Evaluation of Over Temperature Delta T and Over Power Delta T Operating Margin in Krsko NPP

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ABSTRACT

The purpose of the reactor protection system is to prevent reactor conditions from exceeding the safety limits by initiating reactor trip. Delta T protection system is designed with assumption that core power is, to a good approximation, proportional to the temperature difference between vessel outlet and inlet. Since the core power level is important parameter in determining when the core is approaching departure from nucleate boiling (DNB) or fuel meltdown, Delta T protection system is used to protect the core against those accidents.

Over Temperature Delta T protection (OTDT) is designed to protect the reactor core against departure from nucleate boiling (DNB) and prevent overheating of the fuel rod cladding. Measured DT signal is compared with continuously calculated OTDT setpoint and if actual Delta T exceeds OTDT setpoint the OTDT protection will generate a reactor trip signal. OTDT setpoint is a function of average RCS temperature, pressurizer pressure and axial flux difference.

Over Power Delta T protection (OPDT) is designed to protect the fuel from reaching melting point and prevent fuel rod cladding failure. Measured Delta T signal is compared with continuously calculated OPDT setpoint and if actual Delta T exceeds OPDT setpoint the OPDT protection will generate a reactor trip signal. OPDT setpoint is a function of average RCS temperature only.

This paper will show how margin between measured DT and calculated OTDT and OPDT setpoints change with the change of different plant parameters (average RCS temperature, pressurizer pressure and axial flux difference).

Keywords: *OTDT protection, OPDT protection, DNB, fuel meltdown, operating margin*

1 INTRODUCTION

One of the many functions of the reactor protection system is to generate an automatic reactor trip in case that reactor power, which is calculated as a difference between Reactor Coolant System (RCS) hot leg temperature and cold leg temperature (DT = Thot – Tcold), exceeds calculated setpoints. The purpose of DT protection functions is to protect the reactor core against the departure from nucleate boiling (Over Temperature DT protection) and fuel meltdown (Over Power DT protection).

The purpose of this paper is to show how the margin between actual DT signals and DT setpoints change with the change of different RCS parameters and/or power distribution within the reactor core. In a plant operation, change in the DT measurement can be introduced by actual change in the RCS parameters, actual change in power distribution or by a failure in measurement (e.g. sensor failure or electronics failure).

DT protection system in Krsko NPP consists of four independent temperature channels (two channels on each RCS cooling loop), where each temperature channel continuously performs following functions:

a) Measures the temperature of RCS hot leg and cold leg,
b) Calculate actual DT,
c) Calculate OTDT and OPDT setpoints,
d) Makes comparison between actual DT and calculated OTDT and OPDT setpoints,
e) If actual DT signal is equal or greater than OTDT (OPDT) setpoint, generates a request for reactor trip which is then sent to reactor protection system.

Each of the four RCS temperature channels performs independent calculations and provide information to reactor protection system. In case that two or more channels generate a request for trip, reactor protection system will actuate a reactor trip (2 out of 4 logic). Logic diagrams of the reactor trip logic for OTDT protection and OPDT protection are shown on Figure 1 and Figure 2.

