Developing Dynamic Models For Nuclear-Based Small Modular Reactors (SMRs) For Load-Following Operation & Electrical Side Transient/Dynamic Analysis of The SMR Power Plants in RTDS

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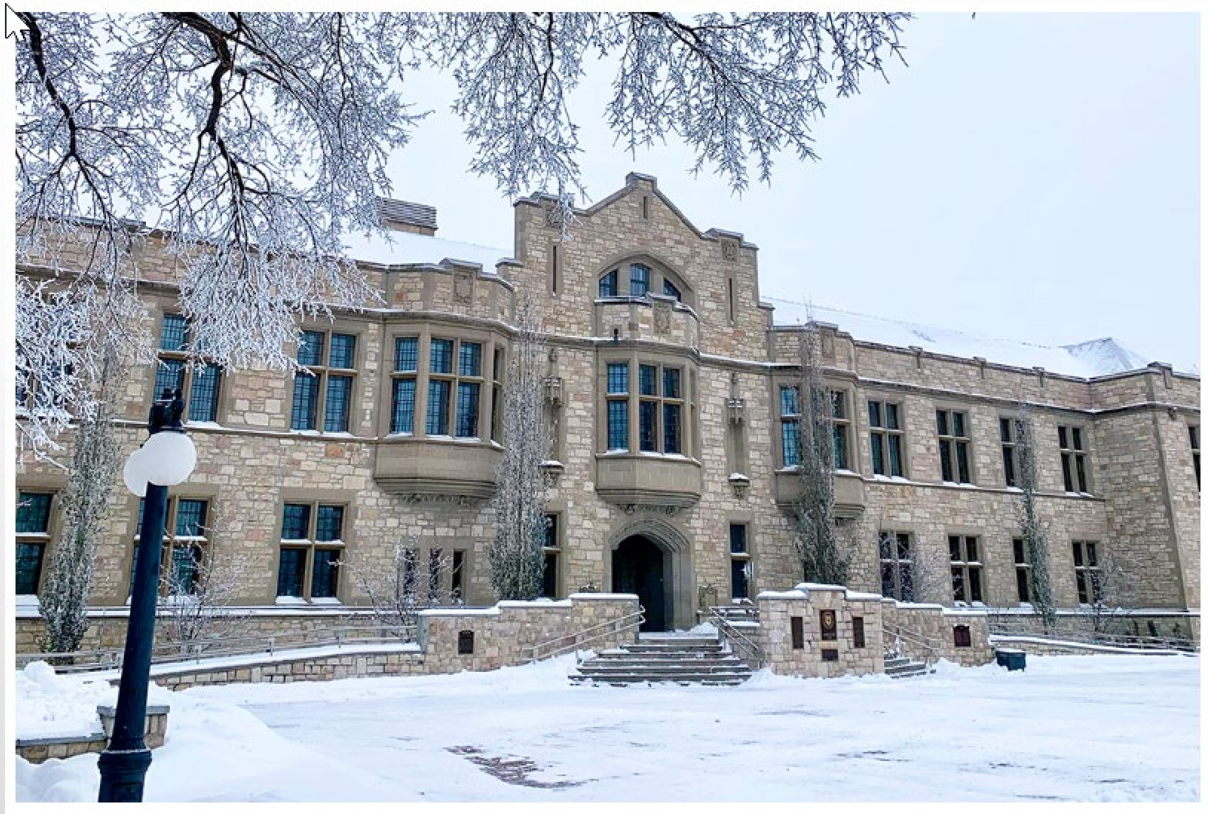
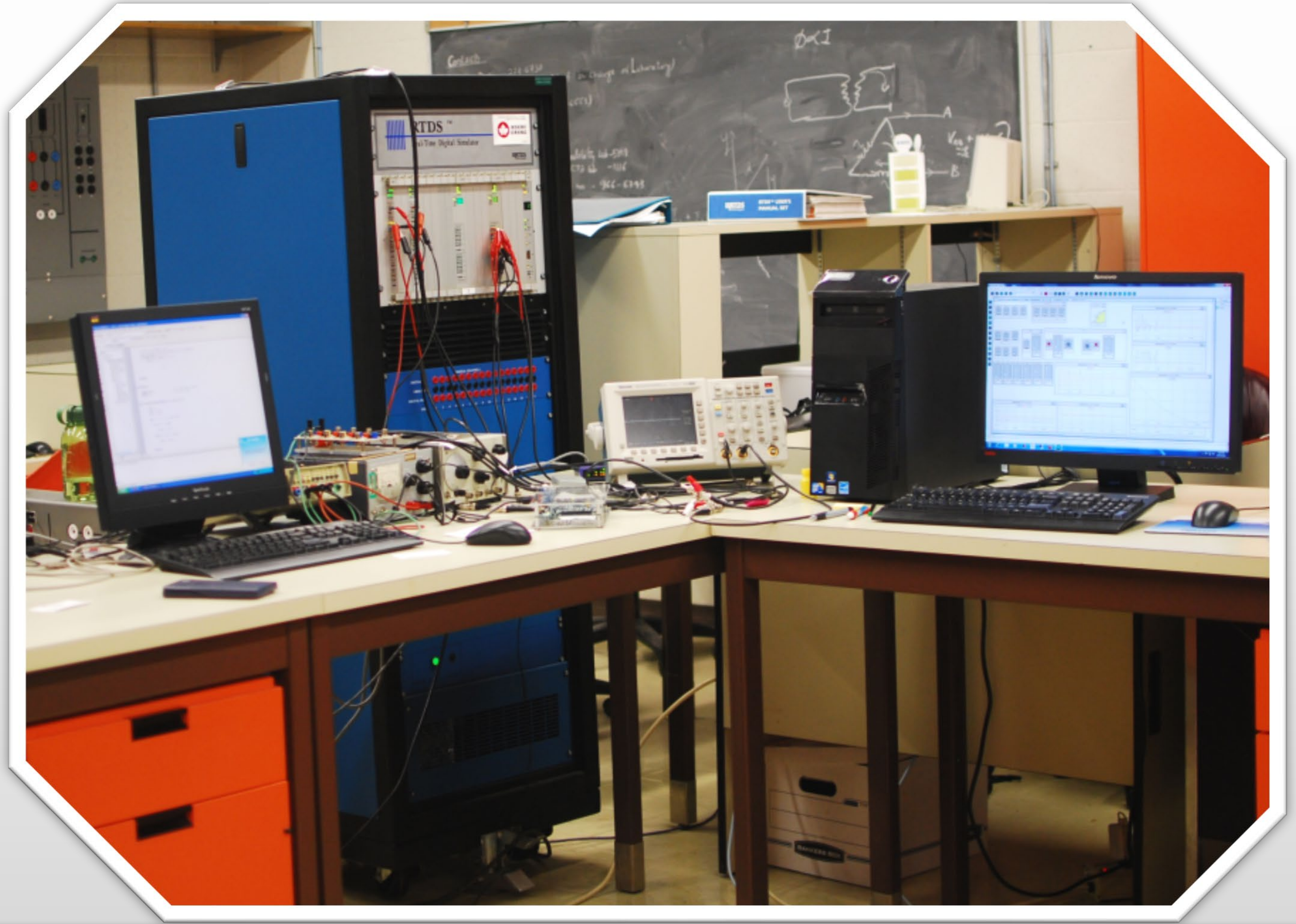


