UDC 621.3 13.175.32 **doi: 10.20998/2074-272X.2016.3.04**

V.B. Finkelshtein, A.B. Yegorov

# CHARACTERISTICS OF A 4-PHASE VALVE RELUCTANCE MOTOR WHEN POWERED BY UNCAPACITOR SWITCHBOARD

***Purpose. Nowadays more and more in a variety of machines and mechanisms applied switched reluctance motor. When designing these engines solve the problem selection switch. While the switch scheme comprises symmetrical bridge and eight transistors, eight diodes; Miller switch comprises six transistors and six diodes; in company Graseby Controls Ltd switch circuit but four transistors and four diodes includes two capacitors. The aim is to develop a mathematical model, calculation program, a numerical analysis of the characteristics and parameters of the WFD and the characteristics of their work. Methodology. It is assumed that the resistance in the open state transistors and diodes for direct current is zero and the resistance of the transistors in the closed state, and diode reverse voltage is infinity. When feeding a single-phase motor and power at the same time two adjacent phases determined by the flow through the tooth. Results. The motor powered by a switch on the circuit symmetrical bridge power, which provides a maximum permissible winding temperature is 1.665 kW. But at the same time the surge up to 38.8%, resulting in high levels of noise and vibration. Through the installation of switching angles, ensuring reduction of torque ripple and reduce engine power to a level below which there is a decrease in the value of torque ripple, received power of 1,066 kW and a torque ripple value of 21.18 %. For engines with improved vibration acoustic characteristics necessary to use a switch of four transistors and four diodes. Practical value. For motors with improved vibration acoustic characteristics appropriate to apply uncapacitor switch on four transistors and four diodes, which allows you to receive half the value of torque ripple than the lowest value of the motor torque ripple, eating from a switch on the circuit asymmetric bridge. The cost of reluctance motor with uncapacitor switch on the circuit with four transistors and four diodes is more than two times less than the motor with the switch on the circuit asymmetric bridge.*** References 9, tables 1, figures 10.

*Key words:* **valve reluctance motor, switchboard, flux linkage of phases, rotor angle of rotation, motor power.**

***Рассмотрены электромеханические процессы в вентильном реактивном двигателе и его характеристики при питании от коммутатора фирмы Graseby Controls Ltd с изъятыми из его схемы конденсаторами. Разработана математическая модель, проведен численный и экспериментальный анализ характеристик и параметров вентильного реактивного двигателя. Результаты, которые представлены в статье, разрешают проводить выбор числа витков и мощности двигателя в сравнении с двигателем, который питается от коммутатора по схеме асимметрического моста в зависимости от технических требований.*** Библ. 9, табл. 1, рис. 10.

*Ключевые слова*: **вентильный реактивный двигатель, коммутатор, потокосцепление фаз, угол поворота ротора, мощность двигателя.**

**Introduction. Problem definition.** Nowadays more and more in a variety of machines and mechanisms applied switched reluctance motor (SRM), known in the western countries and the United States as the Switched Reluctance Motor (SRM) [7-9], in Russia – as the valve-inductor motors [6] (VIM) and valve inductor-reluctance motors [2] (VIRM), in Ukraine – VRM. When designing these engines a problem of switch selection is solved.

**Analysis of recent achievements and publications on the subject.** While the switch scheme asymmetric bridge [9] (Fig. 1) comprises eight transistors, eight diodes; Miller switch [9] (Fig. 2) contains six transistors and six diodes; a switch circuit by Graseby Controls Ltd [9] (Fig. 3), but four transistors and four diodes includes two capacitors. Furthermore, in the switch (Fig. 3), a voltage imbalance that increases the torque ripple and a significant reduction in motor power.

