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THE INFLUENCE OF MECHANICAL DEFORMATION CONSIDERATION ON THE RESULTS OF THE CALCULATION OF THE VACUUM CIRCUIT BREAKER DRIVE SHAFT

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One of the important directions of theoretical, computational and experimental research related to the improvement and development of new design elements of modern electrical devices, primarily medium voltage circuit breakers and contactors, is the study of not only electromagnetic, but also mechanical processes in these electrical devices. The paper is devoted to the creation and use of computational models for calculating mechanical forces and deformations of an absolutely rigid and real drive shaft of a medium voltage vacuum circuit breaker in static mode with the aim of quantitative comparison of the obtained numerical results. Calculation studies are performed using the finite element method. A comparative analysis of the calculation of mechanical stresses in the drive shaft of a vacuum circuit breaker in a static mode for an absolutely rigid and real shafts is carried out in this paper on the basis of the developed models. The obtained results of computer modeling are given in detail in tabular and graphic forms, including the shape of the deflection of the medium voltage vacuum circuit breaker shaft at the maximum stroke of the actuator of the electrical device under study. It has been demonstrated that the mechanical deformation of the shaft causes a decrease in contact drop and contact pressure forces, but with a correctly selected cross-section, these values are not critical and have little effect on the circuit breaker operation (about 20% and 7%, respectively). It is shown that as a result of shaft bending, additional axial forces appear in the supports, which significantly affect the choice of bearings according to the equivalent static load.

***Keywords**: vacuum circuit breakers, stresses, shaft deformation, numerical analysis, finite element method.*

Introduction

One of the design elements of medium voltage vacuum circuit breakers with electromagnetic actuators is the drive shaft, or as it is also called, the synchronizing shaft. The shaft's purpose is to transfer motion and effort from the actuator to the contacts of the circuit breaker. The leader in the production of such circuit breakers is the ABB concern, which was the first to present such a circuit breaker (VM1) in 1990 [1]. In Ukraine, such circuit breakers are manufactured by CJSC "Vysokovoltny Soyuz" and "AVM AMPER" [2]. Circuit breakers with electromagnetic actuators are simple in design, reliable and do not require preventive maintenance for many years.

Works related to research, improvement and development of new design elements of medium voltage circuit breakers and contactors have been carried out for a long time at the department of electrical devices of the National Technical University "Kharkiv Polytechnic Institute" [3–6]. One of the directions of these works is the study of mechanical processes in vacuum circuit breakers.

Fig. 1 shows the construction of the drive shaft of the circuit breaker with a vertical arrangement of vacuum chambers.

The actuator rotates the shaft through axis 3. The shaft's axes 4 are connected to the moving contacts of the vacuum chambers through thrust insulators with contact pressure springs.

Fig. 1 shows that the shaft design is quite complex, and as a result of applying significant efforts, the shaft will be prone to complex deformation. At the same time, contact failure, final contact pressures and reactions in the shaft supports (reactions in the bearings) will be somewhat different than in the case of a simplified calculation for a completely rigid shaft. So, the main issue is the quantitative assessment of the specified differences.

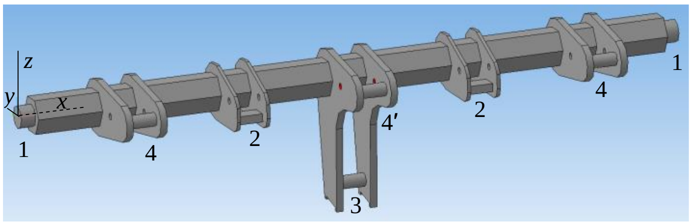

Fig. 1. The drive shaft of the circuit breaker:
1 – shaft mounting axes in bearings; 2 – planes of force application of the disconnecting springs; 3 – thrust attachment axis of the electromagnetic actuator; 4, 4′ – attachment axes of thrusts of movable contacts in the extreme and middle poles; *x*, *y*, *z* – coordinate system axes

Problem and purpose of the research – creation and use of mathematical and calculation models for the numerical study of mechanical forces and deformations of an absolutely rigid and real drive shaft of a medium voltage vacuum circuit breaker in a static mode for the quantitative comparison of the obtained numerical results.

