NPP refueling process monitoring based on the refueling machine current signals

E A Abidova, A E Dembitsky, I V Zarochintseva, A A Lapkis and A V Chernov
Volgodonsk Engineering Technical Institute - a branch of the National Research Nuclear University "MEPhI" (VETI NRNU MEPhI), 73/94 Lenin St., Volgodonsk, Rostov region, 347360, Russia

E-mail: e-abidova@mail.ru

Abstract. The paper is aimed at safety improvement of nuclear power plants by monitoring the refueling process carried out by the fuel-handling machine. The article confirms the necessity to develop a monitoring system that prevents failures during refueling operations. It is shown that the development of the monitoring system should be preceded by the stage of monitoring the object current parameters in the process of multiple operations with fuel and absorbing rods. The schemes of diagnostic signals registration and approaches to their analysis are presented. The paper presents results of the current signals analysis of the main hoist drive of the refueling machine at Rostov NPP. The development of refueling operation portraits based on current parameters is demonstrated. The principal component method is applied to them for the purpose of clustering. The paper shows the possibility to control the refueling machine efforts when extracting fuel by presenting diagnostic signals from the main hoist drive in the principal component space. In general, the paper substantiates the prospects of developing a refueling monitoring system through current consumed by the main hoist drive of the refueling machine.

1. Introduction
The refueling process, performed during the period of scheduled preventive maintenance of the VVER-1000 reactor using a refueling machine (RM), is one of the most important operations performed at a nuclear power plant. At present, the refueling process is monitored using weight sensors on grippers (strain gauges), displacement sensors and by means of a television system [1]. The existing approach makes it possible to establish the fact of a refueling operation, or to state a failure after it has occurred. The development of a refueling monitoring system is a task-on-demand to prevent failures during one of the most crucial technological processes at nuclear power plants [2].

The following design and operation RM features make it difficult to introduce universal approaches to process monitoring and equipment diagnostics:

- performing various operations (lowering and raising loads, coupling and uncoupling with loads, etc.) requiring the operation of the object in various modes;
- non-standard design of the machine, including several functional groups - drives;
- production conditions - increased ionizing radiation, humidity, a high level of electromagnetic interference in electrical equipment in the reactor central hall, a special access mode to the work area with an uncovered reactor;
the refueling time is limited by the refueling period, which is 3-5 weeks per 1.5 year fuel cycle at Russian NPPs with VVER-1000 reactors.

The first two features suggest that the development of a monitoring system should be preceded by the stage of observing the equipment characteristics in the process of multiple performing of different operations. This stage allows to set the range of parameter change that is characteristic for the operation of various functional groups of the object, i.e. to realize portraitization of the refueling process, as described in [3] for vibroacoustic methods of RM monitoring. Comparison of the portraits obtained as a result of previous refueling campaigns with the results of subsequent diagnostics permits to reveal trends in the state of the equipment before a failure occurs.

The peculiarities associated with the operating conditions of the facility make it difficult to use portable and stationary vibration diagnostics for monitoring the RM parameters [4] during refueling. In this case, the use of current control devices has a number of advantages:

- signals can be registered outside the object operation area [5];
- reduction of the external interference influence while registering data [6];
- the same portable means can provide registration of RM signals of all units at a multi-unit NPP.

Therefore, this study, aimed at improving the NPP equipment reliability, is devoted to the problem of recording and analyzing the current consumed by the RM drives during its operation.

2. Registration and preprocessing of current signals of the refueling machine

The values of the current and voltage on the bus bars are measured after the frequency converters and filters to analyze the supply network signals of RM electric drives (figure 1). These measurements are performed using the test bench “Krona-517”. A horizontal working surface with a width of at least 0.5 m. is required to deploy the test bench “Krona-517”.

![Figure 1. Signal release scheme from the RM using the test bench "Krona 517".](image)

The current signal of the three phases is used to calculate the following parameters:

- operating current;
- harmonic component;
- asymmetry coefficient;

The oscillation coefficient (OC) is also calculated by the envelope. The operating current in the phases $I_p^A$, $I_p^B$, $I_p^C$ [A] is estimated by the formula
\[ I_p^\phi = \sqrt{\sum_{j=1}^{N} (x_j^\phi)^2} / N, \]

where \( I_p^\phi \) – Operating current in phases \( I_p^A, I_p^B, I_p^C \);
\( x_j^\phi \) – \( j \)-th sample value of the operating current phase \( \phi \in \{A,B,C\} \);
\( N \) – sample size.

