Sensitivity of Integral Reactor Configurations to Parametric Fluctuations

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1. Objective

- Focus on the reactor transient behaviors in the IAEA integral-PWR(i-PWR) simulator.
- Quantify sensitivities of the observable balance of plant performance parameters to fluctuations.
- Analysis of the oscillations and trends during nominal daily operation conditions, especially for the normalized power and generator load.

2. Summary of the i-PWR simulators features and capabilities

- i-PWR is one type of SMRs
- IAEA defines SMR electrical power level as below 300 MWe

- Advantages:
  - Reduce the emergency planning zone (EPZ)
  - Minify the number of vessels and pipes to decrease the leakage probability
  - i-PWRs have a larger volume of pressurizer and reactor coolant water inventory.
  - i-PWR pipes’ diameter is smaller than PWRs

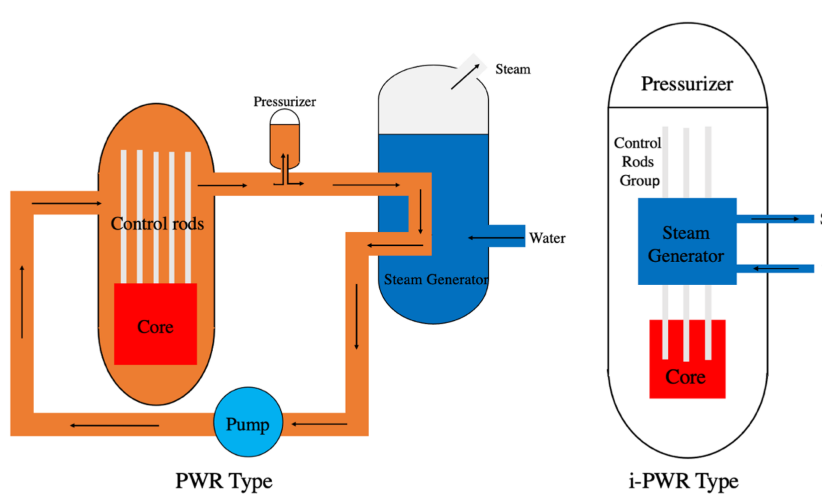

Figure 1. The main design differences between PWR (left) and i-PWR (right)

- IAEA SMR simulator:
  - Open Source.
  - Do not reflect a specific vendor’s design.
  - Easy to operate on PC.

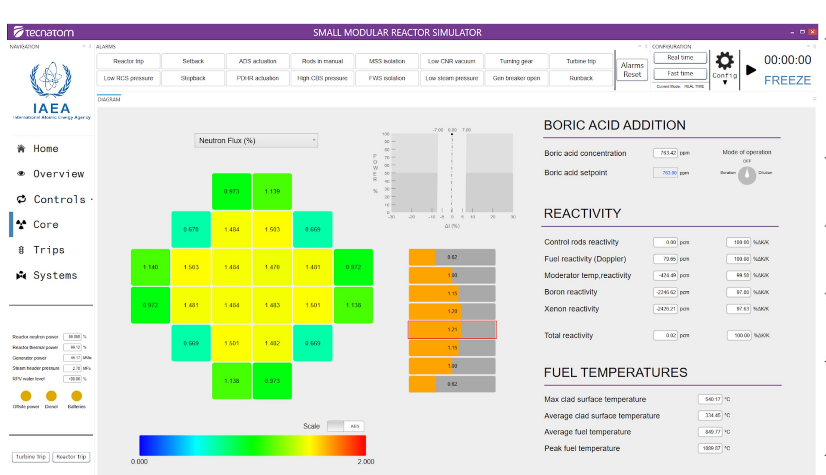

Figure 2. The reactor core overview of the IAEA model.

Simulator	IAEA	PCTRAN-NuScale	Modelica code-based model	Fortran based model	
Open source	O	X	X	X	X
Max reactor power (MWth)	150	160	160	500	150
Max generator load (MWe)	45	60	53	158	45
Neutronic model	NEMO[a]	Point Reactor Kinetic equation with six precursors			
Thermal hydraulic model	TRAC_RT[b]	Lumped-loop approach with two-phase critical flow	2-D conduction and conservation law		Hann's model
Steam Generator model	Helical	Helical	Helical	Helical	Three lumps
Coupling hybrid energy system	X	X	O	O	N/A
Environment platform	Windows	Windows	Matlab simulink	Matlab simulink	Siemens PTI PSS/E
Based design model	N/A	NuScale	N/A	IRIS, NuScale, SMART	NuScale
Developer	Tecnatom	Micro-simulation Technology	ORNL, INL, NC state university	ORNL, INL	IEEE

Table 1 The overview and comparsion of i-PWR simulators.

