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Original Article

Electric power frequency and nuclear safety - Subsynchronous resonance case study

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A B S T R A C T

The increase of the alternate current frequency results in increased rotational speed of the electrical motors and connected pumps. The consequence for the reactor coolant pumps is increased flow in primary coolant system. Increase of the current frequency can be initiated by the subsynchronous resonance phenomenon (SSR).

This paper analyses the implications of the SSR and consequential increase of the frequency on the nuclear power plant safety. The Simulink MATLAB® model of the steam turbine and governor system and RELAP5 computer code of the pressurized water reactor are used in the analysis.

The SSR results in fast increase of reactor coolant pumps speed and flow in the primary coolant system. The turbine trip value is reached in short time following SSR. The increase of flow of reactor coolant pumps results in increase of heat removal from reactor core. This results in positive reactivity insertion with reactor power increase of 0.5% before reactor trip is initiated by the turbine trip. The main parameters of the plant did not exceed the values of reactor trip set points. The pressure drop over reactor core is small discarding the possibility of core barrel lift.

1. Introduction

The nuclear power plant (NPP) requires electrical power for activation and operation of the active non-safety and safety systems. The electrical systems of the NPP's differ considering the reactor type, site and power grid characteristics. Fig. 1 shows electrical energy distribution system of the NPP developed from the configuration given in Ref. [1]. The electrical power system of the NPP can be divided into offsite and on-site power system. The offsite power system represents the power system where the nuclear power plant is connected. The on-site power system consists of two distinct subsystems, safety related and non-safety related power system.

Main elements of the non-safety power system include the main generator (MG on Fig. 1), generator step-up transformers (GT1 and GT2 on Fig. 1), unit (T1 and T2 on Fig. 1) and auxiliary transformer (T3 on Fig. 1) with the corresponding buses. The unit transformers T1 and T2 are connected to the generator bus and serve as the normal source of power for non-safety buses. The unit transformers also serve as the preferred source for startup through the generator step-up transformers and with the generator load break switch (LBS on Fig. 1) open. The station auxiliary transformer, marked T3 on Fig. 1, is alternate source of power when main sources are not available. The motors of the reactor coolant pumps (RCP1 and RCP 2 on Fig. 1) are normally connected to non-safety section buses of the plant power system. Plant batteries (Bat A and Bat B on Fig. 1) are ultimate source of power when all other sources of electric power are lost.

There are multiple overspeed trip systems that limit the speed of the turbine in case of the increase of speed above nominal value [2]. The failure of these systems can result in destructive turbine overspeed as it was case in Salem Unit 2 NPP [3]. The main purpose of these systems is to trip the turbine, in order to limit the turbine rotational speed and prevent ejection of turbine missiles. The turbine rotational speed also limits the speed of the shaft connected main generator and output frequency of the generated electrical power. The turbine overspeed trip systems are normally set to the speed below 110% of nominal turbine speed [4]. As additional backup, the turbine protection system has an overspeed protection trip, usually set at 110% of the turbine speed. The turbine trip signal initiates reactor trip resulting in automatic shutdown of the nuclear reactor.