Real-Time Power System Simulation Lab



Talk Outline:

- Background: Small Modular Reactors (SMRs) for Power Generation
- Part I: SMR Dynamic Model for Power System Studies
- Part II: SMR-RES Hybrid Energy System for Electricity and District Heating (DH)
- Part III: SMR-RES Energy System for Electricity and Hydrogen
- Conclusions

Background

Clean energy movement

- ✓Ageing fossil-fuel-based thermal plant
- ✓Diesel generators in remote/off-grid communities

Renewable energy sources (RESs)

- ✓Wind, photovoltaics (PVs)
- ✓ Intermittency and uncertainty

Small Modular Reactor (SMR)

- ✓Small (few MW-300 MW), modular, enhanced safety features, flexible operation, wide energy applications

SMR Research and Development

- ✓More than 100 designs under development[1]
- ✓Five SMRs in an advanced stage of development/operation[1]
- ✓Nuclear (SMR)-Renewable hybrid energy system- INL, NREL, MIT[2]

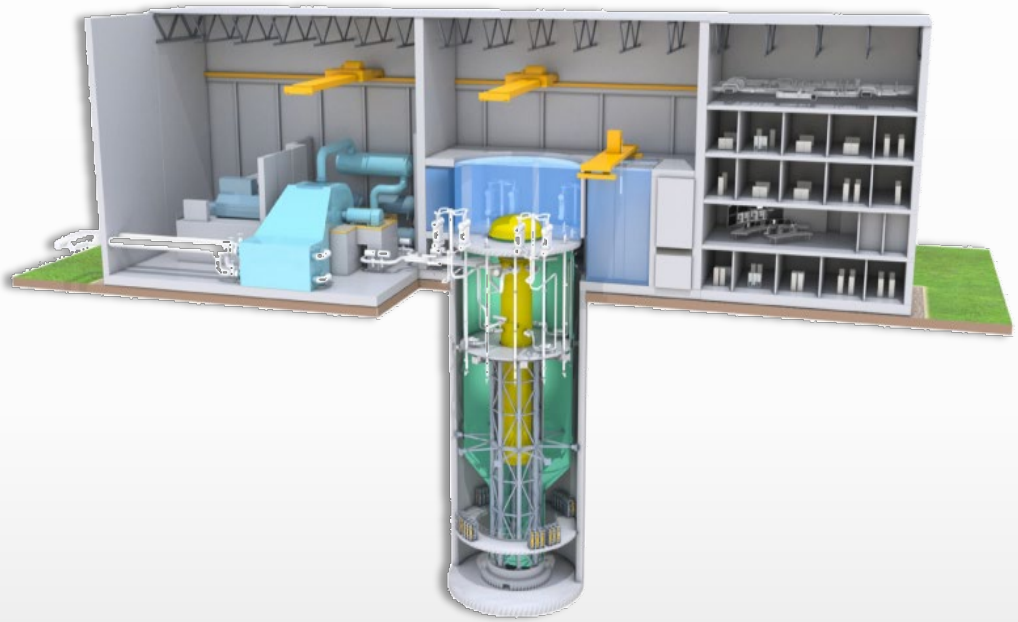


Fig 1: BWRX-300 small modular reactor

[1] "Small Modular Reactors: Advances in SMR Developments 2024," International Atomic Energy Agency, Vienna

[2] "Nuclear and Renewable Energy Synergies Workshop: Report of Proceedings," Joint Institute for Strategic Energy Analysis (JISEA), Colorado, 2011

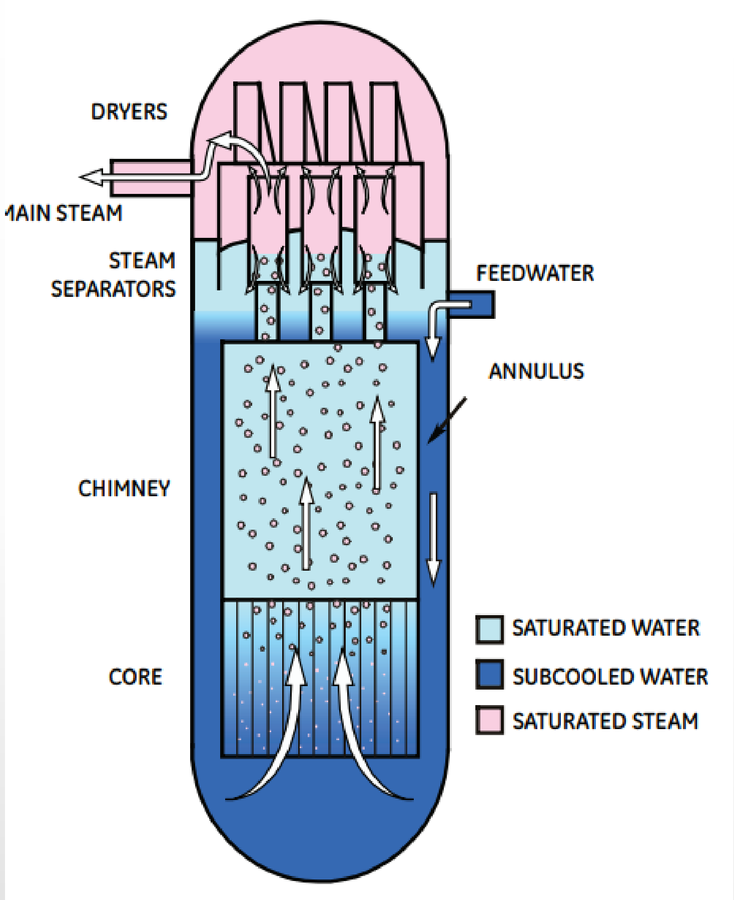
SMR Reactors

- SMRs: < 300 MWe, offer inherent & passive safety features, reducing risk of severe accidents.
- A large variety of SMR designs:
  - Water-cooled (land based) - High-temperature gas-cooled
  - Water-cooled (marine based) - Molten salt
  - Fast neutron spectrum - Micro-sized