3. Introduction of IAEA simulator

- The IAEA i-PWR model simulator was developed by Tecnatom in 2017.
- The build-in fuel is UO_2 with 4.95% enrichment with 17X17 fuel pins with 24 assemblies. (Figure 2)
- 150 MWth and 45 MWe (when reactor runs full power of the reactor)
- Saturation temperature is 344.8℃ at 15.5 MPa
- Helical type steam generators
- Passvie safety system includes ADS, PDHR, PIS, and GIS. (Figure 3)
- Advantages of the IAEA SMR simulator:
  - Open Source.
  - Do not reflect a specific vendor’s design.
  - Easy to operate on PC.

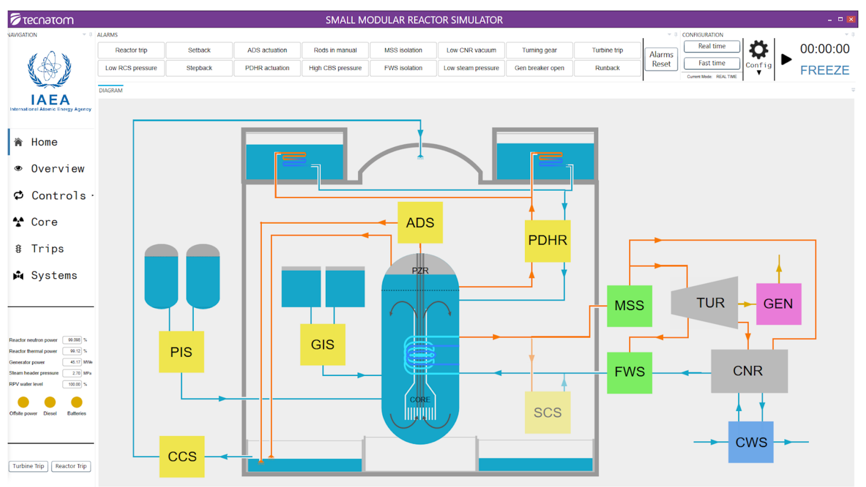

Figure 3. The overview scope of the IAEA simulator.

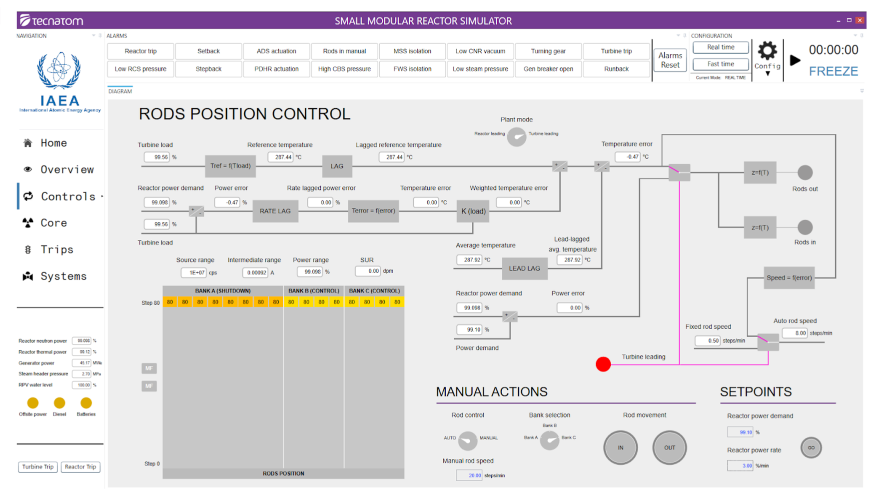

Figure 4. The rods position’s control panel of the control system.

4.Methods and Scenarios

Category	Scenarios	Normalized power setpoint (%)	Operating time (hr)	Parameters	Annotation
Base-load					
	1	100	6		
	2	100	12		
	3	100	24		
	4	100	48		
	5	100	72		
	6	75	6	Generator load, Normalized power, Average generator load, Average normalized power, Range of generator load, Range of normalized power, Standard deviation of generator load and Standard deviation of normalized power	
	7	75	12		
	8	75	24		
	9	75	48		
	10	75	72		
	11	50	6		
	12	50	12		
	13	50	24		
	14	50	48		
	15	50	72		
	16	25	6		
	17	25	12		
	18	25	24		
	19	25	48		
	20	25	72		
Load-following					
	1	100-50-100	12-3-6-4	Generator load, Normalized power, Average generator load, Average normalized power, Range of generator load, Range of normalized power, Standard deviation of generator load and Standard deviation of normalized power	Based on France daily operation
	2	100-50-100	12-12		Based on Giorgio Locatelli et.al and Germany recommended daily operation

- Select plant mode
- Load initialization (IC#1)
- Natural circulation status
- Select auto mode of control rods
- Boric concentration uses the simulator default (763ppm)
- Set power demand points to achieve my scenarios setups
- Reactor power rate:
  - Base load: 3%/min
  - Load-following: 3~5%/min

Table 2
The overview of scenarios setup descriptions and parameters will be analyzed.

6. Results

Base load:

- When the normalized power setpoints decrease, the ranges have an incrementing trend.
- The 75% cases and 50% cases have the opposite trend of 100% normalized power case
- The normalized power at 25 % of cases has a maximum standard deviation value at running 6 hours.
- 75% of normalized power cases have a bigger standard deviation for 24 hours situation
- The 50% normalized power running 48 hours has a larger value of standard deviation.