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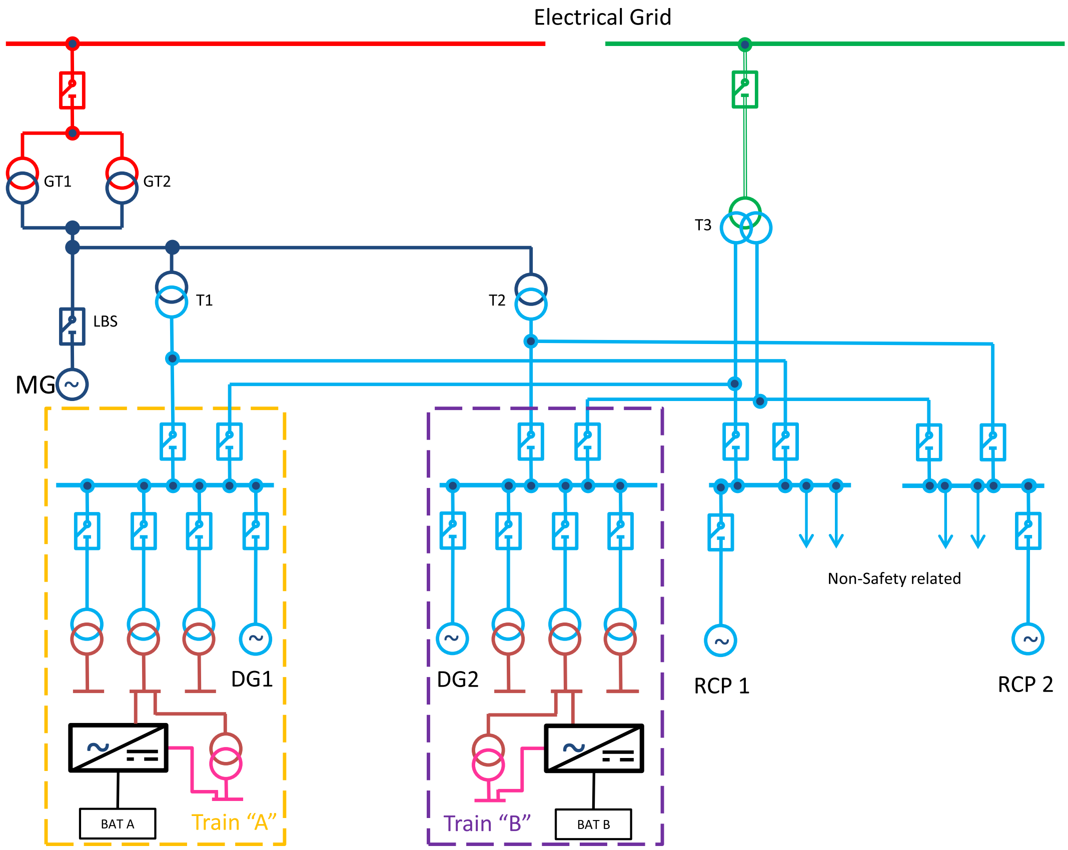

Fig. 1. Example NPP electrical energy distribution system.

The electrical faults that can result in generator overspeed include short circuits in the offsite power system [5], failures of the turbine control system [6] and Subsynchronous Resonance. Failures that occur on or above the generator bus bars, as shown on Fig. 1, will affect simultaneously all underlying bus bars. The rotational speed of the electrical motors connected to these buses, including RCP, will depend on the rotational speed of the generator.

In this paper the increase of the RCP pumps speed due to the Subsynchronous resonance phenomenon is analysed. The change of the parameters in the primary coolant system of the nuclear power plant resulting from the increased RCP speed and flow are assessed and obtained results are presented.

1.1. Description of RCP

The reactor coolant pump of the pressurized water reactors is a vertical, single stage, centrifugal shaft seal pump designed to pump large volumes of main coolant at high temperatures and pressures [7–9]. The reactor coolant pump alternate current (AC) motor is tested at overspeeds up to and including 125% of normal speed [10]. The integrity of the flywheel during a large loss of coolant (LOCA) accident is also checked during the tests.

The reactor coolant pump ensures an adequate core cooling flow rate for sufficient heat transfer from the reactor core to the steam generators. Sufficient pump rotation inertia is provided by a flywheel, in conjunction with the impeller and motor assembly, to provide adequate flow during coast-down. This forced flow following an assumed loss of pump power and the subsequent natural circulation effect provides the core with adequate cooling.

The speed of the RCP pumps lower than nominal result in decrease of flow and core cooling. There are multiple trip signals resulting from pumps underflow, both directly (for example under voltage of RCP), or indirectly (change of temperatures and pressure in the primary coolant system). There are no direct trip signals initiated from the RCP overspeed in standard nuclear power plant with pressurized water reactor [11].