Small Modular Reactors (SMRs)

- BWRX-300 can be constructed in 24-36 months while achieving an approximate 90 percent volume reduction in plant layout.
- Safety: Natural circulation and passive cooling.
- Steam condensation and gravity allow the BWRX-300 to cool itself for a minimum of seven days without power or operator action

Natural Circulation



- Because hot water is less dense, it rises through the core while the cool water flows down to the bottom of the core. These natural differences in density create circulation.
- Improvement is accomplished by the removal of recirculation pumps and associated motors, piping, valves, heat exchangers, controls, and electrical support systems that exist with forced circulation.

Electric Grid Operation Challenges with Renewable Energy Transition

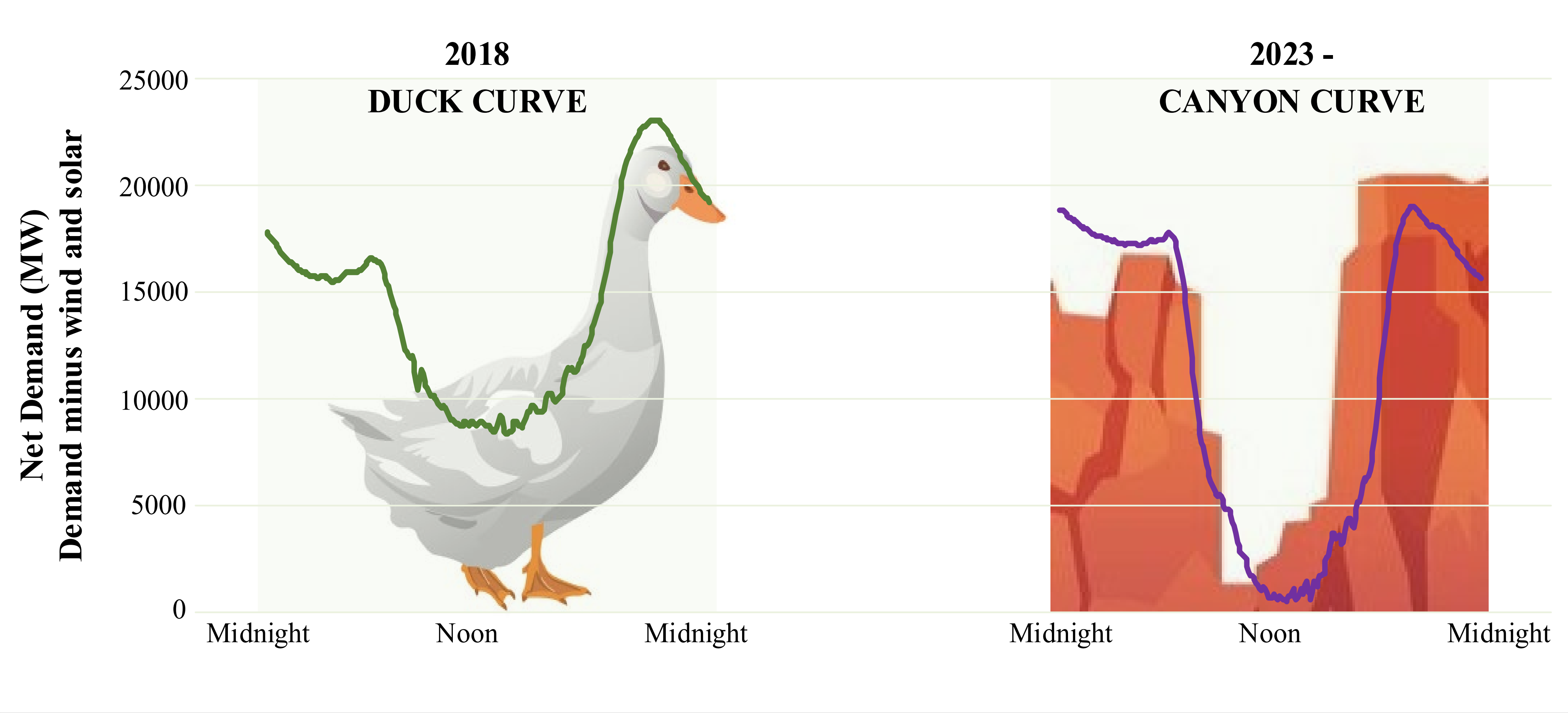
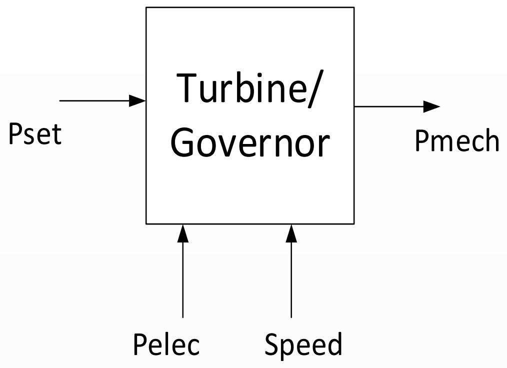


