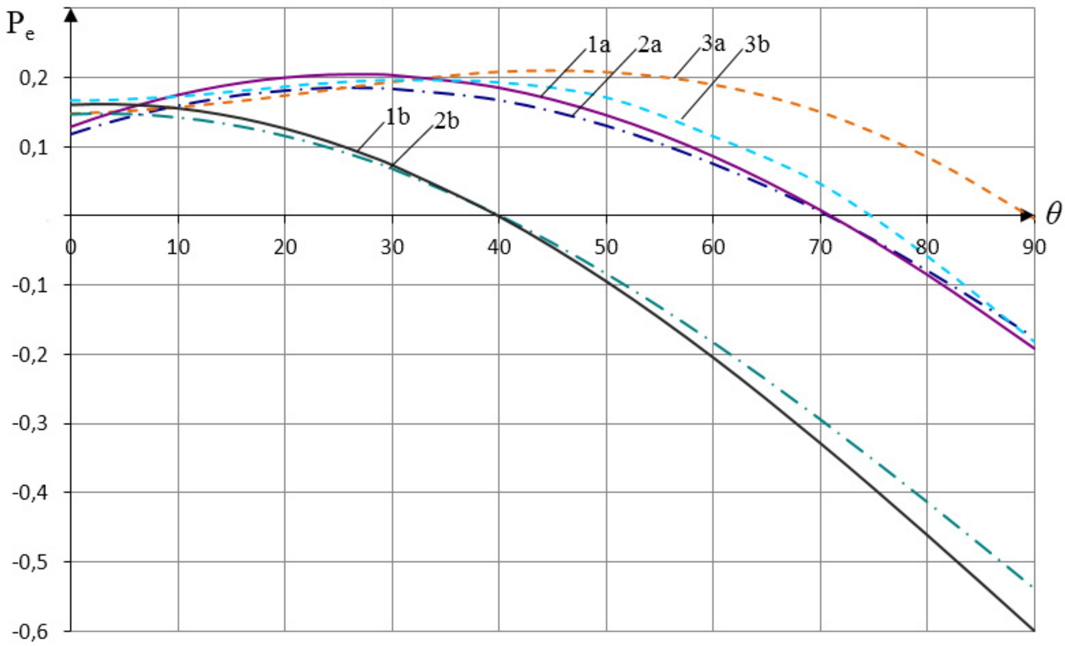

Fig. 3. Ratio of electromagnetic power Pe and switching angle θ at ν = 0.8 for ξ= [0.5; 0.05], where 1a – Pe under vector control for ξ= 0.5; 1б – for ξ= 0.05; 2a – Pe at 180-degree switching for ξ= 0.5; 2б – for ξ= 0.05;3a – Pe at 120-degree switching for ξ= 0.5; 3б – for ξ= 0.05

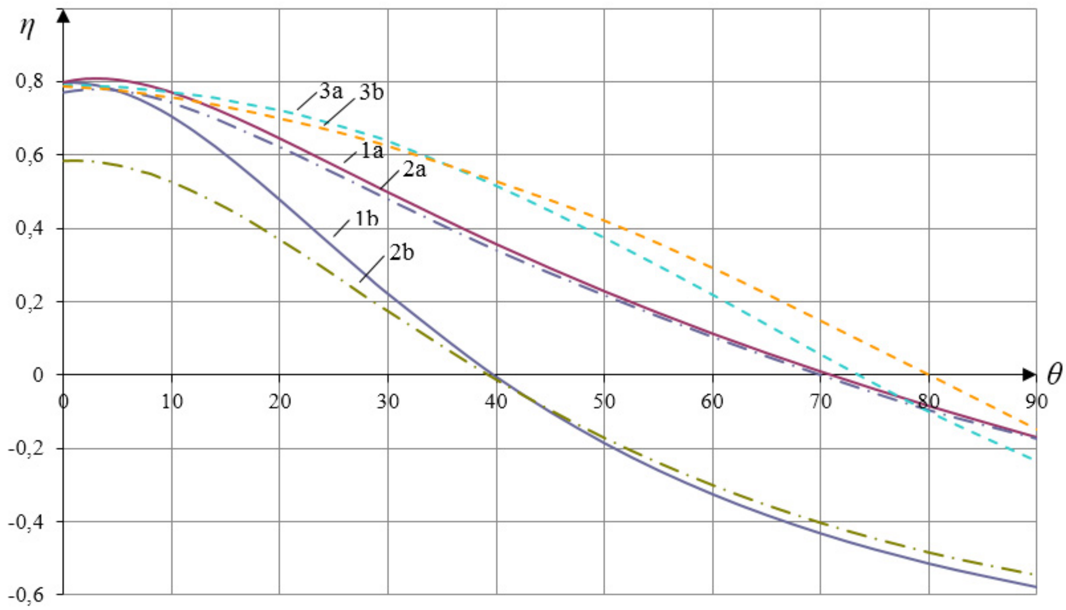

Fig. 4. Ratio of electromagnetic efficiency and switching angle θ at ν = 0.8 for ξ= [0.5; 0.05], where 1a – efficiency under vector control for ξ= 0.5; 1b – for ξ= 0.05; 2a – efficiency at 180-degree switching for ξ= 0.5; 2b – for ξ= 0.05; 3a – efficiency at 120-degree switching for ξ= 0.5; 3b – for ξ= 0.05