The secondary systems in NPP, as shown in Ref. [12], are recognized to be dominant factor to make unplanned turbine-generator trips which can ultimately result in reactor trips.

The speed of the RCP pumps is correlated to the frequency of the AC power delivered to the motors of the pump. During normal operation, when electrical power is provided by the main generator, the frequency of the current depends on the generator speed. Increase of the generator speed results in increase of the frequency in the onsite AC power distribution system. This results in consequential increase of speed of the electrically coupled AC motors including RCP.

1.2. Subsynchronous resonance phenomenon

The Subsynchronous resonance phenomenon (SSR) is one of the most severe accidents that can occur in large synchronous generators [13–17]. The SSR is attributed to the catastrophic damage to the turbine-generator at Southern California Edison's Mojave Power Plant in 1970 [18]. The SSR results from interaction between the electromechanical system of the generator on one side and the long compensated transmission line on other. The consequences of SSR include increased speed and stresses on turbine-generator shaft. Sub synchronous oscillations in the range of 10–50 Hz result from mechanical oscillations among individual turbine masses and the generator coupled into a long shaft. These mechanical oscillations are electrically coupled with the electrical system via the generator [18].

2. Input models

2.1. Subsynchronous resonance model

In this study the Simulink MATLAB® model [19] of an SSR benchmark system [20] is utilized for assessment of the generator rotation speed. The SIMULINK model has been utilized in previous studies for simulation of Reactor Regulating System [21,22] and integral nuclear reactor model [23,24].

The benchmark system shown on Fig. 2 is used for study of the sub-synchronous resonance and particularly torque amplification after a fault on a series-compensated power system. It consists in a single generator (600 MVA/22 kV/60 Hz/3600 rpm) connected to an infinite bus via two transmission lines, one of which is 55% series-compensated. The mechanical system is modelled by three masses: generator; low pressure turbine and high pressure turbine.

The SSR is initiated by the three-phase fault that is applied at the peak voltage of the generator.

The basic model is modified and following three case studies are created:

- Case 1, with the 25 MW, 5 MVAr load connected to the generator buses, as shown on Fig. 3, simulating house load of the plant.
- Case 2, with 5.22 MVA AC motor connected to the generator buses simulating single RCP pump motor.
- Case 3, with 10.44 MVA AC motor connected to the generator buses as shown on Fig. 4 simulating two RCP pumps motors.

These new case studies were created in order to analyse implications of the additional loads (including RCP pumps) on the change of the generator speed following SSR.

The three-phase fault is applied with 2 s delay in case studies compared to basic model. Delay stabilises generator rotational speed before introduction of the transient. Speed of the generator is recorded and utilized as RCP speed in RELAP5 input model described in the following section.

2.2. RELAP5 input model

The thermal–hydraulic RELAP5 code was developed for a best-estimate transient simulation of light-water cooling systems of nuclear power reactors during postulated accidents [25,26]. In this study the RELAP5/MOD3.3 input model of pressurized water reactor is used for calculations with the latest version of RELAP5/MOD3.3 Patch 5 thermal hydraulic computer code [27]. Both primary and secondary side are modelled. The primary side consists of reactor pressure vessel, pressurizer with sprays and relief valves and two loops, including hot leg, cold leg, intermediate leg, RCP and primary side of steam generator. Secondary side includes secondary side of steam generators, steam generator relief valves, main steam lines up to turbine, turbine valves, main steam isolation valves and main feedwater piping up to the main feedwater (MFW) pumps. Reactor protection system, including reactor trip system and engineered safety features actuation system, is modelled too. For more details refer to Refs. [27,28]. Modification of the model is done in order to include change of the RCP speed. Speed of other pumps (i.e. main feedwater) is not changed in the model because of their small impact or disconnection following turbine trip. Four scenarios described in Section 2.1 are analysed. In scenarios is assumed that concurrently with the reactor trip on turbine trip there is loss of offsite power. This results in loss of the non-safety systems like control systems (pressurizer pressure and level, steam dump etc.). The loss of offsite power also results in loss of main feedwater pumps. In the model is assumed successful start of the diesel generators and with 30 s delay the start of auxiliary feedwater pumps. The auxiliary feedwater pumps feed the steam generators after loss of main feedwater pumps. Several plant parameters are obtained in the analysis. For the purpose of this study focus is given

