Dynamic Simulation of NEK Reactor Coolant Pump with a Best Estimate Full Scale Model in APROS

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ABSTRACT

This paper presents the simulation of the Krško NPP (NEK) Reactor Coolant Pump (RCP) start-up test when pump is supplied from the normal bus (off-site power source) and the RCP coast down test on the loss of offsite power signal. The simulation model was developed in APROS - Advanced PROcess Simulation environment. APROS is a multifunctional software for modelling and dynamic simulation of various physical processes in power plants which enable a coupled simulation of thermal-hydraulics, electrical and regulation systems including reactor kinetics.

The goal was to create a simulation model which enabled simulation of the transient process occurring at the RCP start-up and coast down tests. The entire integrated model consists of NEK primary system and a part of the secondary systems. The RCP pump model, as a part of the reactor coolant loop, is supplied from the normal bus (electric power distribution systems connected to external power grid). The RCP moment and current slip characteristics were simulated and compared with the RCP vendor data to confirm the validity and accuracy of the APROS pump model. It is shown that, by using the available characteristic data of the pump as well as the inputs obtained from the motor data sheet, an accurate dynamic simulation of RCP start-up is possible. Furthermore, the paper discusses the simulation of the RCP motor start-up transient and coast down of primary mass flow after a RCP trip.
1 INTRODUCTION

All nuclear plants have redundant emergency electrical systems that are designed to provide backup AC and DC power to the emergency safety equipment if the normal sources of electrical power are lost. If the normal AC power is lost, the emergency diesel generators (EDGs) start to provide electrical power to a safeguards electrical load centre (also called switchgear or bus). Each bus then supplies power directly to important safety electrically-driven components. However, the capacity of EDGs is not sufficient for driving the RCP pumps and the reactor has to be cooled down by a natural water circulation process through the steam generators (SGs). Complete loss of reactor coolant forced flow is caused by simultaneous loss of electrical supplies to all RCPs and lead to a rapid increase in the reactor coolant temperature. This increase could result in departure from nucleate boiling (DNB) with subsequent fuel damage if the reactor are not tripped promptly and long core term decay heat removal established.

This paper describes the partial validation of the NEK RCP pump model taking into consideration the real plant test data. The main task for this analysis is to show the code capabilities in the modelling a start-up of induction motors with their nonlinear load. Our full NEK APROS simulation model consists of the primary and part of the secondary systems. The model consists the Reactor Pressure Vessel (including the core and associated neutron kinetics model), Reactor Coolant Legs with RCPs, Pressurizer, Resistance Temperature Detector Bypass – RTD Bypass, Steam Generator 1, Steam Generator 2, Main Steam & Steam Dump, Feedwater 1 and Feedwater 2 and part of the main electrical power distribution systems. The regulation systems that maintain the model in the steady state are also modelled; Reactor Coolant Pump Power Loss, PORV & Safety Valve Control System 1 and 2, Pressurizer Liquid Level Control, Pressurizer Pressure Control, Rod Control, Steam Dump Control, Steam Generator and Feedwater Flow Control 1 and 2. The model consists of over 400 thermal hydraulic volumes. The APROS NEK integrated model and the associated steady state evaluation have been already presented on ICONE conference 2014 in Prague [1].

It is known that verification and validation should be performed on all computer codes and models used for the deterministic safety analysis of NPPs. The purpose of validation (also referred code assessment) is to provide confidence in the ability of a software package to realistically or conservatively predict the values of the modelled parameters. The RCP model simulation (e.g. validation of moment and current slips characteristics) was performed and results compared with the RCP vendor data to confirm the validity and accuracy of the APROS pump model.

