

DIAGNOSTICS OF CONTROL ROD DRIVE. POSSIBILITIES TO EXTEND ITS LIFETIME AT NPP'S

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Summary

According to specifications, lifetime of a linear stepping electromagnetic drive in WWER-1000 nuclear reactors is limited by the pre-assigned lifetimes of the drive components such as electromagnets, a latch assembly, drive rack, and control rod position sensor. The lifetime of the drive components is from 7 to 20 years. On the basis of diagnostics of these components under real conditions, actual lifetimes of the components at nuclear power plant (NPP) were forecasted. It is shown that in order to extend the lifetime of the drive components up to the reactor lifetime (60 years), it is necessary to replace the sensor of the DPL-type by the new one (of the DPL-KV type) and to decrease the electromagnet temperature. The Measuring and Diagnostic System with the DPL-KV sensor enables diagnosing the sensor, electronic processing unit and drive. Economic effect due to the cumulative technical decisions is estimated to be 7 mln.euro per NPP unit.

Keywords: linear stepping electromagnetic drive, control rod position sensor, lifetime, nuclear reactor.

DIAGNOSTYKA NAPĘDU PRĘTA STERUJĄCEGO. MOŻLIWOŚCI ZWIĘKSZENIA CZASU EKSPLOATACJI NAPĘDÓW W ELEKTROWNIACH ATOMOWYCH

Streszczenie

Zgodnie z dokumentacją czas eksploatacji elektromagnetycznych silników krokowych prętów sterujących w reaktorach jądrowych WWER-1000 jest ograniczony ustalonymi czasami eksploatacji ich składników (blok przesunięcia, pręt, elektromagnesy, czujnik) – od 7 do 20 lat. Na podstawie wyników diagnostyki tych składników w warunkach realnych została zrobiona prognoza ich rzeczywistej żywotności w elektrowniach atomowych. Wykazano, że w celu wydłużenia czasu eksploatacji składników do czasu życia reaktora (60 lat) trzeba wymienić czujnik DPL na inny, bardziej niezawodny – DPL-KV i znacznie obniżyć temperaturę elektromagnesów. Układ pomiarowo-diagnostyczny wyposażony w czujnik DPL-KV pozwala przeprowadzać diagnostykę czujnika, osprzętu elektronicznego i silnika. Całkowity efekt ekonomiczny wprowadzenia zaproponowanych rozwiązań technicznych jest szacowany na 7 milionów Euro na blok energetyczny.

Słowa kluczowe: elektromagnetyczny liniowy silnik krokowy, czujnik położenia pręta sterującego, czas eksploatacji, reaktor jądrowy.

1. INTRODUCTION

At present, more than twenty power units with nuclear reactors of the WWER-1000 type are in operation in Russia, Ukraine, Bulgaria, and Czechia. The expected lifetime of such reactors will be about 60 years (the lifetime of 30 years, which was specified initially, will be prolonged).

In most WWER-1000 power units, the control and protection system applies linear stepping drives which move control rods (CR's).

Each drive comes in the form of a high cylinder and comprises mechanical unit (a housing, motion unit, and rack) and electrical unit (an electromagnet assembly and sensor).

An internal drive part (the motion unit, rack, and a lower part of the sensor) is in the primary coolant (the temperature is up to 350 °C and pressure is up to 18 MPa), whereas an external part (the electromagnet assembly and a higher part of the sensor) is outside the coolant.

The housing provides hermeticity of the internal part. Under a reactor control mode, the electromagnet assembly is moving the rack with the control rod by interaction with the motion unit through the housing. The sensor function is measuring the control rod position. Under the emergency shutdown mode, the electromagnet assembly is de-energized. The rack drops together with the control rod on an arresting device.

The specified lifetime of these drives is not longer than 20-30 years. Accordingly, during the expected reactor lifetime, all the drives should be replaced at least once, that is not economic.