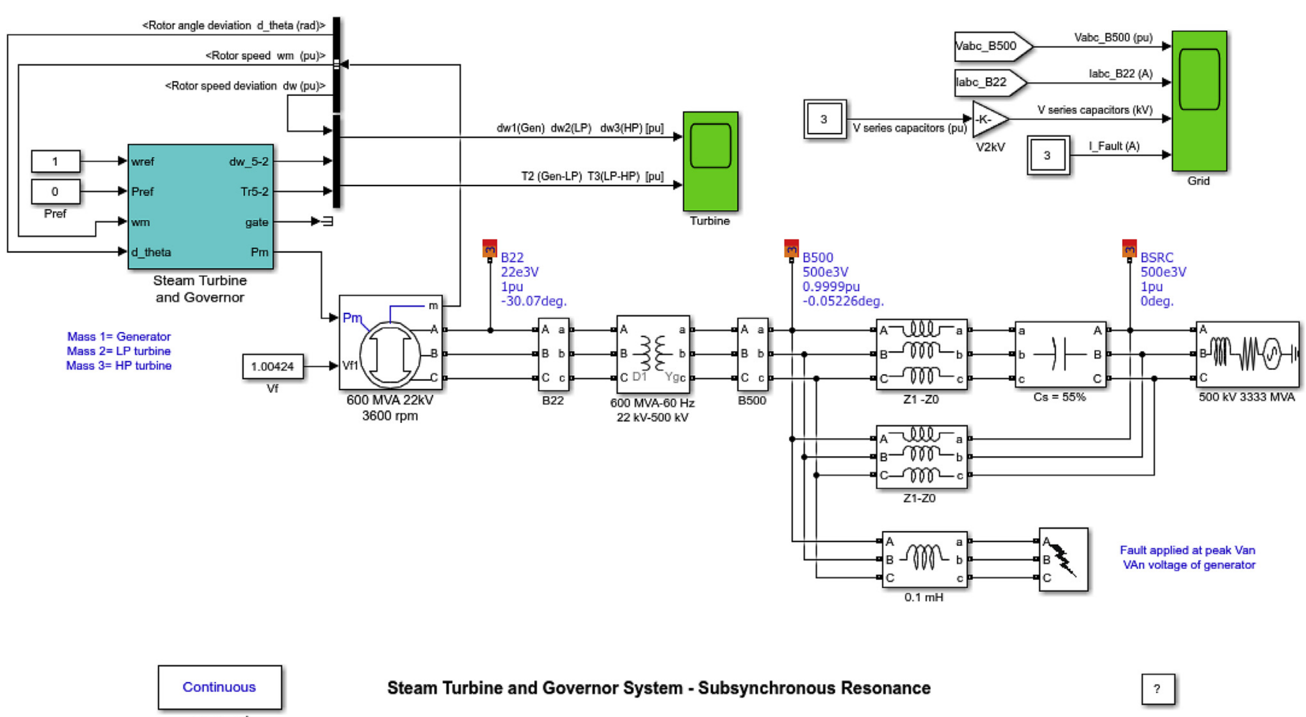

Fig. 2. Basic example model used for SSR simulation.

