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Influence of Supply Current to the Characteristics of Reactive Oscillating Motors

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Problem and its solving

Supply sources of synchronous reactive motors regarding nature of current may be of 1) alternating current and 2) pulsating current (single polarity half of period current pulses). Some authors, for instance, [1] distinguish motors supplied by pulsating current source from other ones and call them as pulsating current motors because operational factors of pulsating current motors are higher.

This paper deals with theoretical clarification of how operational factors depend on character of supply current comparing operating factors of the same motor when it is supplied from different source [2].

Principles of method of investigation

System of differential equations of electrical and mechanical parts of oscillating motors:

$$\begin{cases} u = iR + L\dfrac{di}{dt} + i\dfrac{dL}{dt}, \\ \dfrac{1}{2}(iw)^2\dfrac{d\lambda}{dh} = m\dfrac{d^2h}{dt^2} + R_{mch}\dfrac{dh}{dt} + ch, \end{cases} \quad (1)$$

here u and i – supply voltage and current of motor, R – resistance of active losses, L – inductance, w – number of turns of winding, λ – permeance of air gap, h – coordinate of position of mover, m, R_{mch} and c – mass, impedance and rigidity of mover.

Dependence of permeance on coordinate h of oscillating motors, especially those which pendulum moves perpendicularly to the magnetic field, within oscillating interval is approximated by linear function. Inductance may be expressed

$$L(h) = L + kh, \quad (2)$$

here L_0 – inductance when h=0, k – coefficient (rapidity of changing of inductance).

Substituting (2) into the (1), electromagnetic force may be expressed

$$f_{em} = \frac{1}{2}i^2\frac{dL}{dh} = \frac{1}{2}ki^2. \quad (3)$$

Electromagnetic force is proportional to the square of current. The square changes the current value into the other variable with different spectrum named "converted current". Converted current is abstraction which depends on the set of electrical values, and, at the same time, it is an argument of function which depends on the set of mechanical values. So, from the standpoint of theory, it is important while analyzing operation of reactive motors.

There are three distinctive cases of supply current of the motor of Fig. 1, *a*, *b*, and *c*:

1) $i = I_m \sin\omega t$ – current changes harmonically;
2) $i = |I_m \sin\omega t|$ – current is expressed as positive pulses of doubled frequency;
3) $i = \frac{1}{2}I_m(\sin\omega t + |\sin\omega t|)$– current is sinusoidal form positive half period term pulses.

These three currents correspond to two different converted currents of Fig. 1, *d, e*. First current and second one corresponds to Fig.1, *d*, third one – to Fig. 1, *e*. Electromagnetic force is generated by converted current. In both cases (first and second one of supply current) operation of the motor is the same though second current is pulsating one. Currents of Fig. 1, *b* ,*c* are pulsating ones, and motors supplied by these currents are named differently. Electrical motors of any type change energy of supply source into to mechanical energy which is used for the work of a load of a motor. It is realized by functioning algorithm of a certain type of a motor. Neither supply source nor load of the motor depends on the motors. Nevertheless they have influence on the work parameters of the motor therefore they are not to be used in the names of the motors. Peculiarities of supply sources determined in different algorithms of functioning of the motor are further discussed. Reactive oscillating motors, supplied by alternating or pulsating current, change it to the converted current while realizing the same functioning algorithm.

Therefore detachment of pulsating current motors from the other synchronous reactive ones as being separate not by differences of the motors themselves but their supply source should not be used.

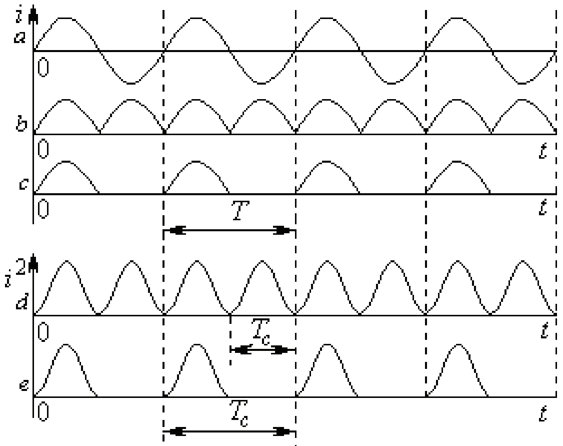

Fig. 1. Supply currents of oscillating motors

Spectrum of converted current has constant component, main and higher harmonics

$$i_c = i^2 = I_{c0} + I_{c1}\sin(\omega_{c1}t + \varphi_{c1}) + I_{c2}\sin(\omega_{c2}t + \varphi_{c2}) + ... =$$
$$= \sum_{n=0}^{\infty} I_{cn}\sin(\omega_{cn}t + \varphi_{cn}), \qquad (4)$$