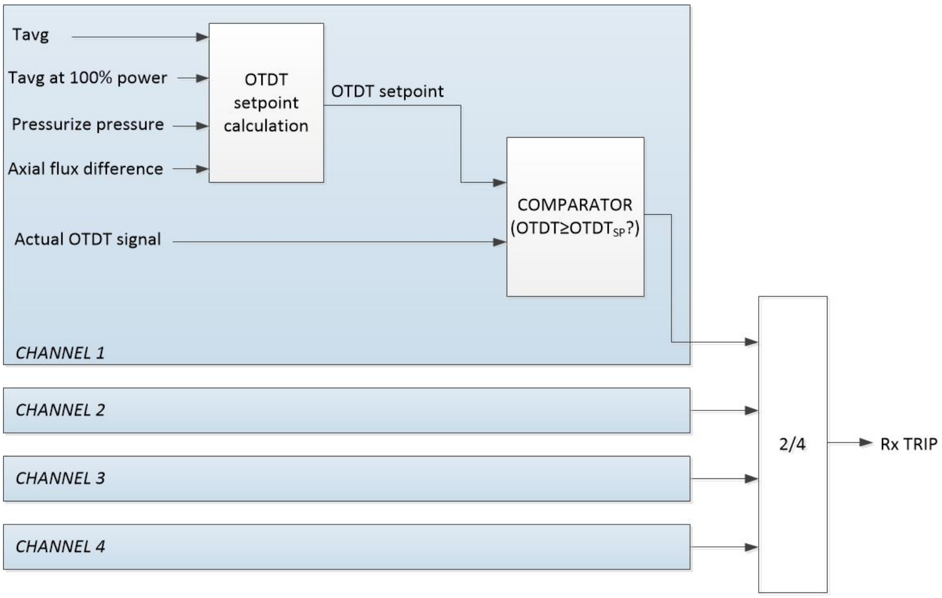

Figure 1. Over Temperature DT reactor protection logic diagram

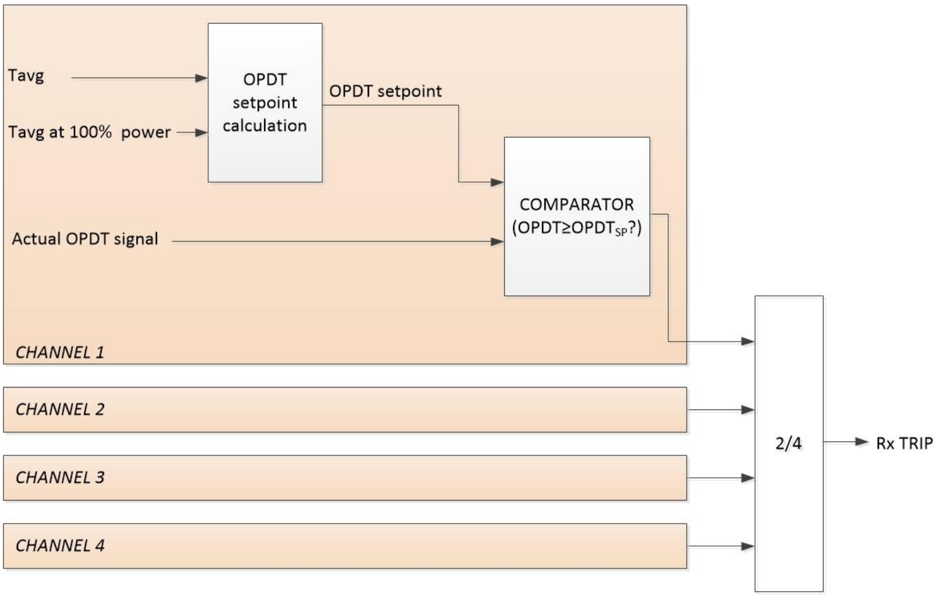

Figure 2. Over Power DT reactor protection logic diagram

All temperature channels have additional control function to generate a turbine runback signal (reduce turbine power) and prevent automatic and manual control rod withdrawal in case the margin between actual DT signal and any DT reduces to 3% or less. Turbine runback will be active as long as the two out of four channels are within the 3% of the OTDT (or OPDT) trip setpoint [1]. The effect of turbine runback on the behavior of temperature loops will not be considered in this article.

More detailed description of OTDT and OPDT setpoints calculations are explained in sections below.

2 DETERMINATION OF OVERTEMPERATURE DT SETPOINT

As it is shown on the Figure 1, OTDT protection is a function of average RCS temperature (Tavg), pressurize pressure (P) and axial flux difference (ΔI). General equation for the calculation of the OTDT setpoint is [1]:

$$OTDT\ setpoint = DT_0\left[K_1 - K_2\left(\frac{1+\tau_1 S}{1+\tau_2 S}\right)\left[T_{avg} - T_{avg\_0}\right] + K_3(P - P_0) - f_1(\Delta I)\right] \quad (1)$$

Where:

DT_0 = indicated DT at rated thermal power, in terms of percent reactor power

T_{avg} = measured RCS average temperature

T_{avg_0} = nominal T_{avg} at rated thermal power

P = pressurizer pressure

P_0 = nominal RCS operating pressure

$f_1(\Delta I)$ = function of axial flux difference

K_1 = manually adjusted preset bias that sets the steady state trip setpoint when other parameters are set at their rated values

K_2, K_3 = manually adjusted preset gains

$\frac{1+\tau_1 S}{1+\tau_2 S}$ = function generated by the lead-lag compensator for T_{avg}

τ_1 = lead time constant

τ_2 = lag time constant

S = Laplace transform operator

OTDT operating margin is a difference between OTDT setpoint and actual DT signal (lead-lag compensated). As long as the OTDT setpoint is higher than the actual DT value (OTDT margin is greater than 0%), reactor protection system will not receive a request for reactor trip.

$$OTDT\ margin = OTDT\ setpoint - DT\left(\frac{1+\tau_3 S}{1+\tau_4 S}\right) \qquad (2)$$

Where:

DT = measured DT, in terms of percent reactor power

$\frac{1+\tau_3 S}{1+\tau_4 S}$ = function generated by the lead-lag compensator for measured DT

3 DETERMINATION OF OVERPOWER DT SETPOINT

As it is shown on the Figure 2, OPDT protection is a function of only average RCS temperature (Tavg). General equation for the calculation of the OPDT setpoint is [1]:

$$OPDT\ setpoint = DT_0\left[K_4 - K_5\left(\frac{\tau_5 S}{1+\tau_5 S}\right)T_{avg} - K_6\left[T_{avg} - T_{avg\_0}\right] + f_2\cancelto{0}{(\Delta I)}\right] \qquad (3)$$

Where:

DT0 = indicated DT at rated thermal power, in terms of percent reactor power

Tavg = measured RCS average temperature

Tavg_0 = nominal Tavg at rated thermal power

f2(ΔI) = function of axial flux difference (equals to 0 at Krsko)

K4 = manually adjusted preset bias that sets the steady state trip setpoint when other parameters are set at their rated values

K5, K6 = manually adjusted preset gains

$\frac{\tau_5 s}{1+\tau_5 s}$ = function generated by the rate-lag compensator for Tavg

τ5 = rate-lag time constant

S = Laplace transform operator

OPDT operating margin is a difference between OPDT setpoint and actual DT signal (lead-lag compensated). As long as the OPDT setpoint is higher than the actual DT value (OPDT margin is greater than 0%), reactor protection system will not receive a request for reactor trip.

$$OPDT\ margin = OPDT\ setpoint - DT\left(\frac{1+\tau_6 S}{1+\tau_7 S}\right) \tag{4}$$

Where:

DT = measured DT, in terms of percent reactor power

$\frac{1+\tau_6 S}{1+\tau_7 S}$ = function generated by the lead-lag compensator for measured DT

4 EVALUATION OF OTDT AND OPDT OPERATING MARGIN IN KRSKO NPP

Initial values on each graph represent the full power operation conditions. For the purpose of this article, change in each chosen parameter is simulated as a ramp change from the initial state to the upper value limit and then back to the initial state, upon which follows a ramp change to the lower value limit and returning back to the initial state. Initial state value, upper value limit, lower value limit and duration of transients are test specific and will be explained in the subsections for each individual test. Transients are set to be short enough to see the effects of the lead and/or lag compensation in the signal processing and also slow enough to have visual interpretation of how OTDT/OPDT signals are approaching or moving away from OTDT/OPDT setpoints. Effects of lead/lag compensation are present only in the T_{cold} and T_{hot} (and T_{avg}) signal processing.

All measurements were made on the one of the actual RCS temperature channels installed in the ACM7300 Process Protection and Control System (obtained data represent real system parameters). Programmable voltage source Yokogawa GS200 [7] was used to simulate the change in the chosen plant parameters, the source generates extremely low-noise DC voltage signal with high accuracy, high stability and high resolution. Dewesoft Data Acquisition System [8] was used for collecting and analyzing data.

