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Multiphase inset SPMSM machine with additional currents injection of the third harmonic

***Abstract**. This paper deals witch the cooperation of the wind turbine - multiphase inset SPMSM generator system with the power grid. The fundamental and 3rd harmonic current cooperation is used to increase the generator performance. This is accomplished by means of the 3rd harmonic current injection. The validity of the application of multi-phase generators is confirmed.*

Streszczenie.** Niniejszy artykuł dotyczy współpracy turbiny wiatrowej - wielofazowego generatora SPMSM z siecią energetyczną. Współpraca podstawowej i trzeciej harmonicznych prądu służy poprawie wydajności generatora. Jest to osiągane za pomocą iniekcji 3 harmonicznej prądów stojana. W ten sposób potwierdza się zasadność stosowania generatorów wielofazowych. **Wielofazowy generator typu 'inset SPMSM' z dodatkową iniekcją prądów trzeciej harmonicznej

Keywords: optimal control, wind turbine, SPMSM low-speed generator, the multiphase generator
Słowa kluczowe: optymalne sterowanie, turbina wiatrowa, wolnoobrotowy generator SPMSM, generator wielofazowy

Introduction

A five phase-machine has a mutual shift of phases of the 2π/5 electric angle. It is characterised by interesting properties. In the $\alpha1$, $\beta1$ coordinate system there exist 1^{st} harmonic component (the basic one), and except it there are concurrent harmonics $10n + 1$ (n is an integer) and backward harmonics $10n - 1$. The 9^{th} harmonic, the next one in the order after the 1^{st} one, has such high harmonic number , that its amplitude is small. Therefore, pulsations of the electromagnetic torque are small and have higher $10\omega_1$ frequency (ω_1 is the angular frequency of the basic harmonic). There is also the $\alpha2$, $\beta2$ coordinate system which includes harmonics number 3, 7 etc. The included harmonics have numbers $10n + 3$, $10n + 7$ etc. The 3^{rd} harmonic can be great enough to generate additional, constant electromagnetic torque. It can be stated that there are two different electric machines linked by the same shaft. The third spatial harmonic may cooperate with the basic harmonic of the $\alpha1$, $\beta1$ system and cause additional moments, as well as cooperate with the 7th harmonic from the same $\alpha2$, $\beta2$ system, creating moment pulsations of $10\omega_1$ frequency (ω_1 is the angular frequency of the basic harmonic).

Generally, it can be assumed that electric machines with odd number of phases are characterised by good distribution of harmonics. They enable to use the 3^{rd} harmonic, which is sufficiently high. For instance, 5-phase machines are divided into virtual machines, which are formed by $\alpha1$, $\beta1$; $\alpha2$, $\beta2$ and o_1 systems. These first big virtual machines are capable of generating electromagnetic moment thanks to harmonic components, mainly the 1^{st} and the 3^{rd} ones. The contrariety to this is a 6-phase symmetric machine. The $6n + 1$ and $6n - 1$ harmonic constituencies belong to the $\alpha1$, $\beta1$ coordinate system, the other ones to the null coordinate system. Thus, there is no possibility to use the 3^{rd} harmonic in order to generate constant electromagnetic moment. It may be stated that such a machine is the equivalent of a 3-phase machine. Its contrariety is an asymmetric 6-phase machine. It was discussed the previous papers [4] as an variation of a 12-phase machine. The $\alpha1$, $\beta1$ system is created here by the harmonic numbers $12n + 1$, $12n + 11$; the $\alpha3$, $\beta3$ system is formed by harmonic numbers $12n + 3$ and $12n + 9$. There is, thus, the possibility for practical application of the 3^{rd} harmonic.

Coordinate transformation of a multiphase machine

A 5-phase machine with the number of teeth on a stator $ns = 50$ and poles number on a rotor (50/14) $p = 7$ was analysed. The stator phases were located evenly, and the reciprocal angle between the stator phase windings was 2π/5 rad. The results acquired have been presented in fig. 1, fig 2.