here $I_{c0}, I_{c1}, I_{c2}, ...I_{cn}, ...$ – constant component and amplitudes of harmonics of converted currents

$$I_{cn} = k_{cn} I_m^2, \qquad (5)$$

here k_{cn} – coefficients of harmonics of the converted current which depends only on form of curve of the current, $\omega_{c1}, \omega_{c2}, ...\omega_{cn}, ...$ – frequencies of harmonics of the converted current, $\varphi_{c1}, \varphi_{c2}, ...\varphi_{cn}, ...$ – phases of harmonics of the converted current, n – numbers of harmonics.

While supplying motor by alternating sinusoidal current spectrum of converted current, it has constant component and second harmonic

$$i_c = I_{c0} + I_{c2}\sin(\omega_{c2}t + \varphi_{c2}), \qquad (6)$$

here $k_{c0} = \frac{1}{2}, \quad k_{c2} = \frac{1}{2}, \quad \varphi_{c2} = -\frac{1}{2}\pi, \; \omega_{c2} = 2\omega. \qquad (7)$

The half of period term was chosen to express the case of supplying motor by pulsating current with the aim of the circumstances in both cases would be as close as possible to sinusoidal pulsating current

$$i = \frac{1}{2} I_m (\sin\omega t + |\sin\omega t|). \qquad (8)$$

Converted current of this current has constant component, main and higher harmonics, as shown in Table 1.

In the second part of the Table 1, it is shown sinusoidal pulsating supply current and converted currents regard to the main harmonic of the amplitude of spectrum. Constant component of the main harmonic of the converted current both absolutely and relative one less and it well suites for the motors of asymmetrical construction. In case of converted current the second harmonic and the third one is sharp.

Expression of harmonics of electromagnetic force spectrum may be obtained by writing (4) to (3) and applying (5) in the term of

$$f_n = F_n \sin(\omega_{cn}t + \varphi_{cn}), \qquad (9)$$

here F_n is an amplitude of electromagnetic force of harmonic number n

$$F_n = \frac{1}{2} k k_{cn} I_m^2. \qquad (10)$$

Table 1. Parameters of spectrum of pulsating current

Current		Pulsating currents		Pulsating converted currents				Pulsating currents	Pulsating converted
Coefficient of amplitudes and phases of harmonics of current		k_n	φ_n	k_{cn}	φ_{cn}	Coefficients of harmonics of current regard to the main harmonic			
	I_0	0,318	-	0,250	-		$\frac{I_0}{I_1}$	0,636	0,589
	I_1	0,500	0	0,424	0		$\frac{I_1}{I_1}$	1,000	1,000
	I_2	0,212	$-\pi/2$	0,250	$-\pi/2$		$\frac{I_2}{I_1}$	0,424	0,59
	I_3	-		0,085	$-\pi$		$\frac{I_3}{I_1}$	-	0,200
	I_4	0,042	$-\pi/2$	-	-		$\frac{I_4}{I_1}$	0,084	-
	I_5	-		0,012	$-\pi$		$\frac{I_5}{I_1}$	-	0,028
	I_6	0,018	$-\pi/2$	-	-		$\frac{I_6}{I_1}$	0,036	-
	I_7	-		0,004	$-\pi$		$\frac{I_7}{I_1}$	-	0,009
	I_8	0,010	$-\pi/2$	-	-		$\frac{I_8}{I_1}$	0,020	-

Every component of the spectrum of electromagnetic force gives movement to the pendulum of the motor. When a load of a motor is linear oscillations of the mover are sum of oscillations which are inspired by separate components of the spectrum of electromagnetic force. The harmonics of the spectrum of oscillations may be found by solving differential equation which is taken by writing (9) to (1) as

$$F_n \sin(\omega_{cn}t + \varphi_{cn}) = m\frac{d^2h}{dt^2} + R_{mch}\frac{dh}{dt} + ch. \qquad (11)$$

