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OPTIMIZATION OF RELIABILITY MANAGEMENT STRATEGIES FOR POWER EQUIPMENT OF SAFETY RELATED SYSTEMS AT NUCLEAR POWER PLANTS

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The concept of optimization of reliability management strategies for equipment of safety related systems at nuclear power plants is proposed. The concept is based on the principles of the priority of elements and phenomena critical for reliability, as well as on optimization criteria in the "reliability – costs" format. An example of the concept of optimization of reliability management strategies for the system with the pump (critical element) and the relatively minimal system reliability when it starts (critical phenomenon) is considered. The result found that a complex technical decisions / measures to reduce the inertia of the head-flow characteristics of the pumps and to install additional damping devices determine optimal reliability management strategy for such a system.

RELEVANCE

Many years of operation of Ukrainian nuclear power units with VVERs have confirmed their adequate safety and efficiency. However complex problem to increase safety and efficiency of nuclear power industry is now actual in Ukraine, especially taking into account lessons of Fukushima-Daiichi great accident in 2011 [1].

Development and implementation of the concept of optimization of reliability management strategies (RMS) of the power equipment (pumps, armature, heat exchangers, etc.) of the safety related systems at nuclear power plants (NPP SRS) is one of the directions to increase nuclear power safety and efficiency. The concept is based on the following principles.

1. Principle of priority of systems and equipment critical for safety.
2. Principle of priority of the phenomena and factors critical for reliability/operability.
3. The principle of optimization based on complex accounting of reasonable reliability increase and costs.

The concept and the principles of optimization of RMS are based on the following provisions.

The element with the minimum reliability characteristics (a critical element) and priority of the phenomena defining reliability of a critical element (critical phenomena) determine reliability characteristics of system.

It is required to exclude RMS with marginal increase of reliability and unreasonable costs.

An example of implementation of the concept of optimization of RMS for system with the pump (a critical element) and reliability minimum for system at its start is considered below (critical phenomena).

FUNDAMENTALS AND RESULTS OF OPTIMIZATION OF RMS FOR NPP SRS WITH PUMPS. EXAMPLES OF APPLICATION OF THE CONCEPT OF OPTIMIZATION OF RMS

The analysis of operating experience of NPPs with WWER shows that pumping equipment is critical elements for NPP SRS, and the water hammers (WH) accompanied with pulse high-amplitude impact on the equipment and elements of pipelines are critical for reliability (for example, [2–5], etc.).

The analysis of known results of operating experience and modelling of WH in the equipment and pipelines at NPPs with pressurized reactors (PWR/WWER) allows concluding the followings.

1. An additional analysis of conditions and consequences of WH in a reactor caused by various types of thermohydrodynamic instability (THI) during normal operation and normal operation trouble is required.

Under normal operation, WH in a reactor can be generated by thermoacoustic instability during surface (subcooled) boiling of the coolant in the reactor core [6]; the oscillatory hydrodynamic instability of the coolant through an inertia of the head-flow characteristic of the main circulating pump [7]; resonant effects in the transitional modes of reactor start/ shutdown [8], etc.

Under normal operation disturbance or emergency operation, WH in a reactor can be generated by:

the low-frequency oscillatory hydrodynamic instability during loss-of-coolant accidents through an inertia of heat-mass exchange processes in two-phase flows [9];

the oscillatory hydrodynamic instability through inertia of the head-flow characteristic of pumps of active part of an emergency core cooling system [7] and other kinds of coolant THI.

Safety analysis reports of the Ukrainian NPPs with WWER do not consider conditions and consequences of possible WH for deterministic modelling of accidents. But possible WH can be both an initial accident event and a consequence of accident progress when design basis accidents transit to beyond design basis accidents with multiple failures of safety related systems.

The paper considers the characteristic (typical) pipeline system of the thermotechnical equipment at NPPs (Fig. 1). The pipeline is conventionally divided into the supply line L_1 and pressure line L_2.

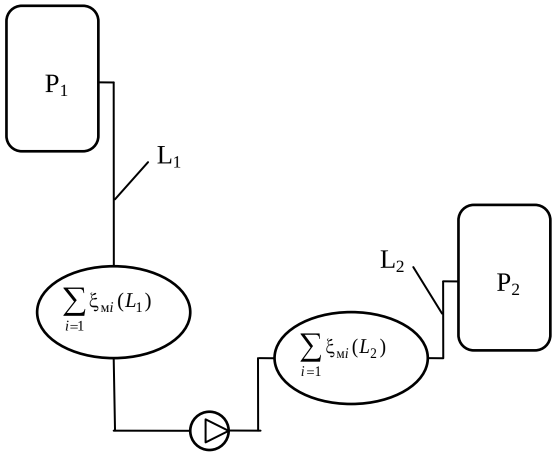

Fig. 1. Typical pipeline system of the thermotechnical equipment

It is assumed that flow THI (a deviation of hydrodynamic parameters from the steady-state (stable) values) is a necessary condition for a water hammer critical for reliability (CWH) on working parts of pumps.