In this case, the quality of the variable frequency sinusoid generated by the converter can be estimated by the coefficient of harmonic components in each phase

\[ K_n^\phi = \sqrt{\frac{I_1^2 + I_2^2 + I_3^2 + \cdots + I_n^2}{I_1}}, \]

where \( K_n^\phi \) – coefficient of harmonic components;
\( I_1 \) – the first harmonic of the current signal;
\( I_2, I_3 \ldots I_n \) – higher harmonics of the signal.

The current signal envelope, taking into account the variable frequency, is calculated by the RMS method according to the formula

\[ D^\phi = \sqrt{\frac{1}{n} \sum_{i=0}^{n-1} |X_i^\phi|^2}, \]

where \( D^\phi \) – current signal envelope;
\( n \) – number of counts, which corresponds to the sampling frequency-to-fundamental frequency ratio;
\( X \) – sampling of the current sensor in the phase.

The ease of movement in the phase can be estimated by the oscillation coefficient, which is calculated from the envelope parameters as a percentage of the range of variability \( R \) to the mean value \( \bar{x} \)

\[ V_R^\phi = \frac{R^\phi}{\bar{x}^\phi} \times 100 \%, \]

where \( V_R^\phi \) – oscillation coefficient;
\( R^\phi \) – range of variability;
\( \bar{x}^\phi \) – mean value.

The uniformity of phase loads in a three-phase network is estimated by the asymmetry coefficient of the operating current in the phases \( \delta_{LAB}, \delta_{LAC}, \delta_{IBC} \) [%]

\[ \delta_{I_1\phi_1\phi_2} = \left| \frac{I_p^{\phi_1} - I_p^{\phi_2}}{I_p^{\phi_1}} \right| \times 100 \%, \]

where \( \delta_{I_1\phi_1\phi_2} \) – asymmetry coefficient;
\( I_p^{\phi_1} \) and \( I_p^{\phi_2} \) – root-mean-square current values of the phases \( \phi_1 \in \{A,B,C\} \) and \( \phi_2 \in \{A,B,C\} \) respectively, while \( \phi_1 \neq \phi_2 \);
\( I_p^{\phi} \) – mean value.

3. Portraitization of refueling operations based on current parameters

The refueling machine of unit No. 1 at Rostov NPP was inspected in March-April 2020. Signals of the current consumed by the main hoist drive were recorded with the help of the test bench “Krona 517” while fulfilling the following operations:

- lowering without load (fuel assembly) at low speed;
- lowering with load at low speed;
- lifting without load at low speed;
• lifting with load at low speed;
• lowering without load (fuel assembly) at high speed;
• lowering with load at high speed;
• lifting without load at high speed;
• lifting with load at high speed.

Each operation is represented by at least twelve signals registered during the 2020 refueling campaign of Unit 1. As part of preprocessing for each signal, the parameters were calculated - oscillation coefficient, operating current, harmonic component, phase asymmetry coefficient.

When analyzing the parameter values of refueling machine of the unit No. 1, the following dependencies were established:

• working currents negatively correlate with speed, while weakly depend on direction and do not depend on the presence of load;
• oscillation coefficient (OC) positively correlate with speed, but weakly depend on the presence of load and direction;
• the largest values of the asymmetry coefficient are observed between phases A and B, they do not depend on direction, speed and load;
• the harmonic component is positively correlated with speed, does not depend on direction, speed and load.

The ranges of parameter changes are determined when RM operates in the normal mode. The correctness of operations can be assessed during subsequent monitoring of the refueling process at the first unit of Rostov NPP according to the compliance with these ranges.

The most sensitive parameter to the RM operating mode is OC, which, therefore, is best suited for describing its modes. However, the OC ranges for different modes do overlap. For example, the signals when lifting at low speed have an OC calculated by formula 4, for modes without a load it has a range of 0.1 - 4.0, and for modes with a load, the range is 0.2 - 19. It is advisable to use a separation algorithm based on the method of principal components (PC) to separate data clusters corresponding to different operation modes [7,8].

Since OC for different speed modes are easily distinguished without additional processing, the separation algorithm is implemented for four groups of parameters: "lowering without load", "lowering with load", "lifting without load", "lifting with load".