Calculation of the circuit breaker shaft for the adopted model

In the literature, the calculation of shafts is presented quite widely (the most fundamental studies are given in [7–10]), but the problem is that there are no calculations of the shaft of the specified design under the appropriate mounting conditions (Fig. 1). As shown in [11], calculations of complex real structures can be carried out only by numerical methods, therefore, all detailed calculations in this paper were carried out by the finite element method using the COMSOL Multiphysics software product.

Simplified calculation of an absolutely rigid shaft

Fig. 2 shows a model of an absolutely rigid shaft and the forces acting on it.

The system (Fig. 2) is statically determined. To establish the unknown forces, it is necessary to write down the condition of shaft equilibrium through the projection of forces on the coordinate axis and the torque equation relative to the *x* axis.

Initial data: the length of the steel shaft is 574 mm; the section shape is hexagonal with the diameter of the inscribed circle of 32 mm; the ratio of the stroke of the actuator axis and the axes of thrust insulators is 1.5; the total force of the disconnecting springs (acting on surface 2, Fig. 1) is 1000 N; the total force of the initial compression of the contact springs (applied to axes 4, Fig. 1) is 6600 N (2200 N per pole); the stroke of axis 3 (Fig. 1) of the actuator after touching the contacts is 4 mm; the theoretical stroke of the axes of the thrust insulators after touching the contacts (failure of the contacts with a completely rigid shaft, axis 4 in Fig. 1) is 2.61 mm, the stiffness of the contact spring is 280 kN/m.

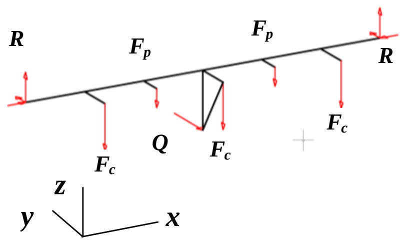

Fig. 2. Calculation model of an absolutely rigid shaft:
R – reactions in supports;
Q – thrust force;
F_c – contact pressure forces;
F_p – forces of the disconnecting springs

In this case, the result will be as follows:

$$R_y = \frac{1}{2} \cdot \frac{3 \cdot F_c \cdot L_c + 2 \cdot F_p \cdot L_p}{L_q}; \quad R_z = \frac{3}{2} \cdot F_c + F_p; \quad R_x = 0;$$

where *R* – reactions of the supports along the corresponding axes; L_c, L_p, L_q – the length of the shoulders from the axis of the shaft to the points of application of the contact pressure forces, the disconnecting springs, and the drive axis 3 (Fig. 1).

Moreover

$$F_c = F_0 + C_c \cdot w,$$

where F_0 – initial contact pressure force; C_c – stiffness of the contact spring; *w* – progress of contacts.

Then the calculation formulas for determining the reactions in the shaft supports will take the following form:

$$R_y = \frac{1}{2} \cdot \frac{3 \cdot (F_0 + C_c \cdot w) \cdot L_c + 2 \cdot F_p \cdot L_p}{L_q}; \; R_z = \frac{3}{2} \cdot (F_0 + C_c \cdot w) + F_p; \; R_x = 0.$$

Shaft calculation using COMSOL Multiphysics

The calculated model of the shaft, imported into the COMSOL Multiphysics software product from the graphic editor, coincides with Fig. 1. Boundary conditions: contact pressure forces and disconnecting springs are applied to the corresponding surfaces of the shaft (surfaces 2, 4, Fig. 1); sliding conditions are set on axis 1 and shaft ends; on axis 3 – displacement.

Results of static calculation

The calculation was carried out assuming there is no deformation of the housing in which the shaft supports are fastened. Fig. 3 shows the calculation results for absolutely rigid and real shafts. As can be seen from Fig. 3, the obtained values are different. The differences in contact thrust for a completely rigid and real shaft are shown in the Table 1.

From the Table 1, it follows that there is a deflection of the shaft, which is determined by the load applied to it. Such a deflection reduces the value of contact deflection compared to a completely rigid shaft by 0.56 mm, which leads to some reduction in the force of final contact pressure.