The flow (network) characteristic of dependence of hydrodynamic pump head $\Delta P_{н}$ on a mass flow rate G or an average flow rate in a pipeline system v:

$$\Delta P_{н} = f(G);\ \ \Delta P_{н} = f(v). \qquad (1)$$

Sensitivity of the flow (network) characteristic to flow discharge/flow rate changes:

$$f' = \frac{\mathrm{d}\Delta P_{н}}{\mathrm{d}G} \ \text{ or } \ f' = \frac{\mathrm{d}\Delta P_{н}}{\mathrm{d}v}. \qquad (2)$$

For force pumps, design sensitivity of the flow (network) characteristic:

$$f'(G,v) \le 0. \qquad (3)$$

It is assumed that liquid is incompressible and processes are isothermal. Therefore, equations of a flow motion in the pipeline system and of the current change of hydrodynamic pump head:

$$\rho L \frac{\mathrm{d}v}{\mathrm{d}t} = \Delta P_{н}(v) + P_1 - P_2 - \Delta P_1(v) - \Delta P_2(v), \qquad (4)$$

$$\Delta P_{н} = \Delta P_{нм} + \int_0^t f'(v)\frac{\mathrm{d}v}{\mathrm{d}\tau}\mathrm{d}\tau \qquad (5)$$

Under initial conditions

$$v(t=0) = 0, \qquad (6)$$

$$\Delta P_{н}(t=0) = \Delta P_{нм}, \qquad (7)$$

where ρ – flow medium density; L – length of the pipeline; $\Delta P_{нм}$ – maximum hydrodynamic pump head related to its technical characteristics; t – current time; v – average flow rate; f' – current sensitivity of the flow characteristic of the pump; P_1, P_2 – static pressure in objects of a source and consumption respectively (see Fig. 1).

The characteristic example of the decision in a criteria form is given in Fig. 2. It allows concluding the followings.

The inertia of the flow (network) characteristic of force pumps of pipeline systems is the dominant factor for conditions of hydrodynamic oscillatory instability of single-phase flows and critical water hammers. It determines "delayed" response of the flow-head characteristic of the pump to changes of hydrodynamic parameters of a single-phase fluid flow. At the maximum (critical) inertia of the flow-head characteristic, oscillation amplitudes of hydrodynamic parameters of a flow reach critical values when there is an inoperative failure of working parts of pumps.

Generation of critical water hammers corresponds to transition of oscillatory THI to the aperiodic THI.

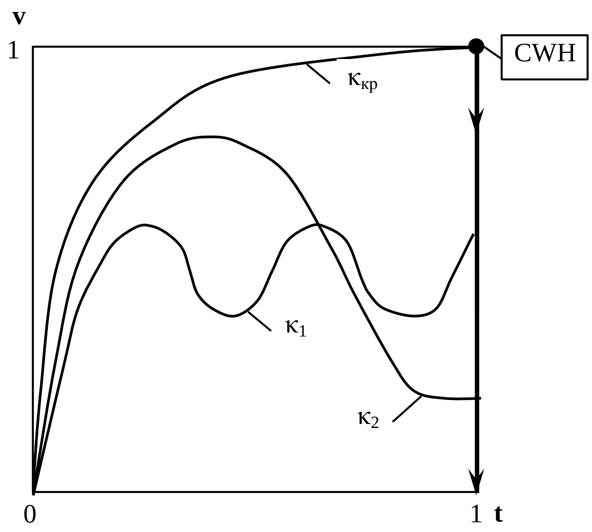

Fig. 2. Change of average flow rate when THI with different sensitivity of flow (network) characteristic of the pump for coefficients of linear approximation $\kappa_1 > \kappa_2 > \kappa_{кр}$

The priority of use of pumps with the minimum inertia of the flow-head (network) characteristic is perspective approach for prevention of critical water hammers.

As an example of optimization of RMS, we will consider three characteristic strategies (Fig. 3):

RMS1 – strategy with the minimum costs of modernization and rather small increase in reliability,

RMS2 – the strategy using only the maximum effective modernizations,

RMS3 – strategy of the maximization of reliability.