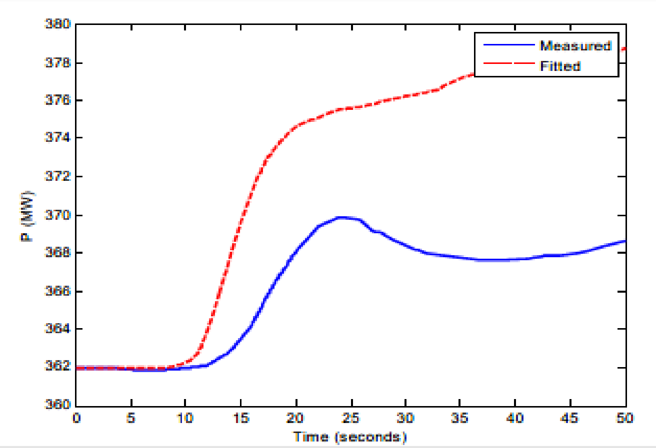
Fig 2: Duck and canyon curve, Source: Electric Power Research Institute (EPRI)

SMR Dynamic Model

- Turbine-governor models in power system simulations
  - Neglect the pressure transient
  - Consider mechanical power a linear function of valve position

- Approximations Only Valid for Small Disturbances





Background: Conventional NPP Dynamic Models

- CRIEPI, Japan based Light Water Reactor (LWR) Dynamic Models for Short-Term Dynamics [2].
  - Disturbance of interest: Faults isolating the nuclear plant from electrical grid.
- CRIEPI-EPRI-OH based LWR Model for Medium- to Long-Term Dynamics [3].
  - Disturbance of interest: Frequency and voltage disturbance affecting the output of auxiliary pumps.
- Pressurized Water Reactor (PWR) Model Simulation for Smaller Disturbances [4].

[2] T. Ichikawa and T. Inoue, “Light Water Reactor Plant Modeling for Power System Dynamics Simulation,” IEEE Trans. on Power Systems, May 1988

[3] T. Inoue, T. Ichikawa, P. Kundur, and P. Hirsch, “Nuclear Plant Models for Medium- to Long-term Power System Stability Studies,” IEEE Trans. on Power Syst., Feb 1995.

[4] S. E. Arda and K. E. Holbert, “Implementing a Pressurized Water Reactor Nuclear Power Plant Model into Grid Simulations,” IEEE PESGM, October 2014.

SMR Dynamic Model

- SMR dynamic simulation model
  - ✓ 45 MW (160 MWth) NuScale integral PWR (iPWR)
  - ✓ Reactor core, primary coolant circuit, steam generator and secondary coolant circuit
  - ✓ Integrated with modified GGOV1 turbine governor model
  - ✓ The GGOV1 model assumes a constant steam pressure, and linear relationships between the governor signal, valve position and mechanical output of the turbine
  - ✓ In the modified GGOV1, the governor signal is mapped to match the nonlinear valve model obtained from International Atomic Energy agency (IAEA) based iPWR simulator