Table 1. Differences in the value of shaft deflection

Shaft model	Initial stroke, mm	Final stroke, mm
Absolutely rigid shaft	0	2.61
Real shaft	–0.56	2.05

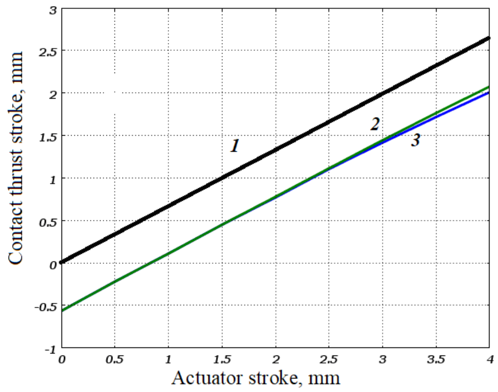

Fig. 3. Dependence of contact thrust stroke on actuator stroke:
1 – for an absolutely rigid shaft;
2, 3 – for the real shaft (central and side thrust)

Fig. 4 shows the shape of the shaft deflection at the maximum stroke of the actuator on a scale of 20:1.

The presence of shaft deflection leads to a change in the reactions in the supports. Figs. 5, 6 show the values of the reactions in the supports for absolutely rigid and real shafts.

Reaction values for absolutely rigid and real shafts at the initial and final points of the actuator stroke are shown in Table 2.

Table 2. Differences in the value of the reaction in the shaft supports

Reaction, N	Absolutely rigid shaft	Real shaft
$R_{y\,min}$	2343	2190
$R_{y\,max}$	3058	3358
$R_{z\,min}$	3800	3582
$R_{z\,max}$	4896	4574

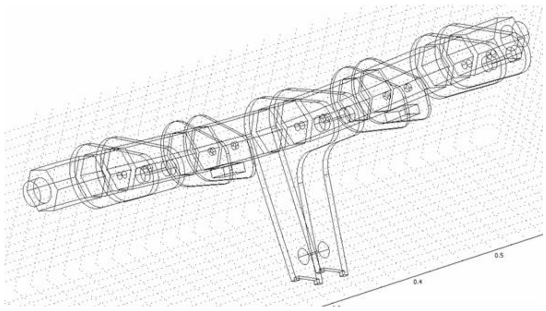

Fig. 4. The shape of the shaft deflection at the maximum stroke of the actuator on a scale of 20:1

From the Table 2, it can be seen that the difference in reactions is approximately 10% (for thinner shafts, this difference will be greater). However, the main difference in the calculation results is that when calculating a real shaft due to its deflection, an additional axial force R_x appears, which could not be present when calculating a rigid shaft and which must be taken into account when choosing bearings.

Fig. 7 shows the change in the value of the axial force depending on the stroke of the actuator for an absolutely rigid and real shaft.

The value of the axial force varies in the range from $R_{x\,min}$= –335 N up to $R_{x\,max}$= –1050 N.

Consideration of axial force is important when choosing a bearing. So, if the choice of radial bearings is made according to the equivalent static load, this value is calculated according to the formula [12]:

$$P_o = F_r \cdot X_o + F_a \cdot Y_o ,$$

where P_o – equivalent static load; F_r – radial load; X_o – radial load factor equal to 0.6; F_a – axial load; Y_o – axial load factor equal to 0.5.

Comparative calculation data are given in Table 3, from which it can be seen that for a hexagonal shaft with an inscribed circle diameter of 32 mm, the equivalent static load on the bearing will be 13.5% greater than for an absolutely rigid shaft.

As it was indicated above, the deflection reduces the value of contact dip and the force of contact pressure in comparison with an absolutely rigid shaft. Fig. 8 shows the change in the force of contact pressure as an actuator stroke function.

Comparative data of the results of calculations regarding the change in contact pressure forces are given in Table 4.

For a real shaft, the total contact pressure is ~93% of the ideal contact pressure and does not significantly affect the operation of the circuit breaker contacts.