Constant component of force pushes the center of oscillation is

$$\Delta H = \frac{kk_{c0}}{2c} I_m^2. \quad (12)$$

A load of such motors has resonant character therefore influence of the components of electromagnetic force to the amplitude of mechanical oscillations depends on quality of a load

$$Q = \frac{1}{R_{mch}} \sqrt{mc}. \quad (13)$$

Amplitude of harmonic of oscillations is obtained while affects harmonic number *n* of electromagnetic force

$$H_n = \frac{F_n}{\omega_{cn} R_{mch} \sqrt{1 + Q^2 \left(\frac{\omega_{cn}}{\omega_0} - \frac{\omega_0}{\omega_{cn}} \right)^2}}, \quad (14)$$

here ω_0 is frequency of mechanical resonance of loads, expressed by

$$\omega_0 = \frac{1}{\sqrt{\frac{m}{c}}}. \quad (15)$$

Phase of harmonic number *n* of coordinate of oscillations in regard to harmonic number *n* of converted current is

$$\beta_n = -\text{arctg} \frac{\omega_{cn}^2 m - c}{\omega_{cn} R_{mch}} - \frac{\pi}{2}. \quad (16)$$

Author [1] proposes that higher harmonics of current of a motor have increased losses in the motor windings while amplitude of oscillations is influenced a little. As force which inspires oscillations is generated by the main and the higher harmonics of the converted current as well as the spectrum of the current of a motor and the converted current are different (Table 1), this proposition is mistaken theoretically though it has quantitative verification.

While changing alternating sinusoidal supply current of a motor by pulsating current when resistance of electrical losses is linear the losses within motor decrease two times therefore amplitude of pulsating current is increased $\sqrt{2}$ times.

Amplitude of the main harmonic of electromagnetic force (10) supplying a motor by sinusoidal current is

$$F_2 = \frac{1}{4} k I_m^2 \quad (17)$$

and supplying a motor by pulsating current amplitude of the main harmonic of electromagnetic force

$$F_1 = \frac{4}{3\pi} k I_m^2. \quad (18)$$

Then ratio of amplitudes

$$\frac{F_1}{F_2} = \frac{16}{3\pi} = 1{,}698. \quad (19)$$

While supplying a motor by pulsating current, amplitude of electromagnetic force is almost 70% bigger. Active power of a load is proportional to the square of amplitude of oscillations therefore the power of a motor increases 2,88 times. Frequency of pulsating current should be increased two times with the aim to get the same frequency of oscillations after changing supply source. Then frequencies of the main harmonics of the converted current in both cases are the same.

The application of theory and modelling

For application of theory it was used synchronous reactive motor with parameters: R=640 Ω, k=2450 H/m, R_{mch}=8 N·s/m, m=0.034 kg, c=11000 N/m, $I_m = 0{,}094$ A (amplitude of alternating supply current), or $I_m = \sqrt{2} \cdot 0{,}094$ A (supply is sinusoidal pulsating current).

Table 2. Calculation and modeling results

Current	Parameter	Results*	Harmonics (n) 0	1	2	3	5
Alternating sin	H_n,m	Calc	0,4920	-	0,9699	-	-
		Mod	0,4920	-	0,9697	-	-
		Err.,%	0,0081	-	-0,020	-	-
	Β$_n$, rad	Calc	-	-	-2,012	-	-
		Mod	-	-	-2,023	-	-
		Err.,%	-	-	-0,161	-	-
Pulsating sin	H_n,m	Calc	0,4920	1,6450	0,1234	0,0166	0,0008
		Mod	0,4919	1,6450	0,1234	0,0166	0,0008
		Err.,%	0,0215	-0,017	0,2457	1,0166	23,637
	Β$_n$, rad	Calc	-	-2,02	-2,910	-3.005	-3,064
		Mod	-	-2,023	-2,915	-3,016	-3.142
		Err.,%	-	-0,161	-0,174	-0,359	-2,46

NOTE: *Calc – calculated, Mod.– modeling, Err.,% - error, %.

Errors of little values, influence of which to the final result is very little, are higher due to sample and influence of specific of machine arithmetic to the measure results. Generally speaking, the good conjunction of the results obtained after theoretic calculations and modeling (Table 2) is the base to trust the results which were received only by modeling but in the work were not compared with the calculated results applying theoretic dependences [3].

Influence of supply source to the main energetic indexes of reactive oscillating motors is shown by data which is given in Table 3. Considerably bigger power and efficiency of the motor in case when motor is supplied by pulsating current only confirmed that there is not supposed difference between motors which are separate out according using of pulsating current but it is determined by used supply source. Practically efficiency in both supply cases of the motor is less than calculated in Table 3.