4.1 Impact of cold leg temperature (Tcold) on OTDT and OPDT measurement

Change in T_{cold} temperature will directly affect DT indication (DT = T_{hot} – $\mathbf{T_{cold}}$) and also the average temperature in the reactor coolant system loop (T_{avg} = (T_{hot} + $\mathbf{T_{cold}}$)/2). Tavg is then used in calculation of the OTDT and OPDT setpoints as it is shown with equations (1) and (3).

Duration of each transient (upward or downward change of T_{cold} signal) between steady state values is 10 seconds, duration of steady states in between those transients are set to 20 seconds. Initial state values of T_{cold} temperature, OTDT and OPDT indications, as well as upper and lower value limits are given in the table below.

Table 1: Initial state, upper value limit and lower value limit for observed parameters

Parameter	Initial state	Upper value limit	Lower value limit
T_{cold}	286.2 °C	332 °C	257 °C
OTDT	100 %	150 %	0 %
$OTDT_{SP}$	115.7 %	150 %	0 %
OPDT	100 %	150 %	0 %
$OPDT_{SP}$	108 %	150 %	0 %

Figures 3 and 4 show how the OTDT, OTDT setpoint, OPDT and OPDT setpoint will change with the change of T_{cold} signal.

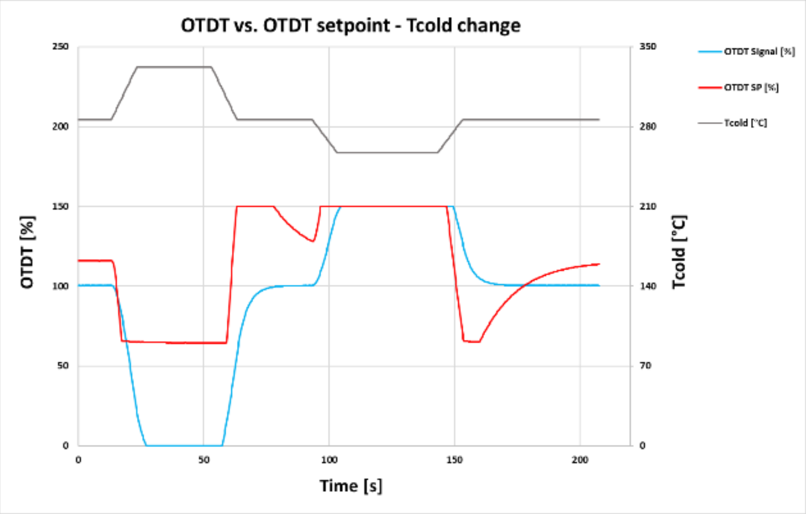

Figure 3. Effect of Tcold change on OTDT signals

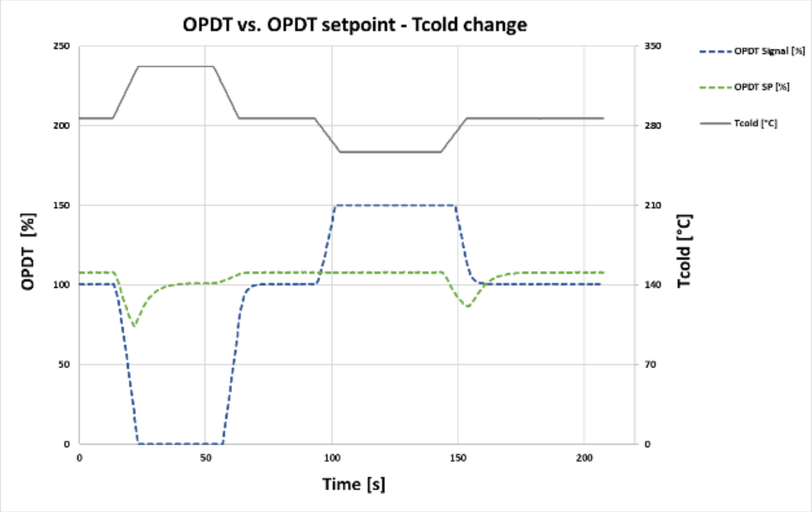

Figure 4. Effect of Tcold change on OPDT signals

Increase in T_{cold} will cause OTDT and OPDT to decrease and Tavg to increase. Due to increased Tavg, OTDT and OPDT setpoints will decrease. Decrease in T_{cold} value will cause the opposite response – OTDT and OPDT indications will increase as well as OTDT and OPDT setpoints. The effect of lead and/or lag compensation can be seen on both OTDT and $OTDT_{SP}$, as well as on OPDT and $OPDT_{SP}$.