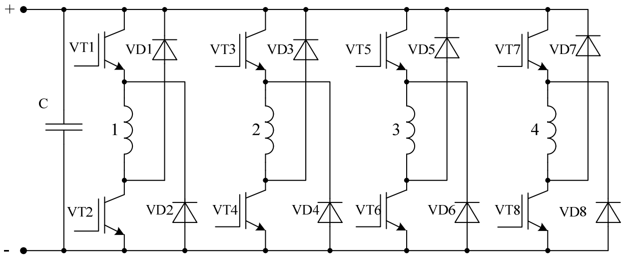


Fig. 1. Switch on the circuit of asymmetrical bridge

When the motor is powered by the scheme Miller its capacity is reduced by 20 % compared to the power of the engine when it is powered by a switch on the circuit asymmetric bridge [4]. Maximum engine power is obtained when it is powered by an asymmetrical bridge circuit compared to the power of the engine when powered by any of switches on other schemes. To a large extent determined by the properties of the switch performance.

In [5, 6], the switch (Fig. 5) used to supply four-phase VRM. This switch consists of four transistors and four diodes, but particularly of the circuit, and a mathematical model of the engine characteristics, as with a normal and a beak rotor during feeding from that switch are not considered.

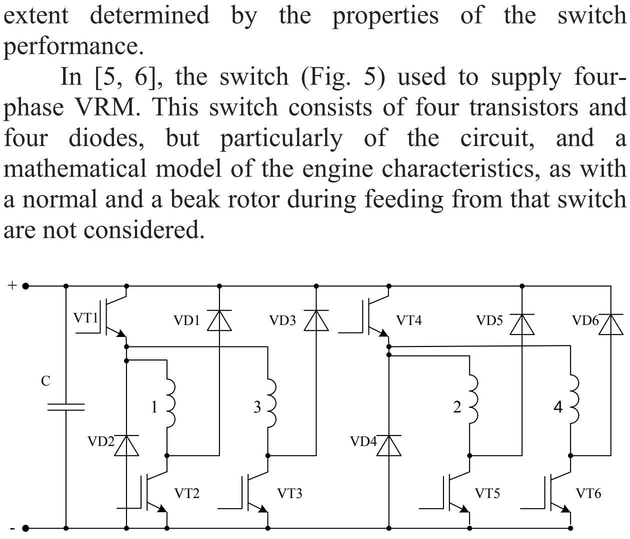


Fig. 2. Miller switch

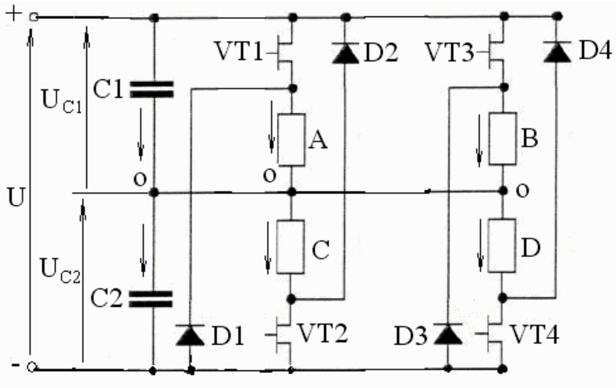


Fig. 3. Switch by Graseby Controls Ltd

**The goal of the work** is to develop a mathematical model to calculate the electromechanical characteristics of the VRM when powered by a switch with four transistors and four diodes to determine the parameters of the motor windings allowing to improve vibroacoustic characteristics and have strong economic performance.

**Development of mathematical model.** The magnetic circuit of the motor with windings with the combined phases is shown in Fig. 4.