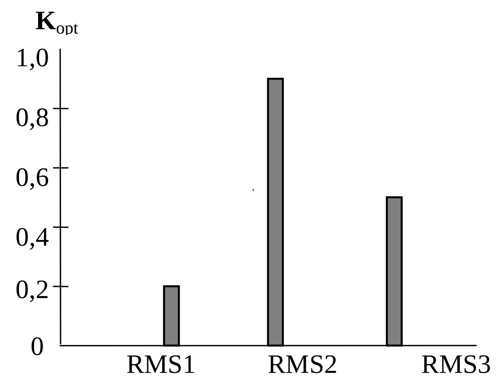

Fig. 3. Optimization criteria of reliability management strategy

Optimization criterion of RMS [2]:

$$\boldsymbol{K}_{\text{opt}} = \frac{\sum_i \boldsymbol{K}_{\text{э}i} \Delta \boldsymbol{C}_i}{\sum_i \Delta \boldsymbol{C}_i} \to \max, \qquad (8)$$

where the index i corresponds to number of separate modernization in specific RMS.

The ratio of integral measures of unavailability of the specified functions for the modernized system $K_{\text{н}}$ and design system $K_{\text{н}0}$ is the key RMS parameter for reliability:

$$\boldsymbol{K}_{\text{н}} = \frac{K_{\text{н}}}{K_{\text{н}0}}, \qquad (9)$$

where generally during operation life t

$$K_{\text{н}} = \frac{1}{t}\int_0^t P(\tau)\mathrm{d}\tau; \qquad (10)$$

$P(\tau)$ – current probability of critical failure in the different operation modes (working, transitional, emergency).

The ratio of costs of modernization C and the cost of design system C_0 is the key RMS parameter for costs of modernization:

$$\boldsymbol{C} = \frac{C}{C_0}. \qquad (11)$$

The following can be characteristic examples of modernizations of systems of pumping equipment of thermal and nuclear power plants.

RMS1 – installation of the damping pretanks in a pump outlet to reduce oscillatory amplitudes of pressure.

RMS3 – installation of the additional regulating armature in pipelines of pumps of emergency core cooling systems to prevent "thermal shock" on a reactor vessel in emergency modes.

RMS2 – parallel duplication of channels of a pipeline system including installation of damping devices before and after pumping equipment.

Results of optimization of RMS are presented in Fig. 3.

MAIN CONCLUSIONS

1. The concept of optimization of reliability management strategies for equipment of safety related systems at nuclear power plants is proposed. The concept is based on the principles of the priority of elements and phenomena critical for reliability, as well as on optimization criteria in the “reliability – costs” format.

2. An example of the concept of optimization of reliability management strategies for the system with the pump (critical element) and the relatively minimal system reliability when it starts (critical phenomenon) is considered. The result found that a complex technical decisions / measures to reduce the inertia of the head-flow characteristics of the pumps and to install additional damping devices determine optimal reliability management strategy for such a system.

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ОПТИМИЗАЦИЯ СТРАТЕГИЙ УПРАВЛЕНИЯ НАДЕЖНОСТЬЮ ЭНЕРГООБОРУДОВАНИЯ СИСТЕМ, ВАЖНЫХ ДЛЯ БЕЗОПАСНОСТИ ЯДЕРНЫХ ЭНЕРГОУСТАНОВОК

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Предложена концепция оптимизации стратегий управления надежностью оборудования систем, важных для безопасности ядерных энергоустановок. Концепция основана на принципах приоритетности критичных по надежности элементов и явлений, а также критериях оптимизации в формате «надежность – затраты». Рассмотрен пример реализации концепции оптимизации стратегий управления надежностью для системы с

насосом (критический элемент) и относительно минимальной для системы надежностью при его запуске (критическое явление). В результате установлено, что оптимальная стратегия управления надежностью для такой системы определяется комплексом технических решений/мероприятий по снижению инерционности напорно-расходной характеристики насосов и установке дополнительных демпфирующих устройств.

ОПТИМІЗАЦІЯ СТРАТЕГІЙ УПРАВЛІННЯ НАДІЙНІСТЮ ЕНЕРГООБЛАДНАННЯ СИСТЕМ, ВАЖЛИВИХ ДЛЯ БЕЗПЕКИ ЯДЕРНИХ ЕНЕРГОУСТАНОВОК

О.О. Чулкін

Запропоновано концепцію оптимізації стратегій управління надійністю обладнання систем, важливих для безпеки ядерних енергоустановок. Концепція заснована на принципах пріоритетності критичних по надійності елементів і явищ, а також критеріях оптимізації у форматі «надійність - витрати». Розглянуто приклад реалізації концепції оптимізації стратегій управління надійністю для системи з насосом (критичний елемент) і відносно мінімальною для системи надійністю при його запуску (критичне явище). В результаті встановлено, що оптимальна стратегія управління надійністю для такої системи визначається комплексом технічних рішень/заходів щодо зниження інерційності напірно-витратної характеристики насосів і установки додаткових демпфуючих пристроїв.