This problem is particularly important for the drives of the SHEM-2 type, which are in operation at the most WWER-1000 Nuclear Power Plants (NPP's). The specified lifetime of mechanical unit of this drive is 20 years. The lifetime of electrical unit of the drive is 10 years or less. In the specification, the value of rated life is 6000 double strokes and the number of rated drops from any height in response to scram signal (the function of emergency shutdown) is 200.

Operation experience of the SHEM-2 drives as well as theoretical and experimental investigations show that at the operating NPP the lifetime of such a drive can be enhanced up to the reactor lifetime. The prolongation can be achieved by drive modernization at a reasonable cost.

2. LIFETIME OF MECHANICAL UNIT

In the first place, the validity of correlation between the specified drive lifetime and specified resource as well as that of the specified resource should be analyzed taking into account operation experience.

The main components of the drive mechanical unit are the motion unit and rack. Dynamic mechanical loads (vibration and shocks) and friction influence the durability of these components significantly. Correspondingly, the lifetime of the motion unit and rack must depend on the time of using of the resource.

The estimate of the average lifetime of the drives can be got on the basis of information about operation of the SHEM-2 drives during a fuel cycle. Such information was obtained in the Measuring and Diagnostic Systems with the DPL-KV sensor (MS's) [1, 2], which were in operation at the 2nd power unit of the Kalinin NPP in Russia. According to the information obtained in 9 fuel campaigns, in the control group, each drive made not more than 217 double strokes, while in the emergency shutdown group the drives made only 100 double strokes.

If the operation intensity is the same, the resource of the motion unit for the control group drives will be equal to approximately 250 years. The drives are usually operating in the control group only during several years. After that, they are moved to the emergency shutdown group. So, during 60 years of operation, the SHEM-2 motion unit will use only a small part of its resource.

The lifetime of the rack depends on both the intensity of control mode (step movement) and the number of drops. The interaction of rack teeth with latches of the motion unit leads to rack teeth

deterioration. Falling loads cause distortion of the rack and wear of a rack damper.

The most period of time during the fuel cycle, the drives of the emergency shutdown groups are at the top end switch and do not move. Meanwhile, the drives in the control group move only in the higher part of the displacement range. Correspondingly, only a part of the drive teeth is wearing in interaction with the rack latches. Therefore, according to the criterion of rack wear, the rack resource depends on the maximum load per rack tooth.

The MS's were recording all the steps of the drives during each fuel campaign.

Fig. 1 shows a typical diagram of distribution of the number of steps during the campaign. In order to identify the position of the control rod, a two-digit decimal scale is applied. After matching the control rod positions with the number of the teeth, it follows from this diagram that the maximum load per tooth during a campaign is 300 times.

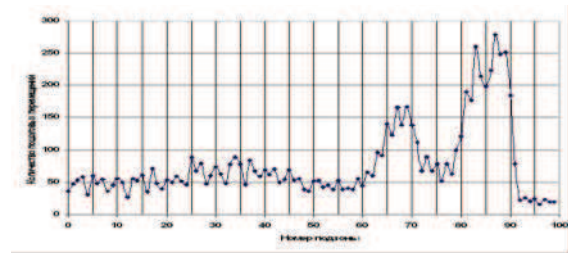


Fig. 1. Typical diagram of distribution of the number of steps during the campaign

The average duration of the fuel cycle was 10 months or so. Therefore, the resource of the rack teeth defined on the basis of maximum load per rack tooth is approximately 80 campaigns. Taking into account maintenance works (2 months), that is equal to 80 years. If the duration of the campaign increases up to 18 months, the above estimate does not change significantly and exceeds 60 year if we use any method of assessment. In reality, the resource will be much higher because of transposition of the drives from the control group to the emergency shutdown group.

According to the information obtained in the MS's, if the equipment is faultless (there is no unscheduled outage) the average number of the drops is not less than 4 times a year. Consequently, the estimate of the forecasted drop rack resource is 50 years. In case of 18-months fuel cycle and the same number of drops during the campaign, the forecasted drop rack resource is more than 80 years.