Table 3. The main energetic indexes of the drive

Drive	P_1, W	P_2, W	η
Oscillating alternating current	4,313	1,48	0,344
Oscillating pulsating current	7,101	4,273	0,602

In the drive of an alternating current, efficiency is more close to the calculated one since their current is closer to the sinusoidal one. Neither higher harmonics are in supply current, nor in the converted current in case by modeling drive of an alternating current therefore efficiency of such drive may be increased only by decreasing resistance of electrical losses and improving coordination with a load.

In reality, current of a motor of pulsating current drive significantly differs from the current which was used in investigation therefore its efficiency differs more than calculated one.

Realization of alternating sinusoidal current source which was used in this work is available, and it does not make bigger problems [4,5]. In the case of pulsating sinusoidal supply, it is complicated already due to the thing that instantaneous value of supply voltage has to be more than 1000 V. Despite of that, this method of investigation and obtained results show potential possibilities to improve the energetic indexes of oscillating drives and may be applied for different supply current of a motor.

Change of coordinate of oscillations *h(t)* after evaluation all of spectrum of converted current and only the main harmonic of the converted current are within interval ±8% and depends on the difference of phases. Therefore should not be objective criterion for estimation of an influence of higher harmonics. Influence of higher harmonics to the work of the drive may be evaluated objectively while comparing the power of the motor when it is taken all spectrum of the converted current with the power when it is taken only the main harmonic. Let us suppose that in the first case the speed of the motor is v_1 and in the second one – v. Then the power increases due to higher harmonics of the converted current

$$\left(\frac{\int_0^T v^2 dt}{\int_0^T v_1^2 dt}-1\right)\cdot 100\ \% = 2{,}58\ \%. \qquad (20)$$

Influence of higher harmonics to the work of a motor is insignificant and power of higher harmonics in supply current is 0,04 %.

Conclusions

1. Neither construction nor principle of operation of oscillating synchronous motors which are named "pulsating current motors" differs from synchronous reactive ones therefore both first and second one have to be called "oscillating synchronous reactive motors".
2. The supply sources of oscillating motors considering character of current should be named: 1) alternating current sources, 2) pulsating current sources.
3. It is needed to use name of supply source in the name of the electrical drive with oscillating reactive motors as it is applicable in the name of the drive with the other type of a motor. Then they should be named as oscillating alternating current drive and oscillating pulsating current ones.
4. This terminology is logical, reasonable and eliminates confusion when the same motor is named in different way while changes supply source, especially considering to the fact that oscillating motors are designed and produced to the specific drive.
7. Despite of fact that investigation was made for certain currents of the motor, the results should be taken as the aim and method of investigation to apply in case of different currents.
8. Realization of supply sources of sinusoidal current for oscillating motors does not make bigger problems, and sinusoidal pulsating current are heavily realised, though realisation of formation of the other forms of currents also does not make any problems.

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Two tasks were solved in this article. It is proven that partition of synchronous reactive oscillating motors to reactive oscillating motors and pulsating current ones is baseless, since some of their behavior features and working characteristics are different only because of different supply currents. It is offered to deny this partition and supply sources and drives of these motors to call alternating current drives and pulsating current drives. The second task – square of motors‘ current is treated as dependent variable and called the converted current. This abstract variable allows to take a look at these motors deeper and visually. Ill. 1, bibl. 5, tabl. 3 (in English; abstracts in English and Lithuanian).

A. Brazaitis, E. Guseinoviene. Maitinimo srovės įtaka reaktyvinių švytuojamųjų variklių charakteristikoms // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 5(111). – P. 115–118.

Straipsnyje išspręsti du uždaviniai. Įrodyta, kad sinchroninių reaktyviųjų švytuojamųjų variklių skirstymas į reaktyvinius švytuojamuosius ir pulsuojamosios srovės variklius neturi pagrindo, nes visi jų skirtumai yra sąlygojami maitinimo srovių. Siūloma tokio skirstymo atsisakyti, o šių variklių maitinimo šaltinius ir pavaras vadinti kintamosios srovės ir pulsuojamosios srovės pavaromis. Antrasis uždavinys – variklio srovės kvadratas traktuojamas kaip priklausomas kintamasis ir vadinamas pakeistąja srove. Šis abstraktus kintamasis padeda įdėmiau ir giliau pažvelgti į šiuos variklius. Il. 1, bibl. 5, lent. 3 (anglų kalba; santraukos anglų ir lietuvių k.).