DYNAMICS OF PROCESSES IN SUBCRITICAL REACTOR DRIVEN BY LINEAR ACCELERATOR*

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Abstract

In this paper dynamics of processes in accelerator driven subcritical reactor (ADS) is considered. ADS operates at subcritical level and the necessary neutron supply comes from the interaction of a charged particles beam with a heavy atom nucleus (spallation reaction). Mathematical model of dynamics of subcritical reactor controlled by linear accelerator is presented. Calculation results of transient processes in the reactor core taking into account fuel feedback. The reactor power level control is carried out through the regulation of linac current impulses frequency.

INTRODUCTION

The subject of research in the paper is subcritical reactor driven by proton linac. Currently, research in this field purposes is carried out in many scientific centers all over the world. They are focused on the problem of ADS design for transmutation of radioactive waste and safe energy production. The proposed projects are mostly supposed the use of accelerator with output energy about 1-2 GeV, that substantially defines the facility high price. In this paper proton linac with lower beam characteristics [1] (E = 300 MeV, I = 5 mA, duty factor 10%, W = 1.5 MW) is considered as an ADS driver.

The ADS control strategy should differ from traditional critical reactors control. In traditional reactors the reactivity effects are compensated by neutron absorber that guarantees the reactor maintenance in the critical condition. But there is no control impact on the subcritical reactor reactivity in ADS, the system power level is regulated only by accelerator.

POSSIBLE CONTROL SCHEMES FOR ADS WITH PROTON LINAC

Thermal power for the reactor core is defined by the following formula

$$N_T = \frac{E_f S k_{ef}}{\nu(1-k_{ef})}, \qquad (1)$$

where E_f - energy, released per a fuel nuclei fission, k_{ef} .- effective multiplication factor, S – external neutron source generation intensity:

$$S = \frac{I_p m_0}{e},$$

where I_p – the accelerator average current, m_0 – neutron yield (the average number of neutrons generated in the target by one accelerated charged particle, depends on charged particles beam energy, target composition and sizes), e – the charge of an accelerated particle.

ADS Power Level Regulation

The ADS power level control can be realized by variation of external neutron source generation intensity which depends on the average accelerator current and charged particles beam energy.

The average current regulation is possible because of pulse current value or pulse repetition rate variation.

Pulse current can be increased by raising current at the exit of plasma ion source (for example, because of increasing the emissive aperture diameter), but the beam emittance grows meanwhile, system of beam formation for injection to the acceleration channel gets more complicated, transient processes in resonators and beam dynamics change. That is the accelerator design and adjustment becomes more complicated in comparison to accelerator with fixed output parameters.

Increasing of average current by increasing pulse repetition rate is a simpler decision because particle dynamics in accelerating tract doesn't change. The effect is achieved due to the control system of rf and injector feed lines.

Increasing of proton energy can be fulfilled by activating additional resonators at the end of the accelerating channel. In should be noted that when the resonators are turned off, the beam output characteristics will get worse.

Thus, the most suitable way to control ADS is the accelerator average current variation by pulse repetition rate change.

It should be noted that because of resonators high quality factor the transient processes in them will have quite large duration. As well known, the process of rf electrical field amplitude stabilization is characterized by the following expression:

$$E = E_\infty\left(1-\exp(-t/\tau)\right),$$

where $\tau = Q/\pi f$ – magnitude which characterize transient (taking into account generator impact); t -time, Q – quality factor, E_∞ – steady value of rf field in resonator (for $t \to \infty$).

The field stabilization time can be comparable with the current pulse duration or exceed it in several times. This can lead to the additional short pulsations of source neutron power.

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ISBN 978-3-95450-170-0

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Subcritical Reactor Feedbacks

The ADS subcritical reactor dynamics depends on outer and inner feedbacks (Fig. 1). The inner feedbacks are determined by the reactor core physical characteristics, the external ones reflect the reactor connection with the power plant (coolant flow, coolant temperature at the entrance).

For stable ADS working at the constant power level, the reactor core should have the negative fuel and coolant temperature inner feedback and the negative mean reactivity coefficient. These conditions ensure the reactor self-control and the average temperature maintenance.