Taking into account that after the life test including 200 drops, the condition of the rack is satisfactory, we can consider the real rack resource to be significantly higher than the specified one.

The diagnostic information obtained in the 9 campaigns of the MS's operation leaves no doubt

that the drop time will not exceed the maximum permissible value of 4 c during 60 years.

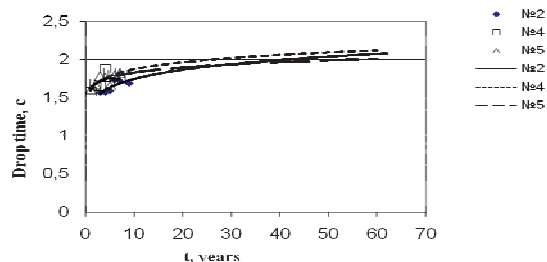


Fig. 2. Dependence of drop time of the rack on time for three MS's (extrapolation to 60 years)

An additional argument that the lifetime of the racks is longer than 60 years is the positive result of tests of similar racks used for SHEM-I and SHEM-3 drives. These tests included 400 and 470 drops, correspondingly.

Thus, the forecasted lifetime of the main components of the SHEM-2 mechanical unit exceeds the lifetime of the reactor.

3. LIFETIME OF ELECTRICAL UNIT

Estimate of a forecasted lifetime of the electrical unit of the SHEM-2 (electromagnet assembly and DPL sensor) is of great importance, because these components are very expensive whereas their specified lifetime is too short.

The drive of the SHEM-2 type comprises three electromagnets identical in design. Depending on their designation, they perform functions of pulling, locking, and fixing electromagnet. According to [3], life time of these electromagnets depends on the coil temperature when the drive is not moving. The lifetime of the fixing electromagnet is 25-30 years, for pulling and locking electromagnets it is much longer than the lifetime of the reactor.

Possible methods for decreasing the electromagnet temperature were analyzed. They are:

- increasing the heat transfer from the electromagnet to air;
- decreasing the power of inner heat generation in the electromagnet coil by reducing the value of current;
- decreasing the radiant heat exchange between the housing and electromagnet.

Decreasing the radiant heat exchange can be achieved by application of a thin heat-reflective screen with a high reflectivity that does not change significantly during long term operation. The screen should be inserted at the inner surface of the fixing electromagnet [3, 4].

Simulation of the electromagnet operation has shown that application of the screen is the most effective method for electromagnet temperature decreasing. Insertion of the screen can be carried out at the operating NPP during maintenance works.

The simulation results made it possible to determine the optimum parameters of the screen, which can provide decrease in temperature not less than 10 °C. Such decrease corresponds to the forecasted lifetime of 60 years. Tests of the electromagnet with the screen under actual environment conditions confirmed the correctness of calculations.

The least durable component of the electrical unit is the DPL sensor. Its specified lifetime is 5-10 years. The reason for rejection of the DPL sensors during operation is mainly concerned with oxidation of a wire and increasing the sensor coil resistance. As a result, actually, the sensor lifetime is 3-7 years.

In order to avoid the multiple replacing of the DPL sensor during the power unit operation, the new sensor of the DPL-KV type that is much more longevous should be applied. At the same time, an opportunity appears to eliminate the other defects which are inherent for the SHEM-2 drive and electronic unit operating with the DPL sensor. They are: significant error of position measurement, unreliability, very small capability to organize diagnostics, etc. The electrical components of the DPL-KV sensor are characterized by the lifetime longer than 60-80 years. The validity of these values is confirmed by diagnostic information obtained in 9 operation campaigns. The sensor signals (at the same positions and under the same conditions) has changed insignificantly. Resistance of the inductance coils tended to stabilization (Fig. 3).