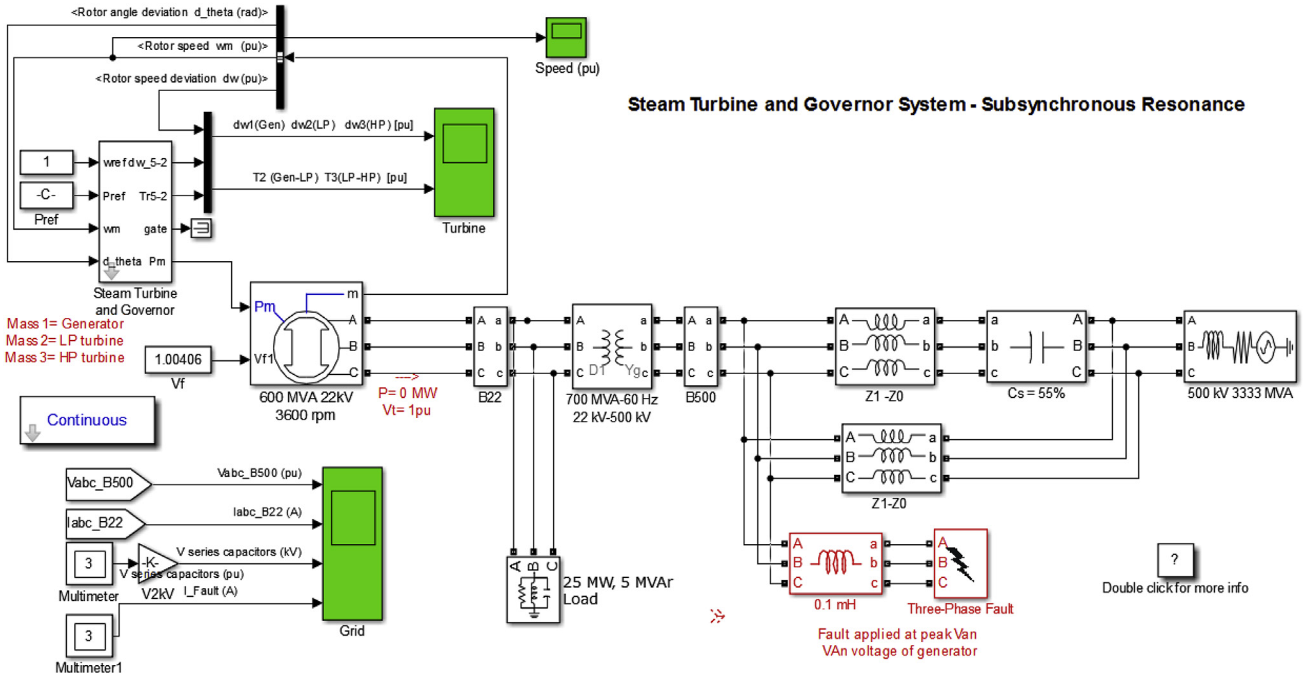

Fig. 3. Case 1 model used for SSR simulation.