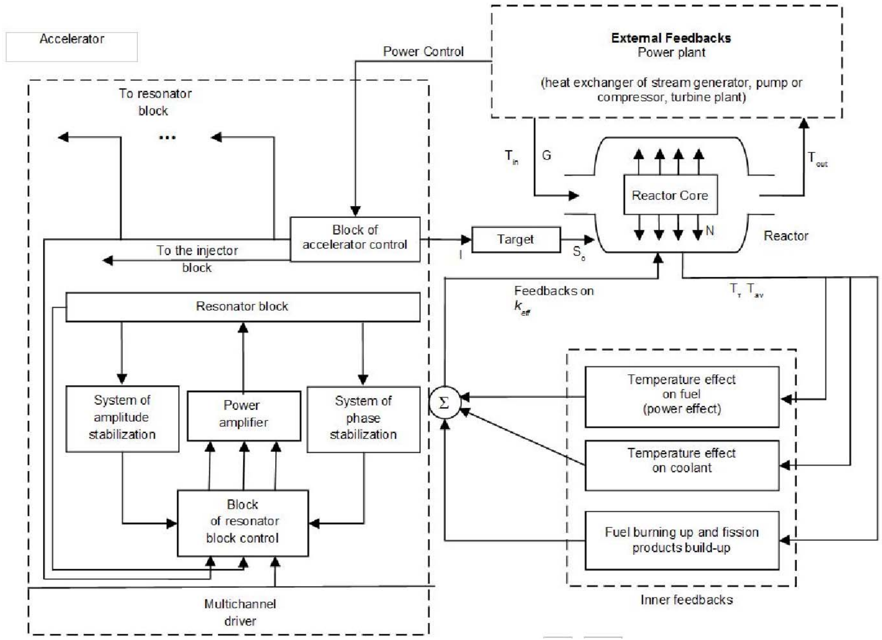

Figure 1: ADS structural scheme with feedbacks.

ADS PARAMETERS CHANGE IN TIME IN STEADY-STATE CONDITION

The law of linear accelerator current variation in time looks like periodic impulses, so it can cause steady-state power level oscillation in the subcritical reactor core. Thereby, kinetics of subcritical reactor with periodical external neutron source should be investigated; the influence of power level oscillation on the fuel elements temperature condition should be estimated.

The ADS reactor core power level change is described by the point kinetics equations for subcritical reactor with the external neutron source:

$$\frac{dN(t)}{dt} = \frac{\rho-\beta}{l}N(t)+\sum_{i=1}^{6}\lambda_i c_i(t)+Q(t), \qquad \frac{dc_i(t)}{dt} = \frac{\beta_i}{l}N(t)-\lambda_i c_i(t). \tag{2}$$

Here *N(t)* – reactor core power level (W), c_i - power of nucleus sources, bearing delayed neutrons, β – effective part of delayed neutrons; λ_i – decay constant for nucleus, bearing delayed neutrons,; l_0 – average prompt life time; $\rho=(k_{ef}-1)/kef$ – reactivity coefficient, determined by Doppler effect; $l=l_0/k_{ef}$, $Q(t)$ - external neutron source intensity.

The average prompt lifetime l_0 depends on neutron energy spectra in the reactor core and changes from $5\cdot10^{-7}$ sec (for fast reactors) to $5\cdot10^{-4}$ sec (for thermal reactors). The effective part of delayed neutrons is $\beta=0.0068$ for U^{235}.

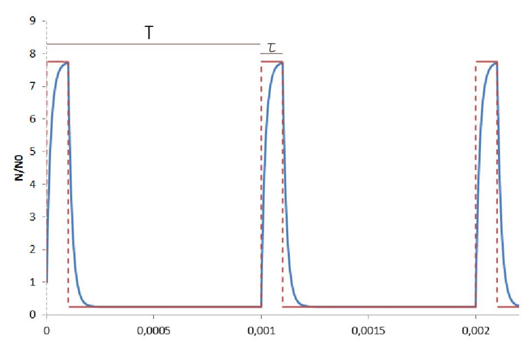

Figure 2: The dependence of accelerator current and ADS reactor power on time.

ADS subcritical reactor kinetics depends on accelerator current pulse period and duration *q*(*t*) (Fig. 2). If pulse period considerably less than the average prompt lifetime in the reactor, then the neutron source can be treated constant with the intensity equals to the average (time) value of *q*(*t*). This condition is fulfilled in cyclotrons.