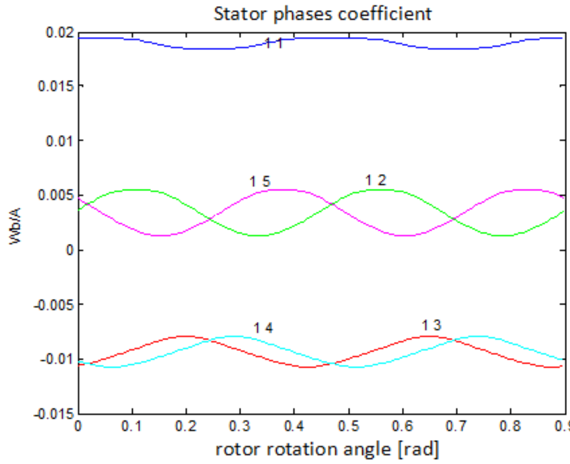

Fig. 1. Some induction coefficients of a 5 phase machine in real coordinates

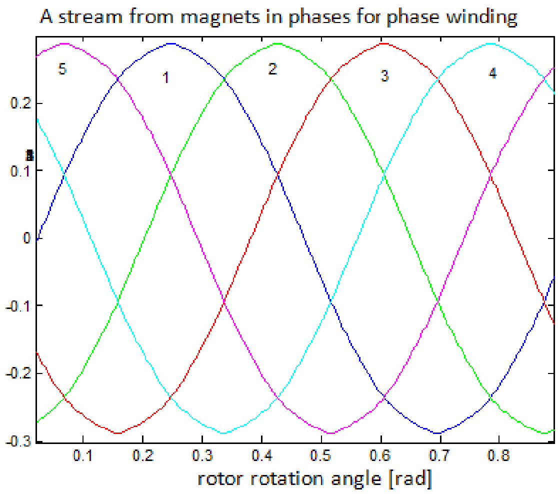

Fig. 2. Magnetic fluxes from the permanent magnet in phases for a 5-phase machine

Transformation matrix C of real coordinates to coordinates (α, β), connected with the stator, for a 6-phase asymmetric machine [4]. Phase currents of the zero component [1;1;1;1;1;1], that cause the neutral conductor current flow in a machine, are transformed into those coordinates (α, β):

$$C \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1.73 \\ 1.73 \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

The expression implies that these currents are connected with the components ($\alpha3$, $\beta3$). Thus, in order to utilise these components in the form of injections, in cooperation with the fundamental components ($\alpha1$, $\beta1$), it is necessary to use the neutral conductor. It also implies using two batteries with voltages U_{cd} connected in a series circuit. The neutral conductor should be connected to the joint point of these batteries. The sum of phase currents of this machine does not equal zero. On the other hand, in order to avoid components ($\alpha3$, $\beta3$), the main component of which is the 3rd harmonic, the neutral conductor should not be applied. In case of stator phase winding they should form two stars, shifted reciprocally by the electric angle of 30°, with insulated star points. It is not possible then to use additional capabilities of a multiphase machine.