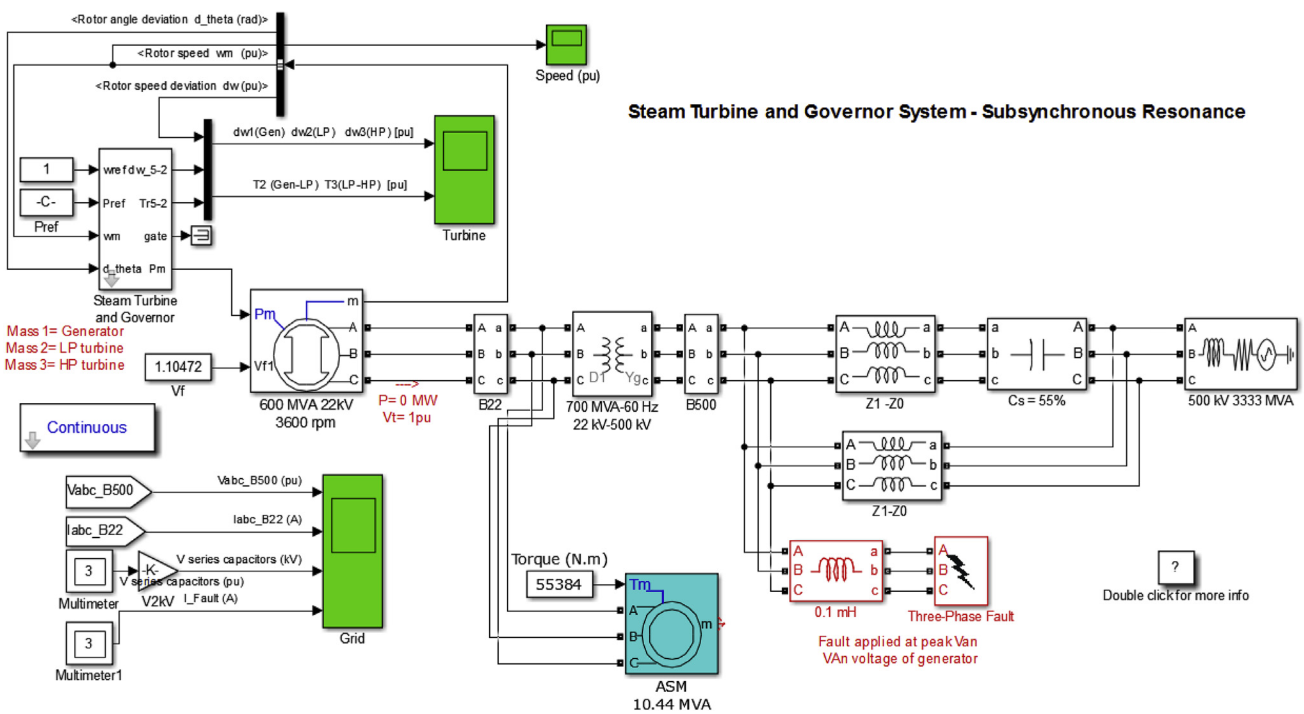

Fig. 4. Case 3 system used for SSR simulation.

on the normalized RCP rotational speed frequency (given as boundary condition of the SSR frequency), RCP mass flow, primary pressure and reactor power. The differential core pressure drop is analysed and presented.

3. Results

The main results for models described in Section 2.1 are given on Fig. 5 through 7.

Fig. 6A shows that SSR in benchmark system results in fast increase of the generator rotational speed and reaches turbine trip value, set on 110% nominal speed (relative speed 1.1 on Fig. 6A), in 11.4 s.

The introduction of active and reactive load in Case 1, as shown on Fig. 5C, practically has no impact on the speed increase compared to the benchmark system. From Fig. 5A and C can also be seen, that change of RCP pump speed has proportional effect on mass flow through cold leg.