Setpoint of normalized power (%)	Time (hr)	Range (%)	Mean (%)	Standard deviation (%)
100	6	1.6232	97.6126	0.1064
	12	1.6213	97.6282	0.0825
	24	1.9621	97.5028	0.1744
	48	2.7536	97.1414	0.4095
	72	3.4162	96.7771	0.6523
75	6	2.5118	75.0420	0.3437
	12	2.5278	75.0248	0.3609
	24	2.5941	75.0044	0.5499
	48	2.6057	75.1703	0.4712
	72	2.5978	75.1544	0.4010
50	6	2.5849	49.9514	0.4103
	12	2.6334	49.9743	0.4144
	24	2.6859	49.9856	0.4576
	48	3.1650	50.0468	0.5910
	72	3.1703	50.1769	0.5275
25	6	13.5660	20.0192	5.9461
	12	13.5709	16.8194	5.7291
	24	13.6537	18.2907	5.7824
	48	13.8350	21.6530	5.3168
	72	13.8264	22.8423	4.5773

Table 2 The statistical normalized power results of steady state scenarios

- Max standard deviation values of generator load are reactor operating 6 hours or 72 hours cases
- Max range values are either operating reactor for 24 hours or 72 hours
- The normalized power oat full power level, and the generator load at 75% power level have smaller range values
- In brief, 100% normalized cases have smaller standard deviation values in the normalized power and the generator load
- Only normalized power at 100% and 25% have strong relative to normalized power and generator load’s range and standard deviation

Setpoint					
Normalized Power (%)	Ideal Generator load (MW)	Time (hr)	Range (MW)	Mean generator load (MW)	Standard deviation (MW)
100	45	6	1.0084	44.2241	0.0507
		12	1.0125	44.2315	0.0388
		24	1.1647	44.1745	0.0806
		48	1.5545	44.0028	0.1946
		72	1.8704	43.8276	0.2997
75	33.75	6	0.5800	32.8051	0.1224
		12	0.5819	32.7693	0.1212
		24	0.5866	32.7100	0.1109
		48	0.5737	32.7475	0.0984
		72	0.5795	32.7287	0.0936
50	22.5	6	0.7778	20.2318	0.1331
		12	0.8121	20.1901	0.1283
		24	0.8158	20.2211	0.1340
		48	0.8024	20.3588	0.1817
		72	0.8061	20.4472	0.1909
25	11.25	6	7.8123	6.7790	2.6482
		12	7.7331	5.3714	2.5531
		24	7.8462	5.9908	2.5788
		48	8.1013	7.7749	2.6048
		72	8.0450	8.3930	2.2937

Table 3 The statistical generator load results of steady state scenarios.

Load-following:

- The average 50% normalized power and generator load of France's daily operation for six hours is slightly less than Germany's recommended operation for 12 hours
- For 100% of normalized power, both values of the normalized power and the generator load are similar.
- For the range side, the generator load at 50% setpoint power level of Germany recommending operation has a remarkably large value
- For standard deviation, it can be noticed that 100% normalized power setpoint result of the normalized power and the generator load are noticeable smaller than 50 %. This relationship also matches the steady-state result owing to the function of the pressurizer and main steam valves to adjust the steam input.
- It shows the range values of 50 % are larger than 100% no matter in France or Germany recommended setups that are correlative to the normalized power of steady-state scenarios

Type of daily operation	Operating time	Normalized power setpoint	Average		Range		Standard deviation	
France			Normalized power (%)	Generator load (MW)	Normalized power (%)	Generator load (MW)	Normalized power (%)	Generator load (MW)
	6	50%	49.9924	20.2199	2.957	1.7748	0.3927	0.1365
	12	100%	97.6280	44.2314	1.662	1.0123	0.0818	0.0389
Germany								
Recommend	12	50%	50.0254	20.2259	2.7181	5.4993	0.4141	0.2130
	12	100%	97.6249	44.2301	1.6227	1.0070	0.0848	0.0407

a. The values are based on the IAEA simulator digital results.

Table 4 The statistical normalized power and generator load results of load following scenarios.

7. Conclusion

- The oscillations of normalized power are relative control rod worth and xenon reactivity fluctuations.
- Lower normalized power level is more sensitive to neutron poision.
- 100% of cases have a smaller standard deviation of normalized power and generator load.
- 75% and 50% of cases’ transient behaviors are similar. The 50% of cases present delayed responses.
- 25% of cases are deeply affected by neutron poisons.
- The fluctuations of generator load are relative to normalized power and the standard deviation of generator load is lower than normalized power.
- The standard deviation of normalized power becomes larger when increasing simulation time except in 25% cases.
- Both load-following cases’ range values of normalized power and generator load at lower power levels are larger than at higher power levels.
- The load-following cases’ statistical normalized power and generator load results are similar to base-load cases.

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