APROS [2], developed by the Research Centre VTT and Fortum Engineering in Finland, is a program package that allows making the dynamical simulations for engineering purposes. The APROS tool is suitable for modelling and simulation of the dynamics of different processes (e.g. thermo-hydraulic, I&C, electric, neutron kinetics etc.) during all phases of nuclear power plants life span from pre-design stage to training, for small simple models up to full scope simulators.
2 MODELLING THE REACTOR COOLANT PUMP START-UP

2.1 The power system outlay

Figure 1 represents a simplified NEK electrical power distribution subsystem that both RCPs models are connected to. During normal operation, main generator G1 supplies electrical network through the main transformers GT1 and GT2. It also supplies onsite power supply over unit transformers. Both RCPs are supplied from Non Class 1E M1 and M2 6.3 kV busses. Alternatively, if normal AC power is lost, both RCPs can be energized from the station auxiliary transformer T3, which is connected to the 110 kV RTP Krško and directly to independent external power source. In this case, the plant is on ‘island operation’ mode separated from the rest of the electric power grid and control systems are used to control frequency and voltage drops during the RCP pump start-up.

Figure 1: NEK simplified electrical power system model in APROS code
2.2 Reactor coolant pump

The APROS model of RCP presents a vertical, single stage, centrifugal, shaft seal pump driven by air cooled, three phase induction motor with nominal active power of 5.4 MW. The motor is connected to a 6.3 kV bus. The pump inertia is provided by a flywheel connected to the shaft above the motor to increase the total rotating inertia, assuring a longer pump coastdown. Interaction of the pump impeller and the fluid is described by empirically developed curves (homologous curves) relating pump head and torque to the volumetric flow rate and pump speed. The pump model is modelled to cover all possibly zones of operation, normal and during the transients. General input data tables for RCP are collected in below table.

Table 1: RCP pump model attributes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal rotation speed</td>
<td>1485.7</td>
<td>rpm</td>
</tr>
<tr>
<td>Nominal volumetric flow</td>
<td>6.35</td>
<td>m³/s</td>
</tr>
<tr>
<td>Nominal head</td>
<td>82.9</td>
<td>m</td>
</tr>
<tr>
<td>Nominal hydraulic torque</td>
<td>32038</td>
<td>Nm</td>
</tr>
<tr>
<td>Nominal active power</td>
<td>5421</td>
<td>kW</td>
</tr>
<tr>
<td>Nominal motor torque</td>
<td>34879</td>
<td>Nm</td>
</tr>
<tr>
<td>Nominal voltage level</td>
<td>6300</td>
<td>V</td>
</tr>
<tr>
<td>Moment of inertia (pump and motor)</td>
<td>2694</td>
<td>kg m²</td>
</tr>
<tr>
<td>Start torque</td>
<td>1.1</td>
<td>of nom.</td>
</tr>
<tr>
<td>Maximal torque</td>
<td>2.45</td>
<td>of nom.</td>
</tr>
</tbody>
</table>

2.3 Basic model of the induction motor

The APROS pump module calculates the motor torque as a function of the speed (slip), frequency and voltage [3]. The pump model is connected to the 6.3 kV bus and voltage drop at the time when the maximal moment occur is less than one percent of nominal. The bus frequency is constant during the simulation. The electromagnetic part of the model is based on the dynamic equilibrium of the motor and hydraulic torques where pump speed is calculated with the aid of the both torques and with the aid of inertia of the entire pump-motor set. The motor torque can be calculated with Eq. (1), where \( s \) is the slip (relative motion between the rotor and the magnetic field), \( s_{\text{max}} \) is the slip when torque gets its maximum value, \( T_{\text{max}} \) is the torque maximum value, \( U \) is current voltage and \( U_n \) is nominal voltage level. The K coefficient is used to correct the torque by Eq. (1) during the transients, when motor is started and speed is near zero. Because the motor torque curve is non-linear some extra linearization terms have been added to the torque derivative according to the speed, frequency and voltage to ensure convergence. Also the dynamic current slip characteristic can be calculated. The motor starting current depends on active and reactive power consumed by the motor. The reactive power is calculated with the help of a power factor vs speed curve determined by interpolation between start and normal power coefficient attribute.

\[
T_m = \frac{U^2}{U_n^2} \cdot K \cdot T_{\text{max}} \cdot \frac{2}{(s/s_{\text{max}}) + (s_{\text{max}} / s)}
\]  

(1)
2.4 RCP motor protection limitations

The following signals provide the necessary protection against a complete loss of forced reactor coolant flow:

- RCP power supply Undervoltage or Underfrequency
- Reactor Coolant Flow-Low
- RCP Breaker Open

The undervoltage RCP bus trips set points are 70% of nominal bus voltage and the underfrequency set points are 47.7 Hz [4].