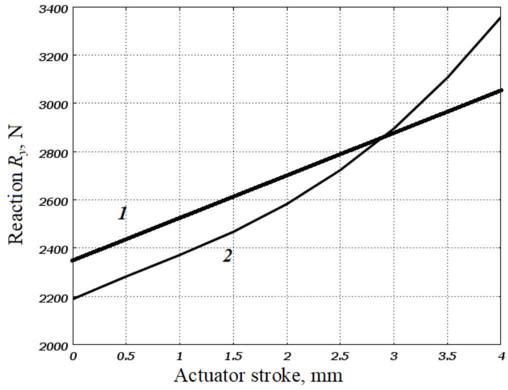

Fig. 5. Reaction R_y for shafts:
1 – rigid; 2 – real

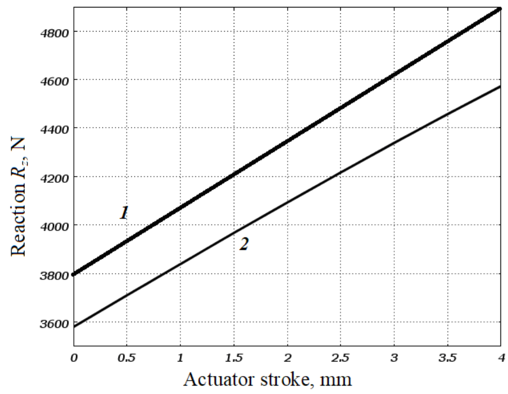

Fig. 5. Reaction R_z for shafts:
1 – rigid; 2 – real

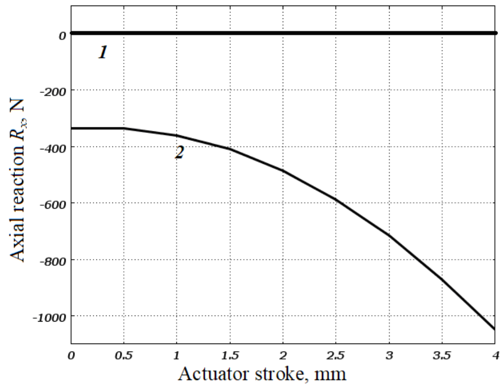

Fig. 7. Axial reaction R_x in the actuator stroke function:
1 – rigid shaft; 2 – real shaft

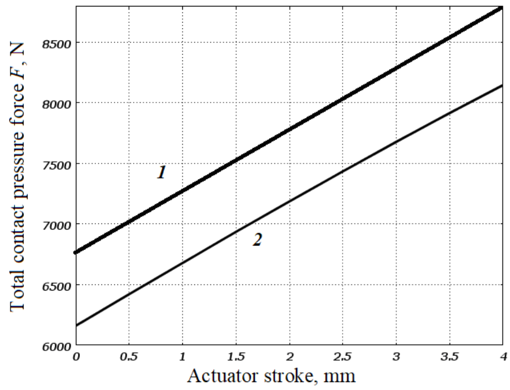

Fig. 8. Total force of contact pressure:
1 – rigid shaft; 2 – real shaft

Table 3. The value of the equivalent static force

Shaft model	P_o, N
Absolutely rigid shaft	3463.5
Real shaft	3929.6

Table 4. The total value of contact pressure forces

Shaft model	F, N
Absolutely rigid shaft	8792
Real shaft	8147

Conclusions

1. A mathematical model for calculating the deflections of the vacuum circuit breaker shaft has been developed.

2. A comparative calculation of the absolutely rigid and real shafts was carried out. It is shown that, due to the complex deformation, the failure of the contacts, the final contact pressures and reactions in the supports differ from the "ideal" ones.

3. The main difference in the calculations is the appearance of the axial component force in the supports, which significantly affects the choice of bearings under the condition of equivalent static load.

4. The cross section of the shaft is chosen in such a way that the calculated deformations do not significantly affect the force of the final contact pressure and, therefore, the operation of the circuit breaker.

5. Calculations in the software product COMSOL Multiphysics were carried out based on the assumption of a non-deformable circuit breaker body in which the shaft supports are attached. Otherwise, the contact failure and contact pressure will be less than ones obtained in this calculation.