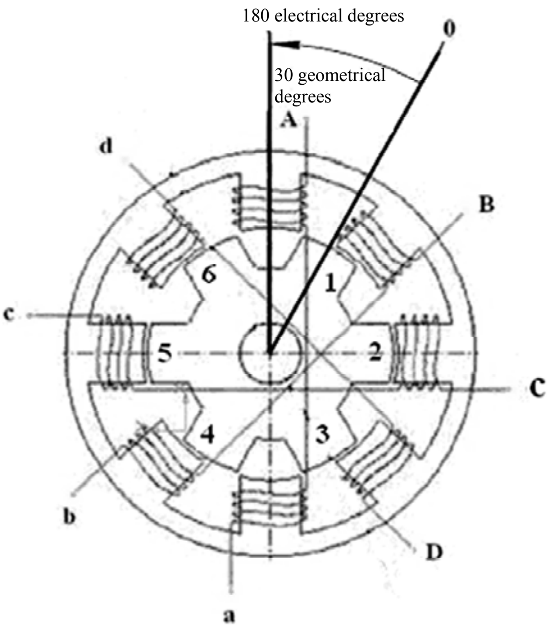


Fig. 4. Magnetic circuit of the motor

The switch circuit is shown in Fig. 5, the individual circuit units consist of the phases *A* and *D*; *C* and *B*.

It is assumed that the resistance of the transistors in the open state, and diode forward current to zero and the resistance of the transistors in the closed condition and co-diode reverse voltage is infinity. When feeding of one motor phase and simultaneously feeding the two adjacent phases (Fig. 4) is defined by tooth stream [2]. When you connect the second phase of the flow of the first phase has changed by 2.5 %. This allows you to accept the assumption of the absence of mutual phase inductance.

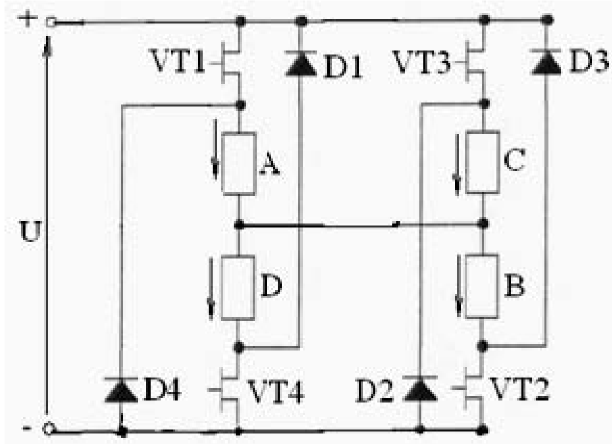


Fig. 5. Applied switch circuit

When the angle of rotation of the rotor $\zeta$ in electrical radians in the range $0 \le \zeta \le \pi / 2$, the transistors VT1 and VT2 are open and, if this current in *D* phases and *C* are not equal to zero, then phase *D* through the D1 diode and VT1 transistor being connected parallel to the phase *A* and phase *C* through VT2 transistor and a diode D2 is connected in parallel to phase *B*. The transistors VT3 and VT4 locked.

In this interval of the rotor rotation angle phase current, flux and torque of the VRM describes by the system of differential equations (1)

$$\begin{aligned} & i_A \cdot r + \frac{d\Psi_A(i_A,\zeta)}{dt} + i_B \cdot r + \frac{d\Psi_B(i_B,\zeta)}{dt} = U; \\ & i_C \cdot r + \frac{d\Psi_C(i_C,\zeta)}{dt} = -i_B \cdot r - \frac{d\Psi_B(i_B,\zeta)}{dt}; \\ & i_D \cdot r + \frac{d\Psi_D(i_D,\zeta)}{dt} = -i_A \cdot r - \frac{d\Psi_A(i_A,\zeta)}{dt}; \\ & i_D = i_A + i_C - i_B, \end{aligned} \quad (1)$$

where $i_A$, $i_B$, $i_C$ and $i_D$ are the phase currents, $\Psi_A(i_A, \zeta)$, $\Psi_B(i_B, \zeta)$; $\Psi_C(i_C, \zeta)$, $\Psi_D(i_D, \zeta)$ are the phase flux linkages as a function of the currents and the rotor rotation angle; *r* is the active phase winding resistance (all values – in SI units).

The fourth equation (1) holds in all bands of the rotor rotation angles.