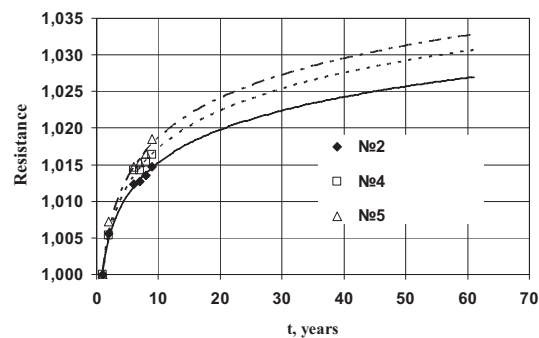


Fig. 3. Dependence of sensor resistance (relative value) on time (extrapolation up to 60 years)

The forecasted variations of the average value of the DPL-KV coils resistance are not more than 3.5%. In practice, such variations do not influence the MS operation. All the more, its algorithm includes adaptive procedures which correct the signals under changing environment.

The specified lifetime of a sensor housing is not less than 30 years. It can be prolonged up to 40-60 years on the basis of diagnostics results.

It follows from the above-said that the stability of the DPL-KV parameters is sufficient to provide its reliable functioning during the expected reactor lifetime. In order to apply the DPL-KV sensor, it is necessary to replace the standard rack by the similar rack that includes a multi-component shunt. Since

the racks which have partly used their drop resource (that is the most critical parameter) will be also replaced, such a replacement will provide the sufficient resource of the new racks which will be capable to operate up to the end of the reactor lifetime.

Thus, the replacement of the DPL sensor and standard rack with the DPL-KV sensor and the new rack, as well as insertion of the heat-reflective screen inside the fixing electromagnet enable prolonging the drive lifetime up to the lifetime of the reactor.

4. DIAGNOSTIC CAPABILITIES OF MS

It should be noticed that the lifetime of each drive component set in the documentation was calculated and confirmed by the life test of several samples. The actual resource of each component depends, to a great extent, on the quality of manufacturing, which is checked ineffectively in many cases [5]. Removal of a failure arisen in the drive during the reactor operation leads to significant expenses. In order to minimize the probability of such a failure, it is necessary to diagnose the drive directly during the fuel cycle. Such diagnostic possibilities are realized in the MS, which provide:

- CR position measurement (accuracy is within 0.3% under all possible conditions);
- metrological diagnostic check of the reliability of CR position measurements (it is not necessary to calibrate the sensor during operation);
- fault tolerance (maintenance of operating integrity if any signal wire breaks or any coil fails);
- automatic correction of a sensor, shunt and processing unit parameters (this eliminates the influence of temperature variations, defects of joints, material and component aging);
- filtration of various noises;
- self-diagnostics of whole MS with failure localization;
- generation of textual recommendations for malfunction elimination;
- assessment of the condition of main drive components (rack teeth, latches of the motion unit and, partly, electromagnets);
- drive condition diagnostics (step missing or delay, as well as teeth slippage);
- checking of the CR and rack coupling;
- sensor to processing unit connection diagnostics;
- control connection diagnostics;
- measurement and recording of CR drop time diagram (this allows to diagnose the condition of a guide sheath and rack curvature in case of CR emergency shutdown or spontaneous drop);
- determination of the top and bottom oscillation points during the CR damping process (this

allows to diagnose the condition of a rack damper);

- checking whether the CR has fallen down on the arresting device.

The high diagnostic sensitivity allows to reveal incipient defects (even before appearance of a significant failure). Diagnostic capabilities can be further enhanced in the future.

Information about all CR moves, control commands, operation modes, malfunctions or failures as well as operator's actions are logged in a "black box" recorder. At the same time, the MS estimates the drive operational conditions by accumulating parameters like the number of drops, steps made, input control signals, etc.

The real time CR position is displayed on a front panel. Complete set of information can be transferred to a special palm computer and shown on its display. If necessary, data can be transferred to a PC for archiving and analyzing. Each MS can be connected to a local network. In this case, the MS can perform cross system diagnostics. This improves the MS fault-tolerance. For instance, the local network gives an opportunity to inform operators about the wrong positions of CR, including the case of CR position mismatch in the control group as well as of any CR slipping down from the end switch.