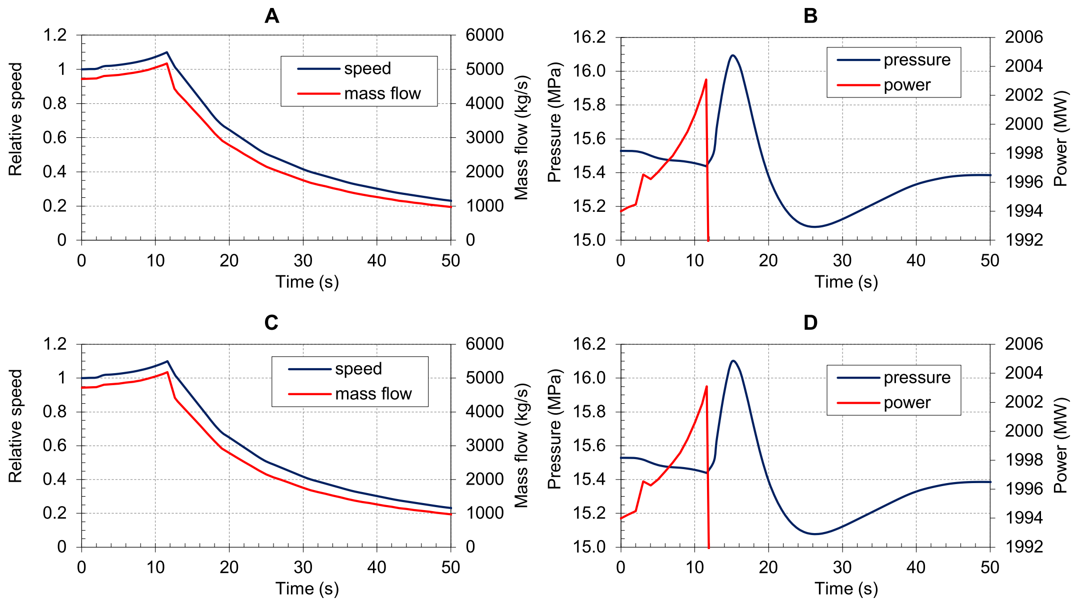

Fig. 5. Main parameters for benchmark SSR (upper figures) and Case 1 (lower figures). Obtained RCP pumps speeds given on Fig. 5A, C, Fig. 6A and C were utilized in RELAP5 model as boundary condition.

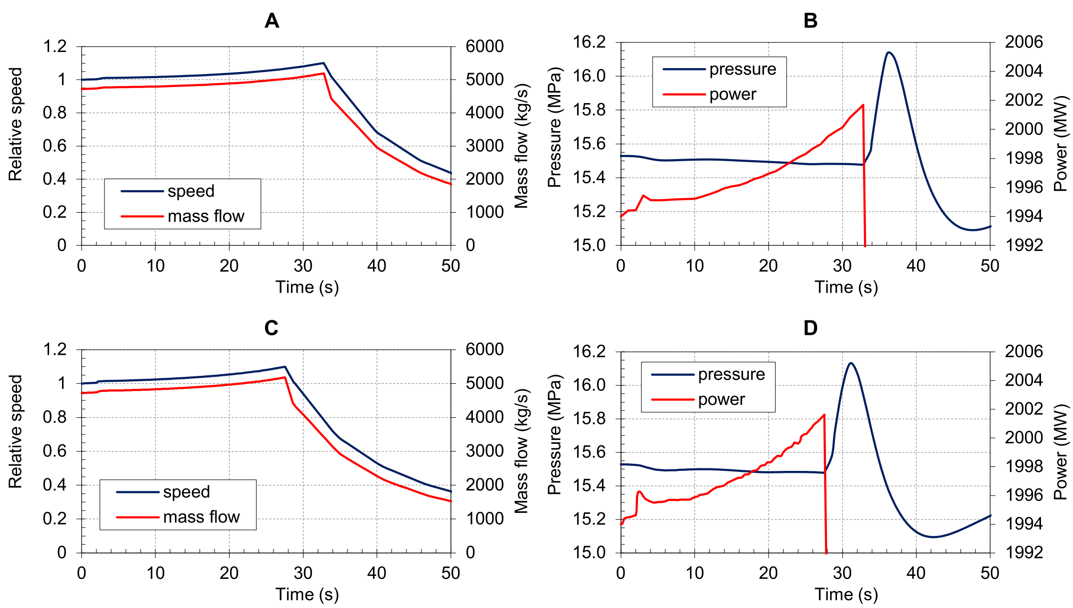

Fig. 6. Main parameters for Case 2 (upper figures) and Case 3 (lower figures).

Fig. 5B and D shows the primary pressure and power for the benchmark system and Case 1, respectively. The heat transfer from primary to secondary system improves with increased mass flow in primary coolant system. This results in decreasing temperature of the coolant and consequential decreasing of primary pressure as showed on Fig. 5B and D. The decreased coolant temperature results in positive reactivity insertion and reactor power increase. At the time of turbine trip on overspeed signal, causing reactor trip, the reactor power drops. The pressure in primary system starts to increase in the initial 5 s due to power mismatch (more heat is produced in core than transferred to the steam generator). After initial 5 s this is reversed resulting in drop of pressure as shown on Fig. 5B and D. Decay heat removal function through steam generator relief valves is maintained with the start and operation of the auxiliary feedwater pumps.