In case of a 5-phase symmetric machine, the transformation matrix to coordinates (α, β) was calculated by means of the subroutine:

```
ksi=2*pi/5; katy=[0,ksi,2*ksi,3*ksi,4*ksi];
Cn=[cos(katy);sin(katy);cos(3*katy);sin(3*katy);cos(5*katy)];
Cc=Cn*Cn'; Ccd=1./sqrt(diag(Cc));
Ca=diag(Ccd); Cn=Ca*Cn; C=Cn;
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The acquired transformation matrix C is orthonormal; by its means one may acquire the transformation of zero component currents (of the neutral conductor) of a 5-phase machine:

$$C \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 2.236 \end{bmatrix} \tag{2}$$

It turns out that the transformed currents equal zero, except for the zero component O_1. It causes only harmful pulsations and it is beneficial to turn it off. It can be achieved without using the neutral conductor. Therefore, the power-supply system can only comprise of one battery, which is very beneficial. The component $\alpha2$, $\beta2$, which includes the 3rd harmonic. A 7-phase machine has similarly beneficial conditions. The component $\alpha2$, $\beta2$, the main part of which is the 5th harmonic, and the component $\alpha3$, $\beta3$, which includes mainly the 3rd harmonic, does make use of the neutral conductor.

Simulation of the multiphase machine with the third harmonic current injection

The compiled method for calculating machine dynamics by means of quick search of characteristics can also be applied to a reluctance machine [4]. A 6-phase asymmetric machine by the constant flow of stator currents has been analysed. It had the same windings as the designed and analysed machine with permanent magnets with stator teeth number ns = 48, where the number of rotor poles p = 7. It differed from this machine by the removal of magnets. The air gap between hypothetic magnets and stator teeth δ_g was reduced to the value of 0.33mm. At the same time, the predicted depth of