4.2 Impact of hot leg temperature (Thot) on OTDT and OPDT measurement

Change in T_{hot} temperature will also directly affect DT indication (DT = $\mathbf{T_{hot}}$ – T_{cold}) and the average RCS temperature (T_{avg} = ($\mathbf{T_{hot}}$ + T_{cold})/2). Figures 5 and 6 show how the OTDT, OTDT setpoint, OPDT and OPDT setpoint will change with the change of T_{hot} signal.

Duration of each transient (upward or downward change of T_{hot} signal) between steady state values is 5 seconds, duration of steady states in between those transients are set to 5 seconds. Initial state values of T_{hot} temperature, OTDT and OPDT indications, as well as upper and lower value limits are given in the table below.

Table 1: Initial state, upper value limit and lower value limit for observed parameters

Parameter	**Initial state**	**Upper value limit**	**Lower value limit**
T_{hot}	323.5 °C	352 °C	277 °C
OTDT	100 %	150 %	0 %
$OTDT_{SP}$	115.7 %	150 %	0 %
OPDT	100 %	150 %	0 %
$OPDT_{SP}$	108 %	150 %	0 %

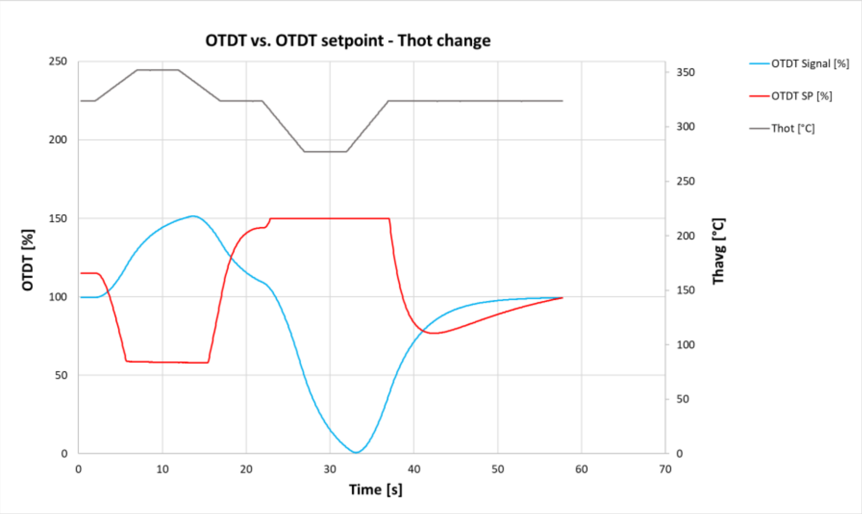

Figure 5. Effect of Thot change on OTDT signals

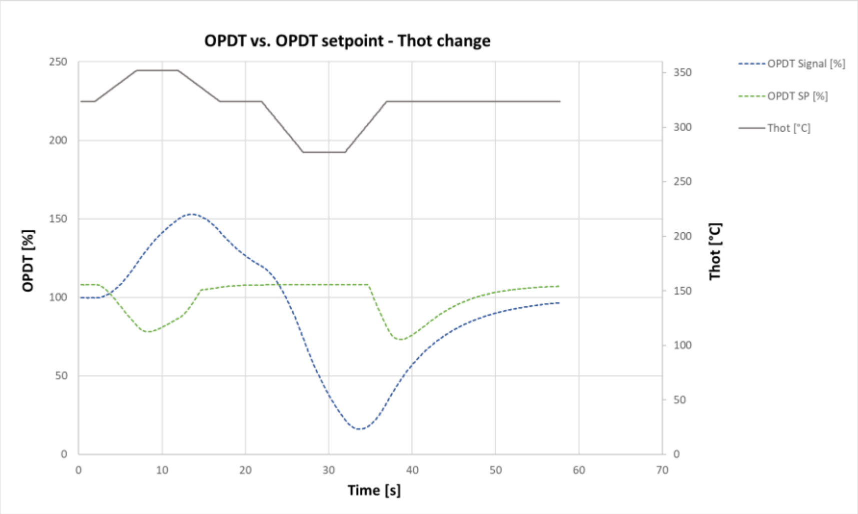

Figure 6. Effect of Thot change on OPDT signals

Increase in T_{hot} will cause both DT and T_{avg} to increase, consequently OTDT and OPDT setpoints will decrease. Decrease in T_{hot} will cause the opposite response – DT indications will increase while T_{avg} OTDT and OPDT setpoints will increase. Since the duration of transient is shorter than it was in the previous test (T_{cold}), the effects of lead/lag compensations are more visible in the signals.

4.3 Impact of pressurizer pressure (PRZR PRESS) on OTDT and OPDT measurement

Change in the pressurizer pressure indication will only have an effect on OTDT setpoint calculation (equation (1)). Figures 7 and 8 show how the OTDT, OTDT setpoint, OPDT and OPDT setpoint will change with the change of pressurizer pressure signal.

Duration of each transient (upward or downward change of pressurizer pressure signal) between steady state values is 5 seconds, duration of steady states in between those transients are set to 5 seconds. Initial state values of pressurizer pressure, OTDT and OPDT indications, as well as upper and lower value limits are given in the table below.

Table 1: Initial state, upper value limit and lower value limit for observed parameters

Parameter	**Initial state**	**Upper value limit**	**Lower value limit**
PRZ PRESS	157.3 kp/cm^2	180 kp/cm^2	120 kp/cm^2
OTDT	100 %	150 %	0 %
OTDT$_{SP}$	115.7 %	150 %	0 %
OPDT	100 %	150 %	0 %
OPDT$_{SP}$	108 %	150 %	0 %