In the rotor rotation angle range in electric radians $\pi/2 \le \zeta \le \pi$ transistors VT1 and VT4 are opened, and the transistors VT2 and VT3 – locked. In this case, the phase *B* is connected in parallel with phase *A* and phase *C* – in parallel with phase *D*. The initial phase of the parallel system of equations for the angles of rotation of indicated rotor interval may be represented as

$$\begin{aligned} & i_D \cdot r + \frac{d\Psi_D(i_D,\zeta)}{dt} + i_A \cdot r + \frac{d\Psi_A(i_A,\zeta)}{dt} = U; \\ & i_B \cdot r + \frac{d\Psi_B(i_C,\zeta)}{dt} = -i_A \cdot r - \frac{d\Psi_A(i_A,\zeta);}{dt} \\ & i_C \cdot r + \frac{d\Psi_C(i_C,\zeta)}{dt} = -i_D \cdot r - \frac{d\Psi_D(i_D,\zeta)}{dt}. \end{aligned} \quad (2)$$

In the rotor rotation angle range in electric radians $\pi \le \zeta \le 3{\cdot}\pi/2$ transistors VT3 and VT4 open phase *A* through VT4 transistor and a diode D4 connected in parallel *D* phase and phase *B* through the diode D3 and transistor VT3 is connected parallel to the phase *C*. Transistors VT1 and VT2 are locked. Electromagnetic processes in the VRM in the rotor rotation angle range described by the system

$$\begin{aligned}
&i_C\cdot r+\frac{\partial\Psi_C(i_C,\zeta)}{\partial i_C}+i_D\cdot r+\frac{\partial\Psi_D(i_D,\zeta)}{\partial i_D}=U;\\
&i_A\cdot r+\frac{d\Psi_A(i_A,\zeta)}{dt}=-i_D\cdot r-\frac{d\Psi_D(i_D,\zeta)}{dt};\\
&i_B\cdot r+\frac{d\Psi_B(i_B,\zeta)}{dt}=-i_C\cdot r-\frac{d\Psi_C(i_C,\zeta)}{dt}.
\end{aligned}\qquad(3)$$

In the range of angles of rotation of the rotor in electrical radians $3\cdot\pi/2\le\zeta\le2\cdot\pi$ transistors VT3 and VT2 open, and transistors VT1 and VT4 – locked. The phase *A* is connected in parallel to the phase *B*, and the phase *D* – in parallel to the phase *C*. The VRM equations can be written as

$$\begin{aligned}
&i_B\cdot r+\frac{d\Psi_B(i_B,\zeta)}{dt}+i_C\cdot r+\frac{d\Psi_C(i_C,\zeta)}{dt}=U\\
&i_D\cdot r+\frac{\partial\Psi_D(i_D,\zeta)}{\partial i_D}=-i_C\cdot r-\frac{\partial\Psi_C(i_C,\zeta)}{\partial i_C};\\
&i_A\cdot r+\frac{d\Psi_A(i_A,\zeta)}{dt}=i_B\cdot r+\frac{d\Psi_B(i_B,\zeta)}{dt}.
\end{aligned}\qquad(4)$$

Analytical flux dependences on the current phase and angle of rotation of the rotor are presented in [3].

To solve systems (1-4) by the Runge-Kutta method should be presented as a system of linear algebraic equations for the production of time-phase currents. Given that

$$\begin{aligned}
&\frac{d\Psi(i,\zeta)}{dt}=\frac{\partial\Psi}{\partial i}\cdot\frac{di}{dt}+\omega\cdot\frac{\partial\Psi}{\partial\zeta};\\
&\omega=\frac{d\zeta}{dt}.
\end{aligned}\qquad(5)$$

Systems of differential equations (1-4), authorized with respect to the first derivatives of currents, in conjunction with the fourth equation of (1), the second equation of (5) and equation (6) allow using Runge-Kutta method, to get depending on the currents, torques and the phase flux linkage on the time and angle of the rotor in the gate, and the speed on time

$$\frac{d\omega}{dt}=\left(\int_0^{i_A}\frac{\partial\Psi_A(i_A,\zeta)}{\partial\zeta}\cdot di_A+\int_0^{i_B}\frac{\partial\Psi_B(i_B,\zeta)}{\partial\zeta}\cdot di_B+\int_0^{i_C}\frac{\partial\Psi_C(i_C,\zeta)}{\partial\zeta}\cdot di_C+\int_0^{i_D}\frac{\partial\Psi_D(i_D,\zeta)}{\partial\zeta}\cdot di_D-M_c\right)/J,\qquad(6)$$

where $M_c$ is the drag torque on the motor shaft; *J* is the moment of inertia of the rotating masses.