![Figure 2. Mapping of the parameter at low speed.](image-url)
According to the algorithm, the parameters of various operations are presented in the form of matrices. The parameter matrices are subjected to singular value decomposition. The next stage is the formation of the reference space, where the distance between the data corresponding to different modes is significantly greater than in the original one. The first two principal components (PCs) are selected for the formation of the space based on the comparison of the singular value decomposition spectra. The original matrices are projected onto the resulting reference space. The result of data identification for each operation in the reference space is shown in figure 2.

As you can see, at low speed, the states "lifting with load" and "lifting without load" are uniquely identified, and "lowering with load" and "lowering without load" partially coincide. Data clusters corresponding to the RM standard operating mode (despite partial overlap with each other) can be used during subsequent monitoring to identify deviations from the RM normal operation.

4. Controlling the refueling machine weight loads when extracting fuel

Some deformations occur in fuel assemblies (FA) with the fuel under the irradiation in the reactor [9]. The deformations require additional efforts during extraction. In a VVER-1000 reactor, fuel assemblies are operated for three lifetimes; the deformations occurring during this time require greater weight loads when extracting heavily burned fuel from the reactor than when extracting fresher fuel. When monitoring the refueling process, identifying the difference in weight loads during fuel extraction helps to prevent possible damage to the fuel cassette cladding.

However, the parameters, the calculation of which is described in the second paragraph of this paper, are not sensitive to changes in weight loads. At the same time, analysis of the current signal using the PC method [6] shows that the signal contains information about the weight loads during extraction.

The RM current signals corresponding to the extraction of fuel assemblies are represented in the form of trajectory matrices, and a singular transformation is applied to them. As a result of the singular transformation, spatial directions are obtained by the number of columns in the matrix. Among the decomposition components, PCs are selected that correspond to the signal separation of the states under study, thereby ensuring their clustering in the PC space.

The corresponding transformations are performed with the signals recorded during the extraction of fuel assemblies. The spectra analysis of the eigenvalues made it possible to choose the space direction in which the differences between the signals appear during the extraction of deformed and undeformed fuel assemblies.

Figure 3 shows the signal clusters when extracting from fuel assembly cells No. 186-190 that have worked one lifetime, they are blue, and from fuel assembly cells No. 149-152 that have worked three lifetimes, they are red. Clusters of cassette signals, in which deformations are assumed, are localized in the PC space area, and it does not coincide with the area of clusters of cassette signals without deformation. Red clusters are also smaller than the blue ones.

![Figure 3. Mapping of current signals when extracting fuel assemblies.](image)
It is proposed to project the signals recorded during the subsequent monitoring of the refueling on the basis obtained during the processing of previously recorded signals. By the position of the signal clusters in the PC space, one can estimate the degree of signal mismatch with the norm.

5. Conclusion
The need to develop a fuel refueling monitoring system that controls changes in the state of the RM is stated. It is shown that the development of such a system should be preceded by the stage of monitoring the current parameters of the object in the process of repeated execution of various operations with fuel and other loads. The scheme of diagnostic signals registration and approaches to their analysis are presented. The results of the analysis of the current signals of the unit No. 1 refueling machine at the Rostov NPP, recorded in March-April 2020 during the operations of installing and extracting fuel, are presented. The signals are processed. On the one hand, this processing is aimed at building portraits of operations, and on the other hand, at increasing the sensitivity when analyzing diagnostic information. As the analysis has shown, portraitization in the description of refueling operations is provided by the following parameters: oscillation coefficient, operating current, harmonic coefficient, phase asymmetry coefficient. However, due to the fact that the ranges of parameter variations when performing various operations partially overlap, an algorithm for separating clusters of operation parameters based on the PC method is proposed. As a result of the algorithm application to the diagnostic parameters, the classes of operations are described, which during the subsequent monitoring of the unit No. 1 refueling at the Rostov NPP can be used as a single reference.

Investigation of the signals during the extraction of fuel assemblies demonstrated the possibility of using the current consumed by the RM main hoist drive to control the weight loads developed during the extraction of fuel assemblies in addition to the standard weight measuring device.

Thus, the performed work substantiates the prospects for the development of the monitoring system for refueling by the current consumed by the RM electric drives.

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