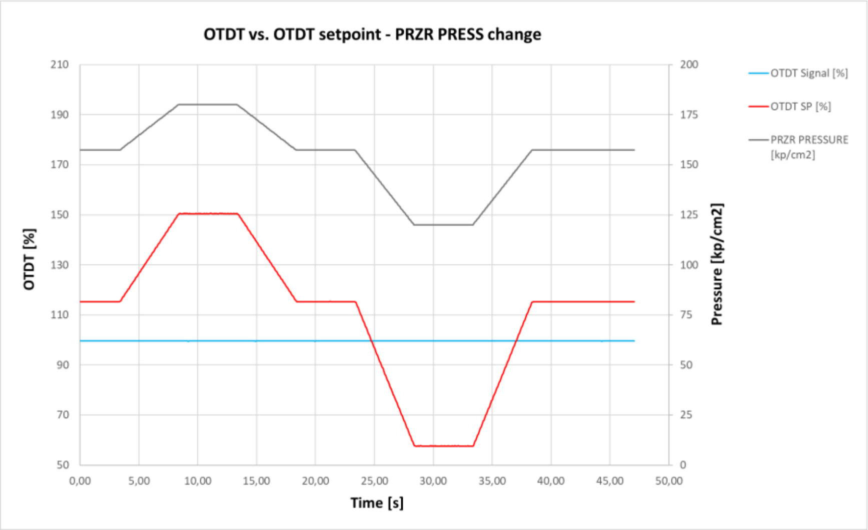

Figure 7. Effect of pressurizer pressure change on OTDT signals

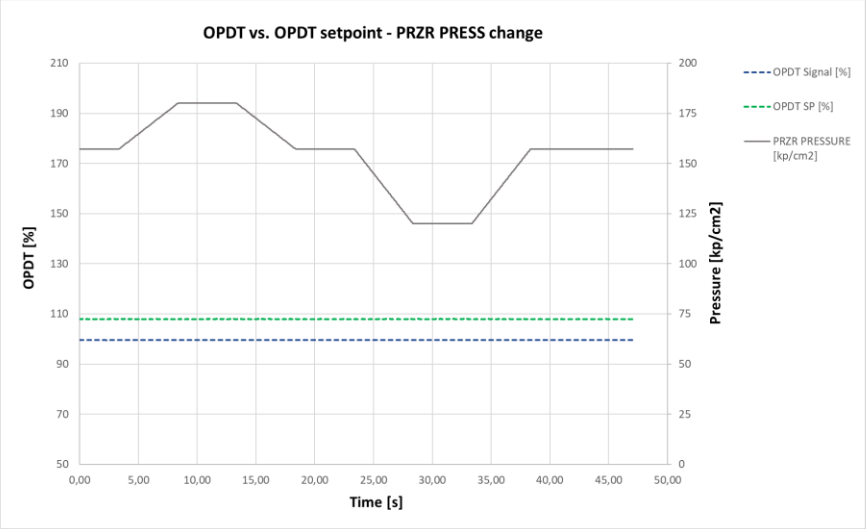

Figure 8. Effect of pressurizer pressure change on OPDT signals

When pressurize pressure deviates from the nominal RCS operating pressure, pressure penalties will cause OTDT setpoint to change in a way that increase of a pressurizer pressure will cause OTDT setpoint to increase and decrease of a pressurizer pressure will cause OTDT setpoint to decrease. Since the pressurizer pressure doesn't go into OPDT protection, there is no change in OPDT or OPDT setpoint signals.

4.4 Impact of axial flux difference (AFD) on OTDT and OPDT measurement

Change in the axial flux difference indication will only have an effect on OTDT setpoint calculation as shown in equation (1), where $f_1(\Delta I)$ represents the function of axial flux difference showed on Figure 9 [4] [5] [6].