Based on diagnostic information obtained during system operation, an individual "registration certificate" is automatically issued for each drive. This certificate contains an assessment of drive condition as well as recommendations for operators how to carry out preventive maintenance.

Fig. 4 illustrates the diagnostic capabilities of the MS. The diagnostics applies the diagrams of displacement. The diagram enables:

- defining the actuation time of the motion unit latches,
- checking the correctness of response to a cyclogram of the electromagnet current,
- checking the control rod and rack coupling.

The ability to obtain such diagrams is determined by both the high displacement sensitivity of the sensor and the fact that the time interval between two consecutive control rod position measurements is very short. In case of the drive fault, the form of the diagram is changing. This makes possible to find out the origin of the fault or to reveal the incipient fault (even before appearance of a significant failure).

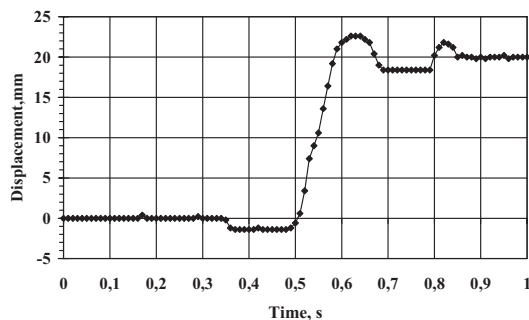


Fig. 4. Diagram of drive rack move: a step up

5. CONCLUSION

In order to increase the lifetime of the control rod drive up to the expected lifetime of the nuclear reactor (60 years), it is necessary to replace the standard sensor and standard rack with the DPL-KV sensor and the new rack, as well as to decrease noticeably the electromagnet temperature, using the screen.

The MS with the DPL-KV sensor excels the analogues at reliability, diagnostic capabilities, fault-tolerance, and accuracy significantly. Diagnostic capabilities of the MS make it possible to switch from pre-assigned terms to forecasting equipment condition during the future campaign and to repairing the drives depending on their technical condition.

The economical effect of the totality of the suggested technical decisions is about 7 million euro per power unit. These decisions can be also applied to the other types of the stepping drives, for example SHEM-3, used at the WWER-1000 nuclear reactor.

REFERENCES

- [1] Sapozhnikova K., Taymanov R., Druzhinin I.: *About the Effective Approach to the Modernization of the NPP Control and Emergency Shutdown System*, IAEA Technical Meeting 13-16 September 2005, Chatou, France, http://entrac.iaea.org/I-and-C/TM_EDF_2005_09/Session%24%20Wedn%20PM/Sapozhnikova%20paper%20updated.pdf.
- [2] Taymanov R., Sapozhnikova K., Druzhinin I.: *Measuring Control Rod Position*, Nuclear Plant Journal, 2007, 2 (March-April), USA, p. 45-47.
- [3] Druzhinin I. I., Gerasimov N. P., Taymanov R. Ye.: *Possibility for Enhancing the Lifetime of Electromagnets of the Drives in the Control and Protection System in a Nuclear Reactor*, Energoma-shinostroenie, 2006, 2-3, p. 18 - 24.
- [4] Patent RU 44867 U1, МПК7 H01F7/16, G21C7/12. *Electromagnet of the Drive moving a Control Rod in a Nuclear Reactor*, Gerasimov, N. P., Druzhinin, I.I., Taymanov, R. Ye., 27.03.2005, Bulletin, 2005, 9.

- [5] Taymanov R. Ye., Sapozhnikova K. V., Lukashev A. P., Pronin A. N.: *About Estimation of the Quality of Manufacturing of Sensors with the Long-term Calibration Interval*, Datchiki I Systemi, 2006, 9, p. 67 - 80.



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