The micro pulses period in the linear accelerator ($T=5\cdot10^{-9}$ sec) is considerably less than the prompt life

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time. However the macro pulses period of the accelerator proposed for ADS ($T = 5 \cdot 10^{-3}$ sec) exceed the prompt lifetime in the reactor. Thus, the additional neutron source intensity in ADS with linac can be described as the sequence of rectangular pulses with a period and pulse duration corresponding to the accelerator current period and macro-pulse duration and with pulse amplitude corresponding to the average current value in the macro-pulse [2]:

$$q_{av} = \frac{Q^{\max}\tau}{T}.$$

Inner feedbacks specify the dependence of power level dynamics in the reactor core on the fuel elements temperature. Because of reactor core heat capacity the time constant, characterizing the fuel rods temperature change, is not less than 0.01 sec. Thus, the subcritical reactor dynamics taking into account the influence of inner feedbacks can be described by quasi-static approximation for prompt neutrons – instantaneous step approximation [3]. In this case the system, describing the ADS subcritical reactor dynamics with external neutron source looks like:

$$\begin{aligned}
&N = \frac{\left(\sum_i \lambda_i c_i + Q\right) l}{\beta - \rho},\\
&\rho = \rho_{cp} + \alpha_T \left(T_T - T_{cp}\right),\\
&\frac{dc_i}{dt} = \frac{\beta_i}{l} N - \lambda_i c_i,\\
&M_T C_T \frac{dT_T}{dt} = N_T - hF\left(T_T - T_{TH}\right),\\
&M_{TH} C_{TH} \frac{dT_{TH}}{dt} = 2GC_{TH}(T_{вх} - T_{TH}) + hF\left(T_T - T_{TH}\right),
\end{aligned} \tag{3}$$

where M_T – the fuel elements in the reactor core mass; M_{TH} – the coolant mass, T_T –fuel elements temperature; T_{TH} –coolant temperature, N_T – reactor thermal power; G – coolant mass flow; F – fuel elements heat exchange area, α_T – Doppler coefficient (fuel) , h – heat-transfer coefficient, $Q=pq_0$ – average source intensity, p – normalization coefficient.

Constants in (3) corresponds to fast reactor BN-350 characteristics (N=1 GW), initial conditions: $N(0)=0$, $c_i(0)$.

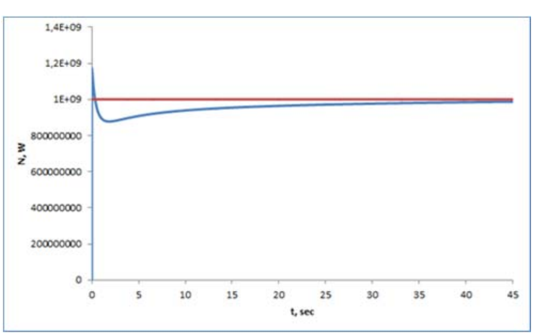

Figure 3: The ADS reactor power level change in time.

In Fig. 4, 5, as an example, calculation results of parameters change during fast subcritical reactor start-up and reactor going to power rating level, are presented. On the basis of the presented model power level change in the ADS subcritical reactor core ($k_{ef} = 0.98$, fuel composition corresponds to BN-350) driven by linac ($T = 10^{-3}$ sec; $\tau = 10^{-4}$ sec) is calculated (Fig. 3).

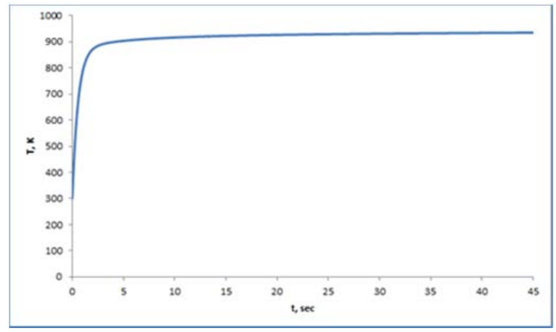

Figure 4: The fuel temperature change in time.

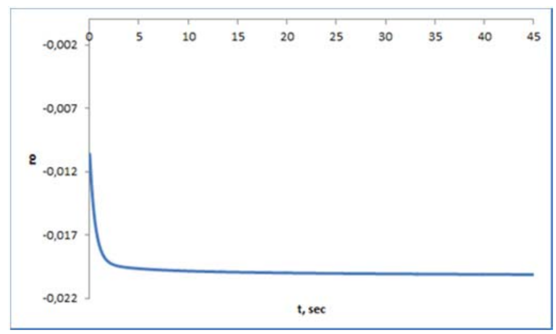

Figure 5: The reactivity coefficient change in time.

CONCLUSION

For ADS control it is necessary to regulate the external neutron source intensity and therefore charged particles beam characteristics.

The most convenient way to control ADS is the average current variation by pulse repetition rate change.

In the steady ADS operation condition neutron flux density in the reactor core changes periodically with a period corresponding to the impulse period in accelerator. The fuel elements temperature is almost constant in time because of their thermal inertia.

At the ADS start-up, driven by linac with the constant average current, a short-time power surge higher the power rating level is possible, but the fuel temperature doesn't exceed its rated value.

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ISBN 978-3-95450-170-0

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