From comparison of the given ratios we can deduce:

1. The highest efficiency for motors with relatively low inductance of winding ($\xi < 1$) we get at 120-degree switching. Vector control is slightly inferior. The worst variant is 180-degree switching.

2. At $\xi > 1$ ratios of $\eta(\theta)$ and $Pe(\theta)$ for SMPM with vector control and 180-degree switching are practically the same and have their maximum in electromagnetic power and efficiency.

3. For the characteristics under consideration at 120-degree switching the value of electromagnetic power and efficiency decreases with increasing of θ with the changing of switching angle from 0 to $\pi/2$. Therefore, the optimal value for switching angle in this switching method is $\theta = 0$ both for the electromagnetic power and efficiency.

It may be noted that for the certain values of parameters and rotation speed, the currant of the section, disconnected from the power supply does not have time to decay to zero during one ISI. As a result, 120-degree switching ceases to differ from 180-degree switching by nature of electromagnetic processes and can be described by the same ratios. The equation of conditions determination for transfer from 120-degree switching to 180-degree is shown in [5] and in adopted system of relative units can be represented as

$$C_1 \cdot (1 - b) - C_2 \cdot b = 0 \ ,$$

where:

$$C_1 = (1 - b) + \frac{(\nu')^2 \cdot \xi}{1 + (\nu' \cdot \xi)^2} \cdot \left(\left[\frac{1}{\nu' \cdot \xi} \cdot \cos\theta - \sin\theta\right] \cdot b - \left[\frac{1}{\nu' \cdot \xi} \cdot \cos\left(\frac{\pi}{3} - \theta\right) - \sin\left(\frac{\pi}{3} - \theta\right)\right]\right);$$

$$C_2 = (1 - b) + \frac{(\nu')^2 \cdot \xi}{1 + (\nu' \cdot \xi)^2} \left(\left[\frac{1}{\nu' \cdot \xi} \cdot \cos\left(\frac{2\pi}{3} + \theta\right) - \sin\left(\frac{2\pi}{3} + \theta\right)\right] \cdot b - \left[\frac{1}{\nu' \cdot \xi} \cdot \cos\left(\frac{\pi}{3} + \theta\right) - \sin\left(\frac{\pi}{3} + \theta\right)\right]\right);$$

$$b = e^{-\frac{\pi}{3 \cdot \xi \cdot \nu}}; \quad \nu' = \frac{6}{\pi} \cdot \nu \, .$$

4. Definition of switching angle, corresponding to maximum value of electromagnetic torque and efficiency

When using 180-degree switching or vector control, the value of switching angle (θ^{max}), corresponding to maximum value of electromagnetic efficiency, can be defined by well-known proportion [9]

$$\theta^{max} = \operatorname{arctg}(\xi) \, . \tag{4}$$

It can be used to set regulating point of switching angle in dynamic modes, when it is important to provide maximum torque for the engine to finish transient process as soon as possible.

Analytic dependence for switching angle in relation to roll speed, which corresponds to maximum electromagnetic efficiency of the given SMPM, can’t be define in elementary functions. Therefore, it is rational to use approximate fitting ratios. For their development there were several numerical experiments, which resulted in switching angle values $\theta_М$, corresponding to the maximum value of electromagnetic efficiency and efficiency values in range of parameters $\nu = (0.1, .., 0.9)$ and $\xi = (0.1, .., 1.5)$. As a result of this experiment with the help of least-square method, some approximate ratios, linking $\theta_М$, ν and ξ became available. Polynomials of the second and third order were taken as basic functions for approximation [10]

$$\theta(\nu, \xi) = C_1 + C_2 \cdot \nu + C_3 \cdot \xi + C_4 \cdot \nu \cdot \xi + C_5 \cdot \nu^2 + C_6 \cdot \xi^2 + C_7 \cdot \nu^2 \cdot \xi + C_8 \cdot \nu \cdot \xi^2 + C_9 \cdot \nu^3 + C_{10} \cdot \xi^3.$$

As a result of the calculation, it is managed to present polynomial of the second order as

$$\theta(\nu, \xi) = 7.15 - 28.11 \cdot \nu + 40.19 \cdot \xi - 34.54 \cdot \nu \cdot \xi + 21.67 \cdot \nu^2 - 5.40 \cdot \xi^2. \tag{5}$$

Here sum squared error, calculated by method [11], is equal to $\Delta = 103.21$, relative error $\delta = 0.54\%$.