References

1. (2018). VM1. Medium voltage vacuum circuit breakers with magnetic drive 12...24 kV – 630...4000 A – 16...50 kA: Distribution solutions. ABB: official site. https://library.e.abb.com/public/bf168419d98544ac873fcb9077e4f387/Cat_VM1(EN)M_1VCP000157.pdf.
2. High quality electrical equipment. AVM AMPER: official site. 2023. https://abm-amper.com/.
3. Klimenko, B. V., Bugaychuk, V. M., & Grechko, A. M. (2004). *Elektromagnitnyye privody vakuumnykh vyklyuchateley srednikh napryazheniy* [Electromagnetic drives of medium voltage vacuum circuit breakers]. *Vestnik NTU «KHPI». Seriya: Problemy usovershenstvovaniya elektricheskikh mashin i apparatov. Teoriya i praktika – Bulletin of the National Technical University "KhPI". Series: Problems of electrical machines and apparatus perfection. Theory and practice*, no. 42, pp. 73–80 (in Russian).
4. Klimenko, B. V., Grechko, A. M., & Bugaychuk, V. M. (2005). *Opytnyy obrazets dvukhpozitsionnogo elektromagnitnogo privoda vakuumnogo vyklyuchatelya srednego napryazheniya* [A prototype of a two-position electromagnetic drive of a medium voltage vacuum circuit breaker]. *Elektrotekhnika i elektromekhanika – Electrical Engineering & Electromechanics*, no. 2, pp. 23–23 (in Russian).
5. Klimenko, B. V., Grechko, A. M., Bugaychuk, V. M., & Vyrovets, S. V. (2006). *Bystrodeystvuyushchiy elektromagnitnyy privod s vytesneniyem magnitnogo polya dlya vakuumnogo vyklyuchatelya srednego napryazheniya* [High-speed electromagnetic drive with magnetic field displacement for a medium-voltage vacuum circuit breaker]. *Elektrotekhnika i elektromekhanika – Electrical Engineering & Electromechanics*, no. 4, pp. 22–26 (in Russian).
6. Klimenko, B. V., Grechko, A. M., & Yeresko, A. V. (2007). *Elektromagnitnyy privod s dvukhpozitsionnoy magnitnoy zashchelkoy dlya vakuumnogo vyklyuchatelya srednego napryazheniya* [Electromagnetic drive with a two-position magnetic latch for a medium voltage vacuum circuit breaker]. *Elektrotekhnika i elektromekhanika – Electrical Engineering & Electromechanics*, no. 6, pp. 40–43 (in Russian).
7. Birger, I. A. (1993). *Raschet na prochnost detaley mashin* [Calculation of the strength of machine parts]. Moscow: Mashinostroyeniye, 639 p. (in Russian).
8. Maslov, G. S. (1980). *Raschety kolebaniy valov* [Calculations of shaft vibrations]: A reference book. Moscow: Mashinostroyeniye, 151 p. (in Russian).
9. Ponomarev, S. D. (ed.), Biderman, V. L., Likharev, K. K., Makushin, V. M., Malinin, N. N., & Feodosyev, V. I. (1959). *Raschety na prochnost v mashinostroyenii* [Strength calculations in mechanical engineering]: in 3 vols. Vol. 3: *Inertsionnyye nagruzki. Kolebaniya i udarnyye nagruzki. Vynoslivost. Ustoychivost* [Inertial loads. Vibrations and shock loads. Endurance. Sustainability]. Moscow: Mashgiz, 1118 p. (in Russian).
10. Serensen, S. V., Groman, M. B., Kogayev, V. P., Shneyderovich, R. M. (1970). *Valy i osi. Konstruirovaniye i raschet* [Shafts and axles. Design and calculation]. Moscow: Mashinostroyeniye, 320 p. (in Russian).
11. Zienkiewicz O. C. (1971). The Finite Element Method in Engineering Science. McGraw-Hill, 521 p.
12. (2015). *Prakticheskiy raschet (podbor) podshipnikov kacheniya* [Practical calculation (selection) of rolling bearings]: Lectures on the "Machine parts and design fundamentals" by the Samara University. https://studfile.net/preview/2114396/page:5/.