The connection of the AC motor in Case 2, which simulation is shown on Fig. 6A, results in slower increase of the rotational speed. Consequently, the trip speed is reached in 31.9 s following the start of the simulation. The increase of the AC motor size in Case 3, as shown on Fig. 6C, results in a bit faster increase of speed compared to the Case 2. The trip speed is reached in 27.3 s following the start of the simulation. Obtained trends of the pressure and reactor power given on Fig. 6B and D for Case 2 and Case 3, respectively, are similar to for benchmark and Case 1 trends.

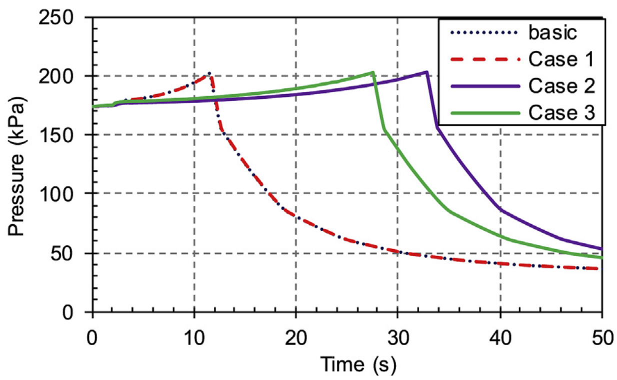

Fig. 7. Pressure drop for basic (benchmark SSR), Case 1, Case 2 and Case 3 models.

Fig. 7 shows the pressure drop across the core obtained for basic model and Cases 1 to 3. The pressure drop trend, as shown on Fig. 7, follows the mass flow (which is following speed) trend of the RCP. Results for basic case and Case 1 are comparable. The pressure drop change for basic case and Case 1 is faster than for Case 3 and Case 2. The overall reactor core pressure drop (from bottom to top of the core) increase is, as shown on Fig. 7, relatively small. Therefore the event of core displacement or core barrel lift can be dismissed for analysed models and plant.

4. Discussion

Results presented in Section 3 show that SSR phenomenon is not posing major challenge for the NPP safety. The assessed parameters of the primary coolant system are below reactor trip parameters set to assure that plant safe operating limits are not exceeded. The study is not considering the other aspects and consequences that can result from the SSR:

- Brittle fracture of turbine blade wells or portions of the turbine root resulting from stresses on turbine-generator shaft resulting from the SSR.
- Implications of the increased frequency on other electrical systems in the plant including safety related sections of the electrical system. Failure of the safety related electrical system can result in loss of all instrumentation and control with large implications on the plant safety.
- Type and speed of turbine control system will also have impact on the plant response. Therefore the plant specific study is necessary in order to assess the probability and implications of the SSR on the plant safety.

Considering the potential impact of the phenomena on plant safety it is recommended to investigate the feasibility and benefit of installation of frequency control and protection relay either on low or high voltage side of the generator step-up transformers buses.

The study demonstrates the capability of the RELAP5 model to simulate events that are outside the design basis envelope.

5. Conclusions

This paper analyses the implications of the subsynchronous resonance phenomenon on the nuclear power plant safety. The analysis is done with Simulink MATLAB® model for assessment of the reactor coolant pumps rotational speed and RELAP5 model for evaluation of the plant parameters.

Obtained results show that subsynchronous resonance phenomenon results in small change of the plant parameters used for reactor trip signals before reactor trip is initiated by turbine trip. The plant parameters are below the reactor trip values of the plant. The increase of the flow in reactor coolant system is proportional to the increase of the reactor coolant pumps speed. The small increase of the reactor power is managed by the removal of heat on secondary side and operation of auxiliary feedwater system. The core displacement or core barrel lift, based on small reactor core pressure drop, can be dismissed for analysed models and plant.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.01.002.

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