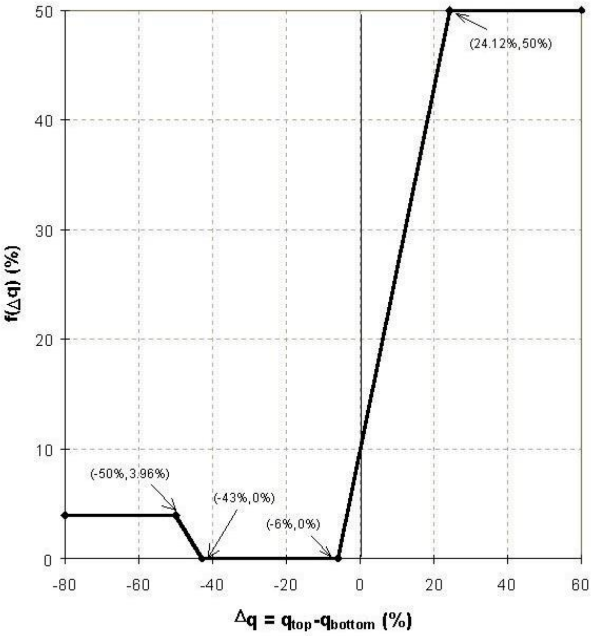

Figure 9. Function of axial flux difference used for calculation of OTDT setpoint

Duration of each transient (upward or downward change of axial flux difference signal) between steady state values is 5 seconds, duration of steady states in between those transients are set to 15 seconds. Initial state values of axial flux difference, OTDT and OPDT indications, as well as upper and lower value limits are given in the table below.

Table 1: Initial state, upper value limit and lower value limit for observed parameters

Parameter	**Initial state**	**Upper value limit**	**Lower value limit**
Axial flux difference	0 %	60 %	-60 %
OTDT	100 %	150 %	0 %
OTDT$_{SP}$	115.7 %	150 %	0 %
OPDT	100 %	150 %	0 %
OPDT$_{SP}$	108 %	150 %	0 %

Figures 10 and 11 show how the OTDT, OTDT setpoint, OPDT and OPDT setpoint will change with the change of axial flux difference.