In the correspondence with the presented mathematical model the calculation program in the environment MathCAD 2001 is developed.

Fig. 6 shows the torque phase of the angle of rotation of the rotor when powered from a switch on the VRM of Fig. 5 at the maximum power (solid curve), at equal specific losses (dot dashed line) with specific losses when powered by the VRM switch scheme asymmetrical bridge, at least torque ripple (dashed curve).

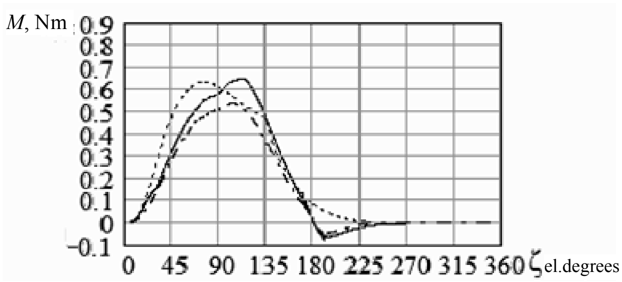


Fig. 6. Dependence of the phase torque on the angle of rotation of the rotor when VRM powered from the switch according to Fig. 5

Fig. 7 shows the resulting torque on the angle of rotation of the rotor when powered from a switch on the VRM of Fig. 5 at the maximum power (solid line), with equation of specific losses (dash dotted line) with specific losses when powered by the VRM switch by the scheme asymmetrical bridge, at least torque ripple (dashed curve).

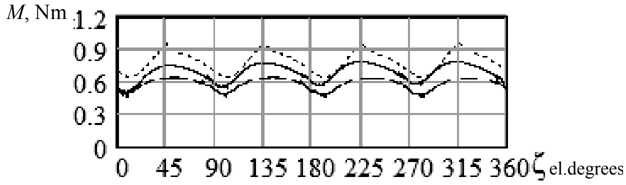


Fig. 7. Dependence of the resultant moment on the angle of rotation of the rotor when VRM powered from the switch according to Fig. 5

Figures 8, 9 show curves of current change and the phase flux linkages, respectively.

Fig. 8 shows the phase current dependence on the angle of rotation of the rotor when powered from a switch on the VRM of Fig. 5 at the maximum power (solid curve), at equal specific losses (dot dashed line) with specific losses when powered by the VRM switch scheme asymmetrical bridge, at least torque ripple (dashed curve).

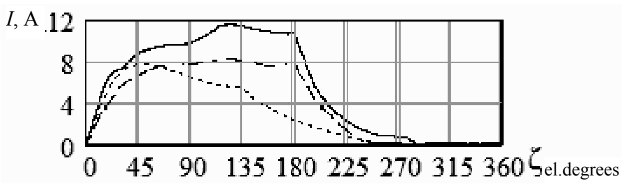


Fig. 8. Dependence of the current phase on the angle of rotation of the rotor when VRM powered from the switch according to Fig. 5

Fig. 9 shows the dependence of the phase flux linkage on angle of rotation of the rotor when powered from a switch on the VRM of Fig. 5 at the maximum power (solid curve), at equal specific losses (dot dashed line) with specific losses when powered by the VRM switch scheme asymmetrical bridge, at least torque ripple (dashed curve).