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Вплив урахування механічної деформації на результати розрахунку приводного валу вакуумного вимикача

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Одним з важливих напрямків теоретичних, розрахункових та експериментальних досліджень стосовно удосконалення й розробки нових елементів конструкції сучасних електричних апаратів, у першу чергу вимикачів і контакторів середніх напруг, є вивчення не лише електромагнітних, а й механічних процесів у зазначених електричних апаратах. Стаття присвячена створенню й використанню обчислювальних моделей для розрахунку механічних зусиль і деформацій абсолютно жорсткого й реального приводного валу вакуумного вимикача середньої напруги у статичному режимі з метою кількісного порівняння отриманих чисельних результатів. Розрахункові дослідження виконуються за допомогою методу скінчених елементів. У статті на підставі розроблених моделей проведено порівняльний аналіз розрахунку механічних напружень у привідному валу вакуумного вимикача у статичному режимі для абсолютно жорсткого й реального валу. Отримані результати комп'ютерного моделювання детально наведені у табличній та графічній формах, у тому числі представлено форму прогину вала вакуумного вимикача середньої напруги при максимальному ході актуатора електричного апарата, що досліджується. Продемонстровано, що механічна деформація валу викликає зменшення провалу контактів і сил контактного натискання, але при правильно обраному поперечному перетину ці значення не є критичними і мало впливають на роботу вимикача (близько 20% і 7% відповідно). Показано, що в результаті вигину валу в опорах з'являються додаткові осьові зусилля, які істотно впливають на вибір підшипників за еквівалентним статичним навантаженням.

***Ключові слова**: вакуумні вимикачі, напруження, деформація вала, чисельний аналіз, метод скінченних елементів.*

Література

1. VM1. Medium voltage vacuum circuit breakers with magnetic drive 12...24 kV – 630...4000 A – 16...50 kA: Distribution solutions. ABB: official site. 2018. https://library.e.abb.com/public/bf168419d98544ac873fcb9077e4f387/Cat_VM1(EN)M_1VCP000157.pdf.
2. Высокоякісне електрообладнання. АВМ АМПЕР: офіційний сайт. 2023. https://abm-amper.com/.
3. Клименко Б. В., Бугайчук В. М., Гречко А. М. Электромагнитные приводы вакуумных выключателей средних напряжений. *Вестник НТУ «ХПИ». Серия: Проблемы усовершенствования электрических машин и аппаратов. Теория и практика*. 2004. № 42. С. 73–80.
4. Клименко Б. В., Гречко А. М., Бугайчук В. М. Опытный образец двухпозиционного электромагнитного привода вакуумного выключателя среднего напряжения. *Электротехника и электромеханика*. 2005. № 2. С. 23–28.
5. Клименко Б. В., Гречко А. М., Бугайчук В. М., Выровец С. В. Быстродействующий электромагнитный привод с вытеснением магнитного поля для вакуумного выключателя среднего напряжения. *Электротехника и электромеханика*. 2006. № 4. С. 22–26.
6. Клименко Б. В., Гречко А. М., Ересько А. В. Электромагнитный привод с двухпозиционной магнитной защелкой для вакуумного выключателя среднего напряжения. *Электротехника и электромеханика*. 2007. № 6. С. 40–43.
7. Биргер И. А. Расчет на прочность деталей машин. М.: Машиностроение, 1993. 639 с.
8. Маслов Г. С. Расчеты колебаний валов: справочник. М.: Машиностроение, 1980. 151 с.
9. Расчеты на прочность в машиностроении: в 3-х т. / Под ред. С. Д. Пономарёва. Т. 3: Инерционные нагрузки. Колебания и ударные нагрузки. Выносливость. Устойчивость. М.: Машгиз, 1959. 1118 с.
10. Серенсен С. В., Громан М. Б., Когаев В. П., Шнейдерович Р. М. Валы и оси. Конструирование и расчет. М.: Машиностроение, 1970. 320 с.
11. Зенкевич О. Метод конечных элементов в технике. М.: Мир, 1975. 541 с.
12. Практический расчет (подбор) подшипников качения: лекции по предмету «Детали машин и основы конструирования». Самарский национальный исследовательский университет им. ак. С. П. Королёва. 2015. https://studfile.net/preview/2114396/page:5/.