The entire pump-flywheel-motor set time constant amounts to 12 s for 100% of the nominal voltage and is increased to 24 s at 80% of the nominal voltage. A further decrease of voltage results in a considerable increase of the motor set time constant and may activate the delayed overcurrent protection [5].

3 SIMULATION AND FIELD TESTS RESULTS

Our aim is to simulate the pump start-up at two different voltage levels and to show that the APROS pump model is capable to accurately simulate real AC induction motor (moment-slip and current-slip) characteristics in comparison with manufacturer and vendor data. Upon this analysis two field tests were simulated, ‘Coast down test’ and pump ‘Start-up test’, to confirm the validity of RCP pump model.

3.1 Coast down test

The complete loss of reactor coolant flow (‘Coast down test’) was analysed for the assumed loss of the RCPs (initially in operation in a full scale simulation model at steady state in the range of the reactor at 100% power). Figure 2 shows the primary circuit mass flow rate transient response after RCP trip between the APROS simulation and USAR [6]. The mass flow rate falling trend is a little different and after 10 seconds of simulation APROS mass flow rate reached 2500 kg/s. This can be explained by the fact that the primary circuit flow resistances between APROS and these used in USAR analysis cannot be compared.
Figure 2: RCS Mass flow during cost down test compared between model in APROS and USAR [6]

3.2 Pump start-up test

During the APROS RCP model validation, the pump start-up has been simulated and compared to the RCP motor characteristics (moment-slip and current-slip) obtained by manufacturer shown in Figure 3 and Figure 4 [7]. The difference between motor and hydraulic torque is sufficient to accelerate a RCP to its operating speed in a very short time. As a result, the motor takes up a high current, with the risk to overheat and damage the motor windings. If there are no forces which accelerate or slow down the speed, the speed is settled down to the position where both torques are equal.

Simulation of both RCPs start was initiated in the integrated APROS NEK model right after ‘Cost down test‘. After pump trip the speed does not ended at zero because the rotor was not considered to be frictionless. RCP is rotating because of the established natural loop circulation driven by the water density difference between core and SGs. The buses M1 and M2 voltage level was changed from 6.3 kV to 6 kV to set the same initial conditions as in testing conditions at manufacturer. The new nominal voltage level is 6 kV and 80% of nominal voltage level means 4.8 kV. The frequency during simulation was set to 50 Hz. The nominal rotation speed is less than the synchronous speed, which is 1500 rpm. The start and maximal torque values assumed in simulation, needed to describe typical induction motor moment speed characteristics, are 1.1 and 2.45 times more than nominal.
Figure 3: Comparison of the RCP torque vs speed curve between APROS simulation and vendor data [7]

In the case where the nominal voltage level is 6000 V the simulated top torque at the time when motor top moment (slip is $s_{\text{max}}$) occurs is 280 % of the nominal torque. The deviations of the APROS simulation from the characteristics curves are negligible at start and more than 10 % when motor reached its maximal moment. A decrease in voltage level to 4800 V (80 % of rated) during the start-up causes the motor torque curve to droop and the time needed for start-up changed from 10 to 18 seconds. In accordance with Eq. (1), the torque drop varies to the square of the voltage. As the results of decreasing in voltage level seen from Figure 3 the trend of torque speed curves in APROS simulation are the same.
The results of the simulation in Figure 4 shows that the current speed characteristic can be accurately simulated by the APROS pump model and compared with the vendor characteristics curves. During the start-up, the maximal current value reaches up to 650% of the nominal current in case of the nominal voltage. A considerable voltage drop on bus decreases the starting current and the time to reached nominal speed extends from 10 to 18 seconds.