magnets pasted into the rotor, by remaining the constant air gap, h_r was increased to 0.49 mm. These changes were supposed to increase the reluctance moment. The calculations were made by the designed system of programs, by the injection coefficients of the 3rd harmonic amounting k_{13} = –0.1 and k_{24} = –0.3 The calculated curves are included in the fig. 7.

Summing up, the 3rd harmonic may be used to generate moment in 5-phase (as $\alpha2$, $\beta2$ system), 7-, 9-, 12- phase and 6-phase asynchronous machines (as $\alpha3$, $\beta3$). The 5th spatial harmonic, the next in the order according to height, may be used separately in 7-phase systems (as the $\alpha2$, $\beta2$ system), whereas the 7th harmonic may be applied in 5-phase systems (as the $\alpha2$, $\beta2$ system) and in 9-phase systems. Therefore, 5-phase systems enable for practical application of the 3rd and 7th harmonics seems to be beneficial. The transformation matrix C for coordinates (α, β) is the same as in the case of the analysed 6-phase asymmetric machine. Only the zero component has only one line, similarly like the *RR_* matrix that projects on axis *q, d*.

For quick control of a 5-phase machine, its characteristic curves by the injection of the 3rd harmonic currents were calculated, assumed according to the coefficients k_{13} = – 0,1, k_{24} = – 0,3 (fig. 3).

The results of machine dynamics results acquired from a programme that makes use of searching machine characteristics were presented in fig. 4-7.

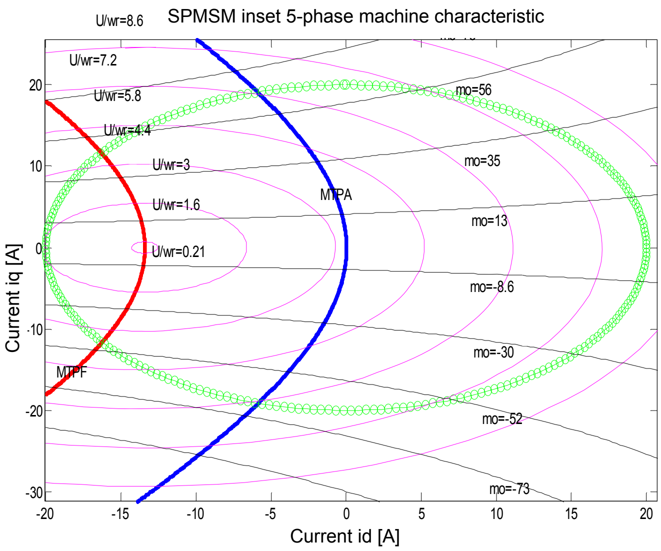

Fig. 3. Characteristic curves of the analysed 5-phase machine by the injection of the 3rd harmonic currents, determined by the coefficients k_{13} = – 0,1, k_{24} = – 0,3; constant moment curves – black colour; constant stream U/w_r curves– pink colour

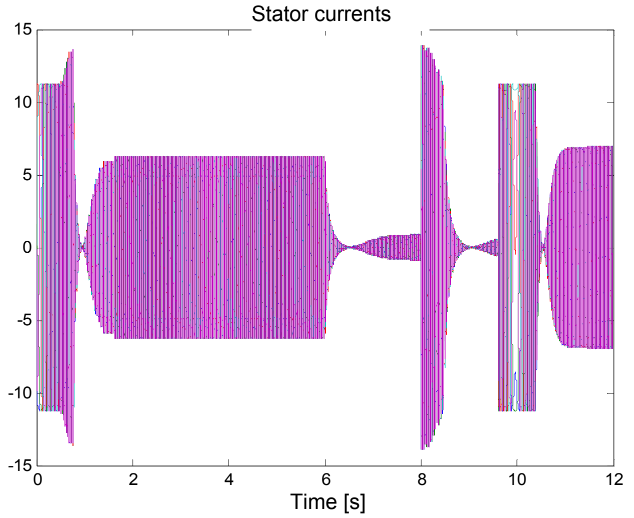

Fig. 4. Flows of stator currents for the injection coefficients k_{13} = – 0,1, k_{24} = – 0,3