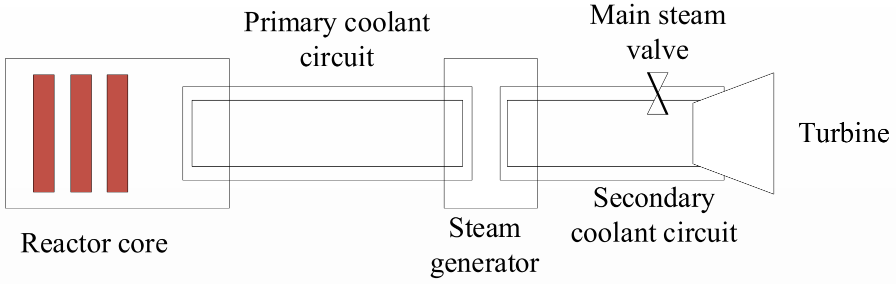


Fig 3: Reactor model components

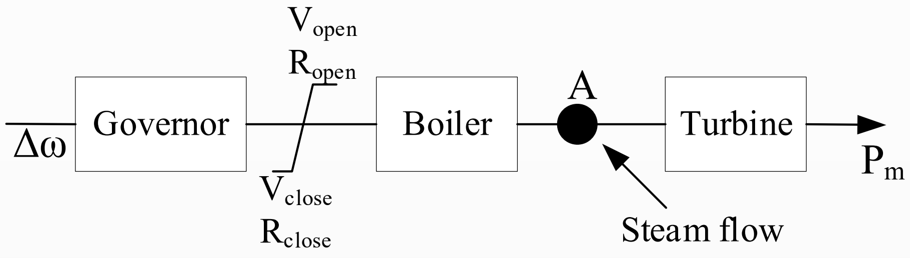


Fig 4: Turbine-governor system

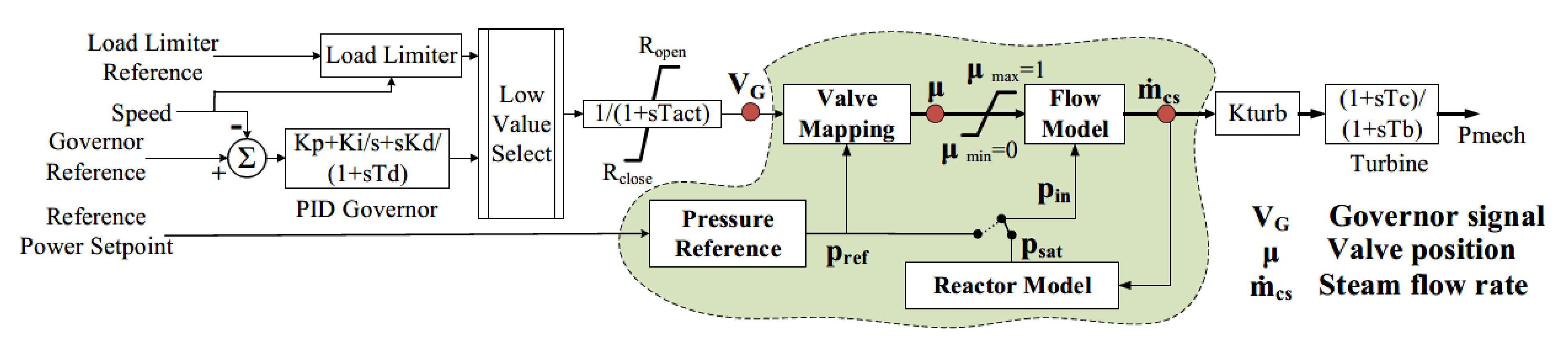


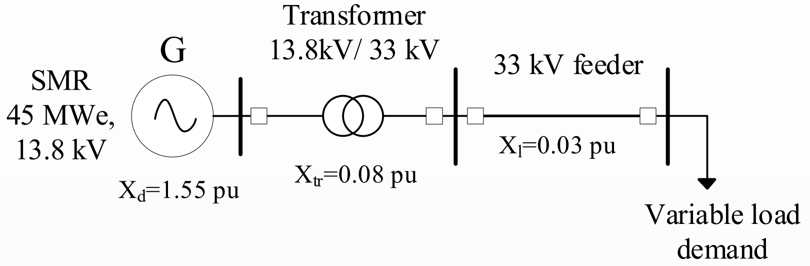
Fig 5: GGOV1 modified and integrated with the SMR model, shaded region shows the modifications with new module

SMR dispatch while following system load changes

- Reactor side and power side responses, for sudden load changes

Legend
- Case I- Without reactor
- Case II- with uncontrolled reactor
- Case III- with controlled reactor