### 3.3 Observation of the results

During the simulation it was observed that the maximal torque is always bigger than the referenced vendor characteristics. Because of this deviation, it was investigated how coefficient $K$, that corrects the torque given by Eq (1), affects the torque calculation during pump start up. The mathematical model of the motor model in the APROS code calculates the motor torque as a function of the speed-slip during the transients. The motor maximal torque is re-calculated to show the correspondence between the simulated and theoretically calculated values. Firstly, the given rated torque $T_r$ may be calculated from the nominal active power and rotation speed attributes listed in Table 1. Eq. (2):

$$T_r = \frac{5424 \cdot 10^3 \cdot 60}{1485.77 \cdot 2 \cdot \pi} = 34878 \text{ Nm} \quad (2)$$
With the assumption that the frequency drop at the time when the maximal moment occurs is less than one percent, the voltage drop at that time is 5972 V (taken from the APROS simulation model) and the correction factor K which corrects torque is 1.18 the maximal torque could be calculated as follows in Eq. (3) and Eq. (4).

\[
T_m = \frac{U^2}{U_n} \cdot K \cdot T_{max} \cdot \frac{2}{(s/s_{max}) + (s_{max}/s)} = \frac{5972^2}{6000^2} \cdot 1.18 \cdot 2.45 \cdot \frac{2}{1+1} = 2.865
\]  

(3)

\[
T_{max, calculated} = T_r \cdot T_m = 34878 \cdot 2.865 = 99942 \text{ Nm}
\]  

(4)

The correction factor K at the time when torque gets the maximum value can be calculated as follows:

\[
K = 1 + (T_s/T_{s1} - 1) \cdot s = 1.18
\]  

(5)

where:

\[T_{s1} = 0.218\] is the value of torque calculated with Eq. (1) when speed is zero

\[T_s = 1.1\] is the real torque when speed is zero.

\[s\] is the slip at the time when the torque gets its maximum value \([s_{max}]\)

In accordance with the Eq. (1) at the time torque reached its pick value (2.45 times of nominal) values are as follows:

\[
\frac{T_{m,max}}{T_m} = \frac{2}{\left(\frac{s}{s_{max}}\right) + \left(\frac{s_{max}}{s}\right)} \rightarrow \frac{M_{top}}{M_r} = 2.45 = \frac{y + \frac{1}{y}}{2}
\]  

(6)

where a quadratic equation has two real solutions:

\[y^2 - 4.9 \cdot y + 1 = 0\]  

(7)

Now the outcome for y is:

\[y_1 = 4.687\]  

(8)

This means that the slip at the time when torque gets its maximum value is

\[s_{max} = s_{nom} \cdot y_1 = 0.045\]  

(9)

where the nominal slip is:

\[s_{nom} = \frac{n_s - n_r}{n_r} = \frac{1500 - 1485.7}{1485.7} = 0.0095\]  

(10)

The simulated maximal torque according to APROS Figure 3 is about 99779 Nm. There is less than 1 % mismatch between the calculated and simulated torque maximal values. It seems that our calculations shows that correction the factor K, which is used to correct torque given by Eq. (1), is valid only when the rotation speed of pump is near zero. This means that the inputs in the NEK APROS pump model are correct but the APROS calculation makes described
differences. The found mismatches between the theoretical induction motor model and the model applied in APROS regarding the motor top torque calculation have been sent to the APROS developers for further investigation and correction.

4 CONCLUSION

The presented results show that, in the case where the motor voltage level is 100% and 80% of nominal, the moment-slip and current-slip characteristics can be satisfactorily simulated by an APROS pump model. The main task of this RCP model investigation and validation is to show the APROS code capabilities in the modelling a start-up of induction motors with their nonlinear load characteristics. It was observed, during the simulations and after the investigation, that the current motor maximal torque calculations in APROS are wrong and the correction factor $K$, that corrects the torque during pump start-up, needs to be investigated and corrected by the developers. Now we are in contact with the developers to collaborate in the solving of this issues.

ACKNOWLEDGMENTS

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[6] USAR NEK, Chapter 15 rev16, 15.3.2 COMPLETE LOSS OF REACTOR COOLANT FLOW