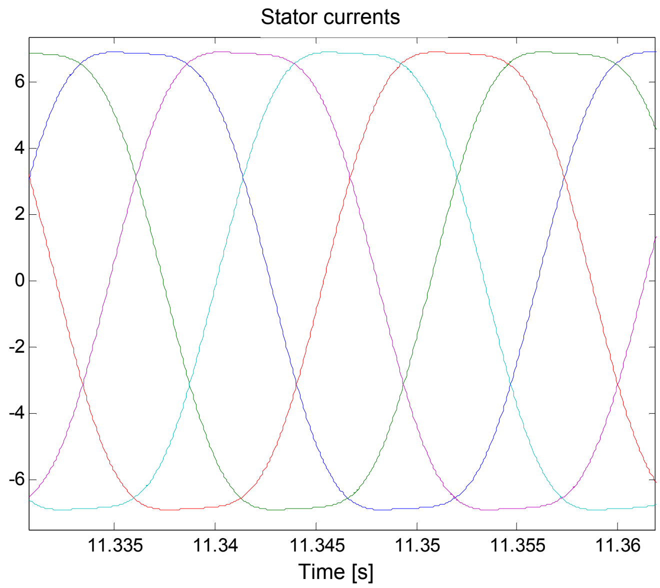

Fig. 5. The acquired approximation of stator currents to trapezium flow (k_{13} = – 0,1, k_{24} = – 0,3)

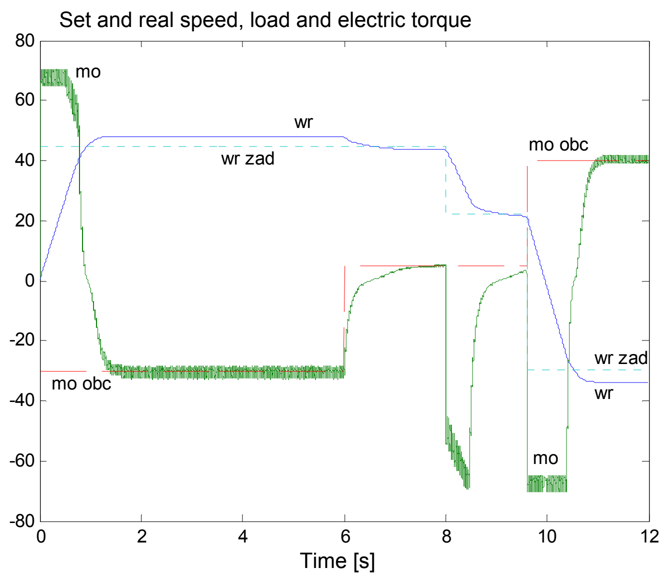

Fig. 6. Dynamic runs/waves of a 5-phase machine acquired by the injection of the 3[rd] harmonic currents.

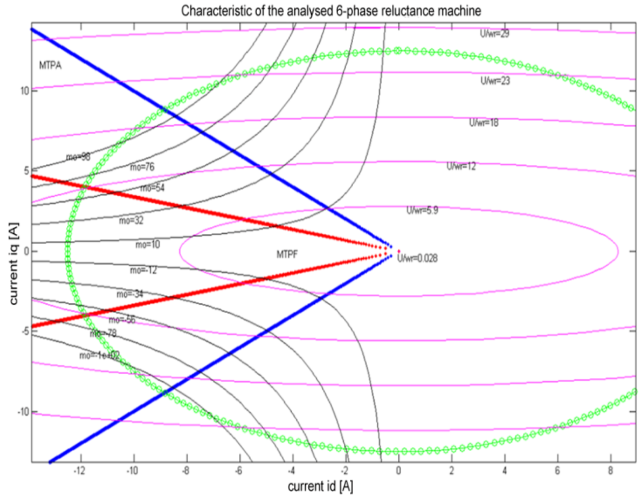

Fig. 7. Characteristic curves of the analysed 6-phase asymetric reluctance machine by the currents injection of the 3rd harmonic currents by the level determined by the coefficients k_{13} = –0.1, k_{24} = –0.3; curves of the costant moment – black colour; curves of the constant stream U/w_r – pink colour; current limitation – green colour.

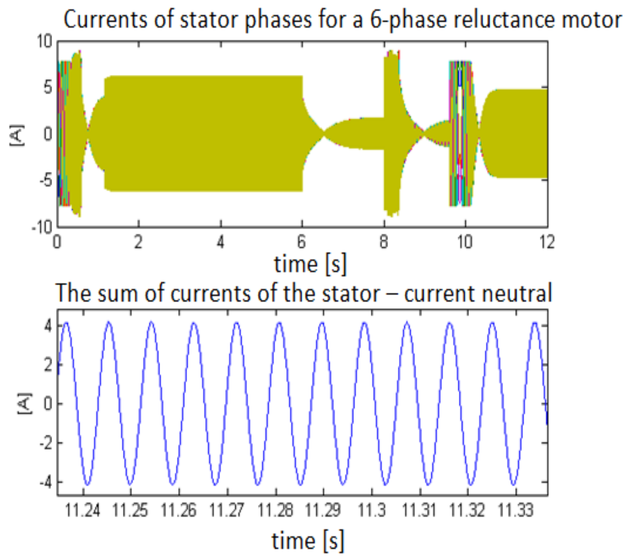

Fig. 8. Flows of stator currents for the injection coefficients k_{13} = – 0.1, k_{24} = –0.3.

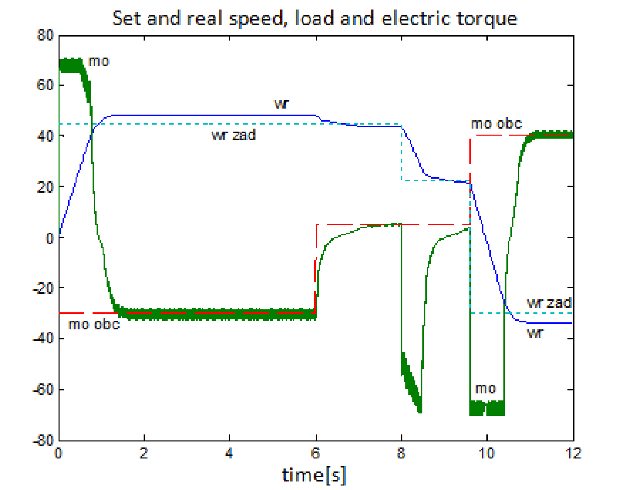

Fig. 9. Dynamic flows of a reluctance machine with asymetric 6-phase winding, acquired by the injection of the 3[rd] harmonic currents.

Conclusion

By means of these characteristic curves it was possible to calculate dynamic states of a reluctance machine. The results are illustrated in figures 8 and 9. It turns out, as it was possible to predicts, that through the neutral conductor flows relatively significant current of the 3rd harmonic.

The presented considerations indicate validity of applying multiphase power supply in machines. The requirements set to inverters are becoming less strict, and, at the same time, the electrical-machine system is becoming more resistant to damage. It is possible to provide better co-functioning of inverters and wind turbines. Thanks to the possibilities of additional currents injection it is possible to decrease electromagnetic moment ripples. The wind turbine – synchronous machine with permanent magnets unit has better control properties.

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