Accordingly, to obtain a third order polynomial

$$\theta(\nu, \xi) = 1.85 - 15.13 \cdot \nu + 56.44 \cdot \xi - 75.69 \cdot \nu \cdot \xi + 26.55 \cdot \nu^2 - 14.86 \cdot \xi^2 + 18.84 \cdot \nu^2 \cdot \xi +$$

$$+13.95 \cdot \nu \cdot \xi^2 - 13.3 \cdot \nu^3 - 1.03 \cdot \xi^3 \quad (6)$$

Here we have Δ=20,154, δ= 0,24%.

For evaluation of ratios (5) and (6) in whole working range of parameters there calculations were made and ratios $\theta_м = f(\xi)$ were built at different values of ν, shown in Fig. 5 (dashed lines – calculated by expression (5), dash-dotted – by expression (6)). Analogical ratios, deduced by searching θм, at the known numerical values of ν and ξ by expressions (1–3) are shown by solid lines. Comparison of these curves shows that it is possible to find θм by the expressions (5) or (6) with sufficient accuracy for optimization of the drive energy performance.

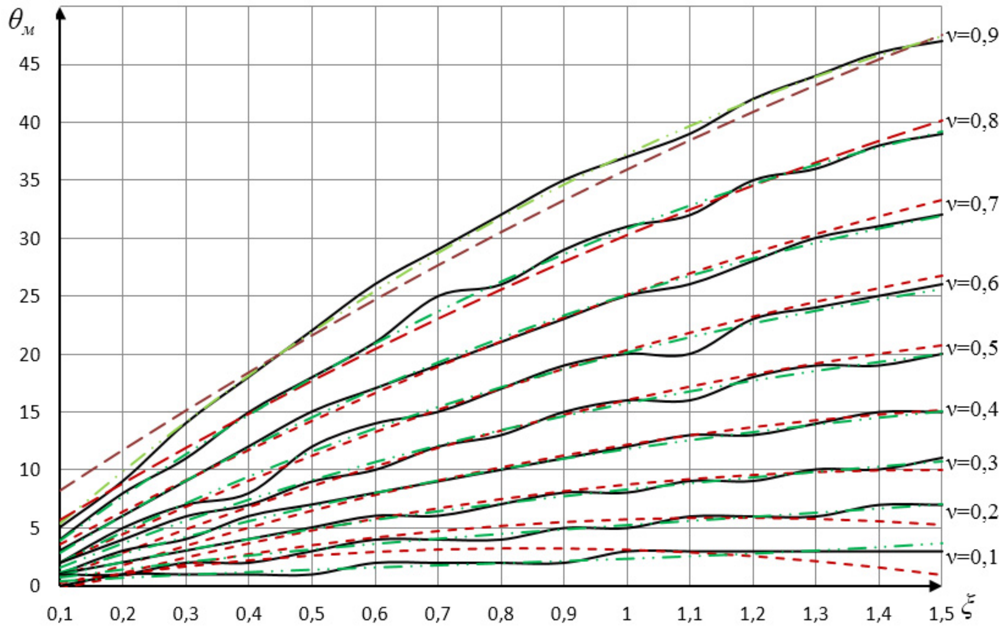

Fig. 5. Set of approximate ratios, allowing to choose the optimal switching angle $\theta_м$ in whole stator rotation speed range (ν) for SMPM of the set construction (parameter - $\xi = \omega L/R$) according to the criterion of maximum electromagnetic efficiency in cases of vector control or 180-degree switching

5. SMPM regulating characteristics under vector control by changing of switching angle

As was noted before, when using vector control it is possible to regulate not only the stator field vector magnitude while it is rotating steadily, but also it's angular position in the respect of stator field vector. Such possibility allows to change the type of mechanical characteristic of the motor and it's working range of rotation speeds.

Fig. 6 illustrates SMPM mechanical characteristics at changing θ, defined by ratio (3) for different values of ξ. The curves illustrate, that by regulating of switching angle type of mechanical characteristics can be substantially changed from ones, corresponding to independent excitation motor to those, corresponding to series-wound motor. It is obvious, that according to requirements for the electric drive it is possible to regulate angle θ independently according to any unspecified law, which is chosen with regard to those requirements.