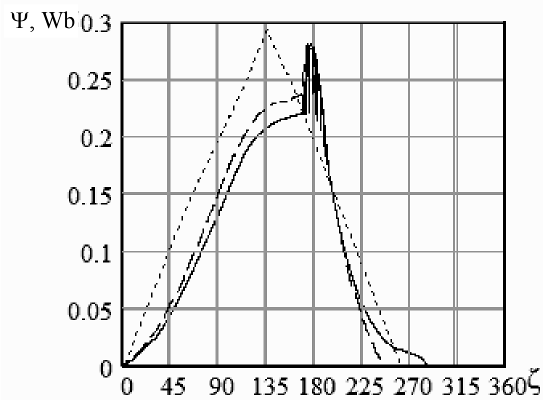


Fig. 9. Dependence of the phase flux linkage on the angle of rotation of the rotor when VRM powered from the switch according to Fig. 5

Fig. 10 shows the dependence of the phase voltage of the rotor rotation angle. The results of calculation of the time of one phase of the VRM are shown in Fig. 6, the resulting torque – in Fig. 7.

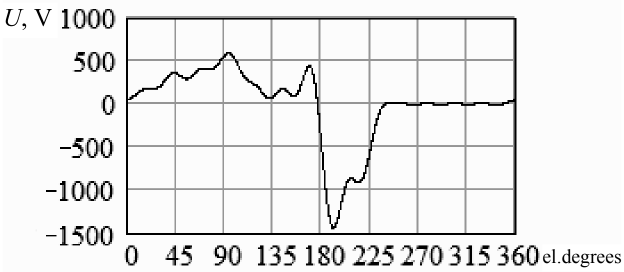


Fig. 10. Phase voltage dependence on the rotor rotation angle

The calculated data of motors are given in Table 1 where $P_2$ is the net power; $n$ is the rotational speed; $I_{ph}$ is the phase current; $P_o$ are the winding losses; $P_{Fe}$ are the iron losses; $P_{sch}$ are the losses in the switch circuit; $P_{mech}$ are the mechanical losses; $\Delta M$ is the value of torque ripple; $p_t$ are the losses per unit of outer lateral surface of the stator core (specific losses – the ratio of total losses in the motor area to the outer lateral surface of the stator core); $W_p$ is the number of turns in the phase winding.

Table 1

| $P_2$, W | $n$, RPM | $I_{ph}$, A | η, % | $P_o$, W | $P_{Fe}$, W | $P_{sch}$, W | $P_{mech}$, W | $\Delta M$, % | $p_t$, W/cm$^2$ | $B$, T | $W_p$ | Switch circuit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1665 | 6006 | 3.863 | 61.6 | 59.8 | 540 | 114 | 325 | 38.8 | 1.621 | 1.121 | 130 | Asym. bridge (Fig. 1) |
| 1066 | 5997 | 2.67 | 60.7 | 34.56 | 256 | 79 | 322 | 21.18 | 1.07 | 0.772 | 143 | Asym. bridge (Fig. 1) |
| 1066 | 5937 | 3.464 | 53.2 | 29.61 | 524 | 30.4 | 325 | 12.18 | 1.59 | 1.128 | 102 | 4 diodes, 4 transistors (Fig. 5) |

* Note. Calculation of losses in the steel is carried out by [1].

The motor powered by a switch on the circuit asymmetric bridge (Fig. 1), the power, which provides a maximum permissible winding temperature is 1.665 kW. But at the same time the surge up to 38.8 %, resulting in high levels of noise and vibration. Through the installation of switching angles, to ensuring reduction in torque ripple and reduce engine power to a level below which there is a decrease in the value of torque ripple, received power of 1.066 kW and a torque ripple value of 21.18 %. The same performance is achieved when the engine power switch to it from four transistors and four diodes. At the same time the cost of the switch according to the scheme of the asymmetric bridge to date is 1200 UAH. The switch according to Fig. 5 cheaper, the cost of it is 540 UAH. The pulsations of the engine torque with the switch, as shown in Table 1, almost half that of the smallest torque ripple motor powered by a switch on the circuit asymmetric bridge.

Consequently, for motors with improved vibroacoustic characteristics it is necessary to apply switch according to Fig. 5.