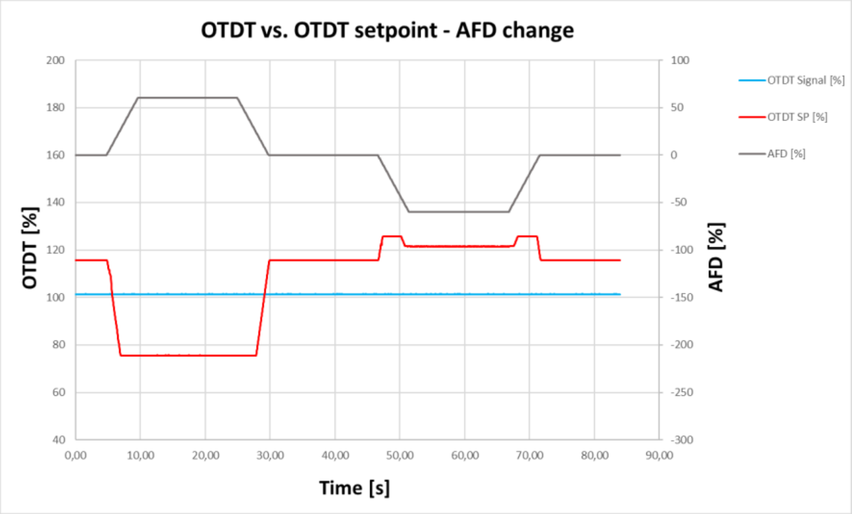

Figure 10. Effect of axial flux difference change on only OTDT signals

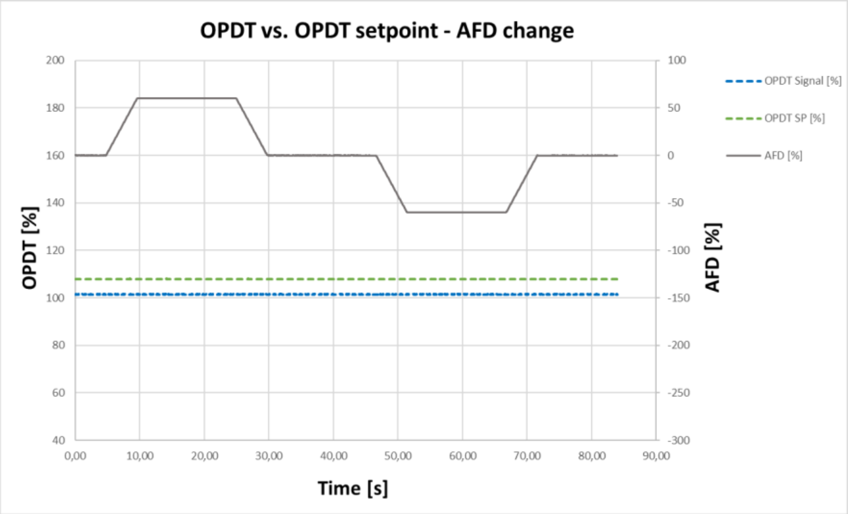

Figure 11. Effect of axial flux difference change on only OPDT signals

When core power is distributed evenly (axial flux difference close to 0%), $f_1(\Delta I)$ function will not have a big impact on the OTDT setpoint. For very large positive values of axial flux difference OTDT setpoint will significantly decrease. Very large negative values of axial flux difference will keep the OTDT setpoint close to the full power operation value. Since the axial flux difference doesn’t go into OPDT protection, there is no change in OPDT or OPDT setpoint signals.

5 CONCLUSION

OPDT and OTDT protection system is important because it protects the reactor core from departure from nucleate boiling condition and fuel meltdown. Keeping the RCS parameters within the normal operating values will ensure that reactor core safety limits are not reached.

In case any of the parameters of DT protection system (Thot and Tcold RCS temperatures, pressurizer pressure, axial flux difference) deviates from normal values, margin between actual OTDT/OPDT value and OTDT/OPDT setpoint will change.

Higher Thot and/or Tcold temperatures, lower pressurizer pressure and higher axial flux difference will reduce the margin between OTDT signal and OTDT setpoint. At the points where OTDT meets OTDT setpoint, the request for reactor trip will be send to OTDT protection system logic.

Higher Thot and/or Tcold temperatures will reduce the margin between OPDT signal and OPDT setpoint, while pressurizer pressure and axial flux difference have no effect on OPDT circuit. At the points where OPDT meets OPDT setpoint, the request for reactor trip will be send to OPDT protection system logic. Conclusions should state concisely the most important propositions of the paper as well as the author’s views of the practical implications of the results.

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