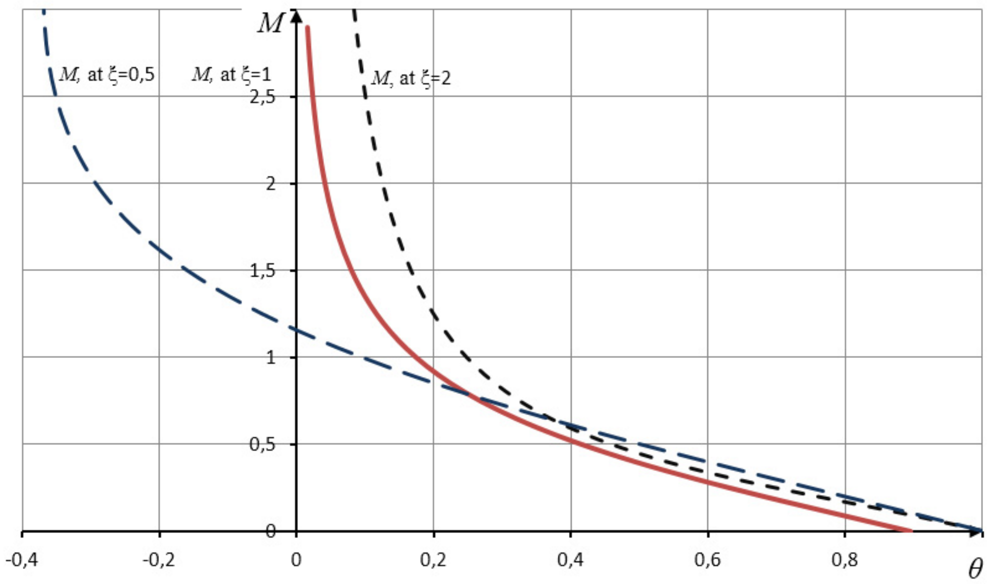

Fig. 6. SMPM mechanical characteristics at changing switching angle θ

6. Conclusion

In engines, having relatively low inductance values of armature winding, while using discrete switching from the point of energetic characteristics it is sensible to use 120-degree switching, which has characteristics not worse than those under vector control. In this case the most effective is neutral switching (θ=0), providing maximum electromagnetic efficiency for the given speed and electromagnetic torque value, which is very close to maximum.

In case of a big relative inductance value, 120-degree switching is turning into 180-degree, that is why it is sensible to program engine work for this switching from the very beginning. At this value of angle θ, corresponding to the maximum efficiency and maximum torque will be different. For the definition of the first one of them, we can use expression (4), for the second one – expression (5) or (6). Those ratios can be used for realization of vector control of electric drive.

When using vector control, regulating SMPM switching angle, with the changing of rotation speed there is a possibility not only to minimize engine's energy consumption, but also change it's mechanical characteristics from ones, corresponding to independent excitation motor to those, corresponding to series-wound motor.

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References

[1] C. Busca, Open loop low speed control for PMSM in high dynamic application, Denmark, Aalborg university, 2010.
[2] S.G. Voronin, D.A. Kurnosov, D.V. Korobatov, P.O. Shaburov, A.S. Kul'mukhametova, Electromagnetic and Resistance Torque on a Synchronous Motor Shaft with Permanent Magnet Excitation, Russian Electrical Engineering. 83(2) 61–63.
[3] F.M. Yuferof, M.M. Kacman, Electricheskie mashini antomaticheskih system, Moskow, 1979.
[4] I.E. Ovchinnokov, Ventilnye Electricheskie Dvigateli i Privody na ih Osnove, 2012.
[5] V.A. Lifanov, S.G. Voronin, B.G. Shumikhin, Issledovanie pulsaciy momenta tikhokhodnikh beskontaktnykh dvagateley postoyannogo toka s diskretnym datchikom pologeniya rotora, Elektrichestvo [Electricity].11 (1977) 54.

[6] N.P. Advolodkin, V.G. Garashenkov, N.N. Lebedev, N.E. Ovchinnikov, Upravlyaemye beskontakthye elektroprivody postoyannogo toka [Contactless controlled DC drives], Leningrad, 1984.
[7] S.G. Voronin, D.V. Korobatov, R.T. Kiyakpaev, A.S. Kulmukhametova, Dynamic processes of brushless DC motor with different combinations of parameters, Izvestiya Akadenii Elektrotekhnicheskih Nauk. (2011)58–63.
[8] V.F. Samoseyko, Theoretical Foundations of Motor Control, 2007.
[9] E.A. Lodochnikov, Yu.M. Yuferov, Mikrodvigateli dlya system avtomatiki [Micromotors for Automation Systems], Moscow, 1969.
[10] Yu.V. Linnik, The method of least squares and the foundation of mathematics and statistical theory of observation processing, Moscow, 1962.
[11] S.A. Ayvazyan, Applied Statistics. Foundations of Econometrics, Moscow, 2001.