**Conclusions.**

1. For improved vibroacoustic characteristics of the VRM is advisable to apply uncapacitor switch on four transistors and four diodes, which allows you to receive half the amount of torque ripple than the lowest value of the motor torque ripple, eating from a switch on the circuit asymmetric bridge.

2. The cost of the VRM with uncapacitor switch on the circuit with four transistors and four diodes is more than two times less than the engine with the switch on the circuit asymmetric bridge.

REFERENCES


***1.*** Galaiko L.P. The account of magnetic losses for want of designing switched reluctance motors. *Elektrotekhnika i elektromekhanika – Electrical engineering & electromechanics*, 2003, no.2, pp. 17-18. (Rus). **doi: 10.20998/2074-272X.2003.2.04**.

***2.*** Gollandtsev Y.A. *Ventil'nye induktorno-reaktivnye dvigateli* [Valve inductor and jet engines]. St. Petersburg, GNC RF CNII Elektropribor Publ., 2003. 148 p. (Rus).

***3.*** Zinchenko E.E., Finkelshtein V.B. T A technique of magnetization curve approximation for switched reluctance motors. *Elektrotekhnika i elektromekhanika – Electrical engineering & electromechanics*, 2009, no.1, pp. 13-16. (Rus). **doi: 10.20998/2074-272X.2009.1.03**.

***4.*** Zinchenko E.E., Finkelshtein V.B. Performance analysis of a switched reluctance motor fed through an asymmetric half-bridge converter and a Millers bridge converter. *Elektrotekhnika i elektromekhanika – Electrical engineering & electromechanics*, 2012, no.1, pp. 33-35. (Rus). **doi: 10.20998/2074-272X.2012.1.07**.

***5.*** Luchko A.R. *Povyshenie effektivnosti electroprivoda bytovyh pogruzhnych nasosov putem ispolzovaniya ventilnych dvigatelei. Diss. cand. techn. nauk* [Increase of efficiency of the electric drive of household submersible pumps by use of valve inductor engines. Cand. tech. sci. diss.]. Zaporozhye, 2005. 160 p. (Rus).

***6.*** Shabayev V.A., Kruglikov O.V., Tubis Ya.B. *Ventil'no-induktornyi chetyrekhfaznyi nereversivnyi dvigatel'* [Valve inductor 4-phase irreversible motor]. Patent Russian Federation, no. 2390085, 2010. (Rus).

***7.*** Krishnan R. *Switched Reluctance Motor Drives. Modeling, Simulation, Analysis, Design and Applications*. CRC Press, 2001. 398 p. **doi: 10.1201/9781420041644**.
***8.*** Lawrenson P.J., Stephenson J.M., Fulton N.N., Blenkinsop P.T., Corda J. Variable-speed switched reluctance motors. *IEE Proceedings B Electric Power Applications*, 1980, vol.127, no.4, p. 253. **doi: 10.1049/ip-b.1980.0034**.
***9.*** Miller T.J.E. *Switched reluctance motors and their control*. Magna Physics Publishing and Clarendon Press. Oxford, 1993.

*Received 22.03.2016*

*V.B. Finkelshtein*[1], *Doctor of Technical Science, Professor,*
*A.B. Yegorov*[2], *Candidate of Technical Science, Associate Professor,*
[1] O.M. Beketov National University of Urban Economy in Kharkiv,
12, Revolution Str., Kharkiv, 61002, Ukraine,
phone +380 57 7319528, e-mail: finalvb@gmail.com
[2] Ukrainian Engineering Pedagogics Academy,
16, Universitetskaya Str., Kharkiv, 61003, Ukraine,
phone +380 66 7228206, e-mail: diaskk@yandex.ru

*How to cite this article:*
Finkelshtein V.B., Yegorov A.B. Characteristics of a 4-phase valve reluctance motor when powered by uncapacitor switchboard. *Electrical engineering & electromechanics*, 2016, no.3, pp. 25-29. doi: 10.20998/2074-272X.2016.3.04.