- Three cases: Case I- Without reactor, Case II- with uncontrolled reactor, Case III- with controlled reactor
- Load variation:
  - At t=0 sec: SMR at 100% rated electrical output (REO).
  - At t=20 sec: Load decreases by 20% REO.
  - At t=400 sec: Load increases by 20% REO.
- SMR is operated in isochronous mode.
- Frequency recovered state: 60 ± 0.5 Hz.
- Valve operation rate limits: ±80% REO/min.
- Key observations:
  - Frequency recovery: T1 = 43 sec (23 sec), T2 = 81 sec (61 sec), T3 = 70 sec (50 sec)
  - Inaccuracies in frequency response without reactor
  - Sluggish frequency response with uncontrolled reactor
  - Case- II: Average temperature will not remain constant.
  - Case- III: Steam pressure recovers by 0.38 MPa.
  - Uncontrolled reactor operation : Simpler but small range of control.



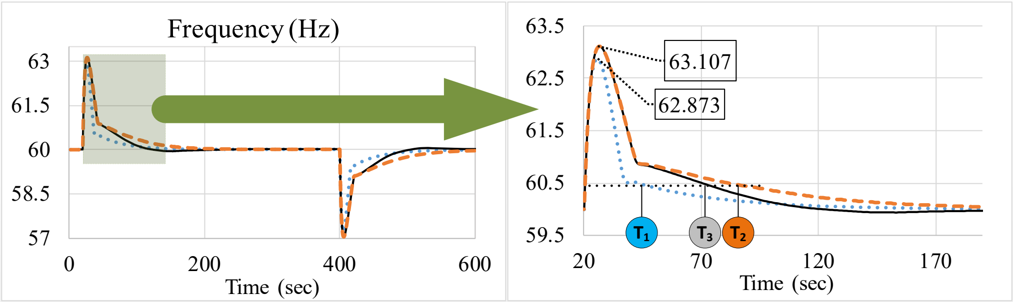


Fig 6: Power side responses

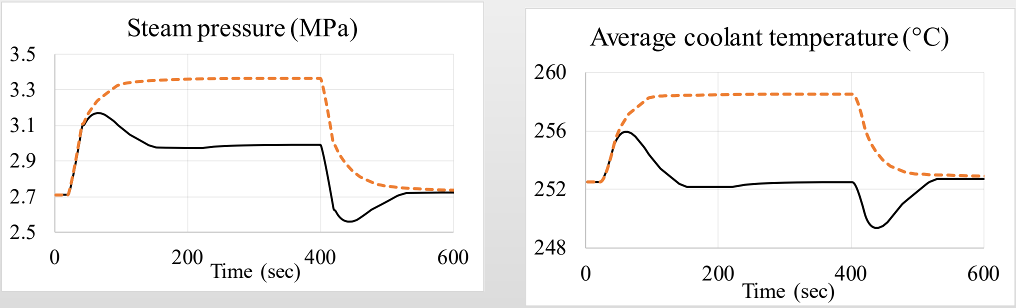


Fig 7: Reactor side responses

Findings of the Research: SMR Dynamic Model

- Approximate (Linear) Turbine-Governor Models Lead to Inaccurate Protection & Control Settings.
- Integrating the Reactor Side Modeling Improves the Accuracy of Electrical Side Responses Characteristics.
- Provides Thermal-Hydraulic Variables and Reactor Side Response.

SMR-RES Hybrid Electricity & District Heating (DH) System

- SMR's flexible operation challenged by various reactor specific issues.
- SMR design limits: Total variation, ramp rate, and number of maneuvers over reactor life
- Cogeneration boosts the load following capability by utilizing excess steam for heat application.
  - Steam excess to turbine supplied to DH system with thermal energy storage (TES)
  - Coarse-load shaping: Control rod operation
  - Load following: Steam extraction

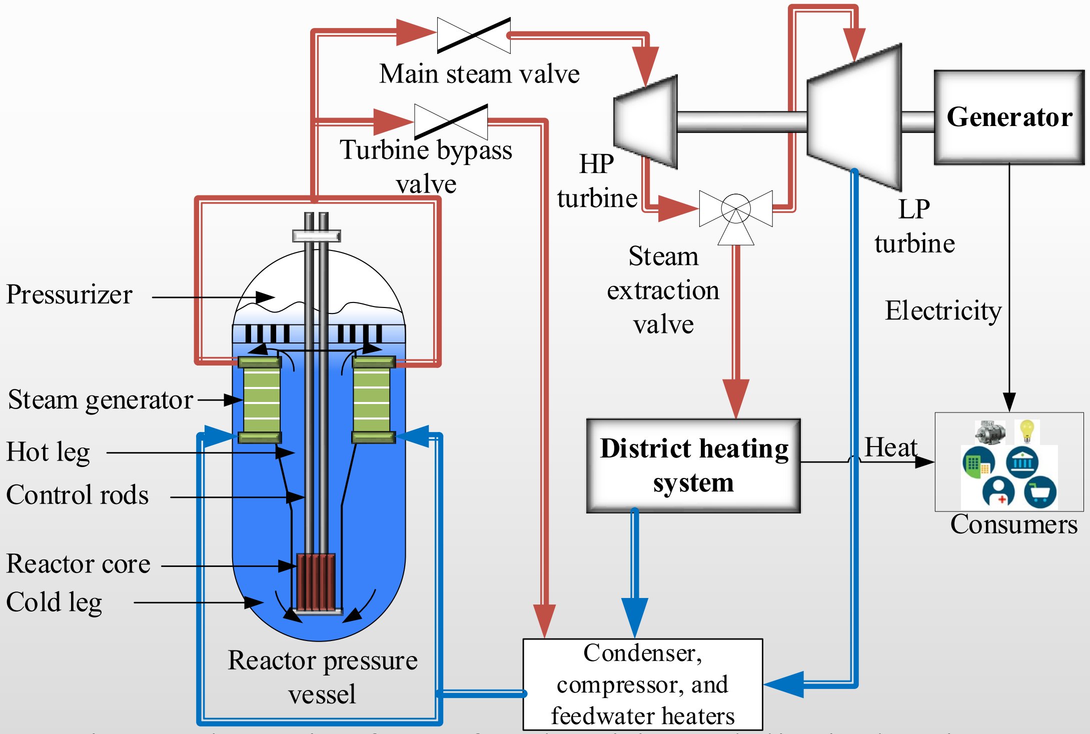


Fig 8: Schematic of SMR for electricity and district heating

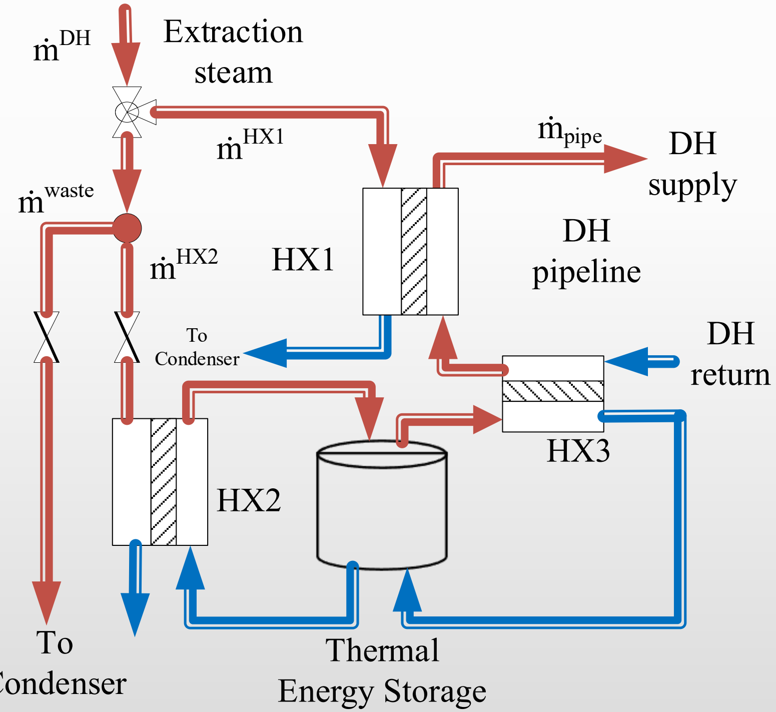


Fig 9: Block diagram of DH system

SMR-RES Hybrid Electricity & District Heating System: Case System

- Modified IEEE 30-Bus System
  - 33 kV network isolated from 230 kV side
  - Annual peak demand: Electrical (102 MW), Heating (80 MWth)
- Two Module SMR Plant (100 MW) at Bus 10
- Wind Plant at Bus 15
- Two PV Plants at Bus 17 and 27
  - PV power output profile (5-sec), wind power output profile (1-min), heat and electrical demand profiles (15-min)

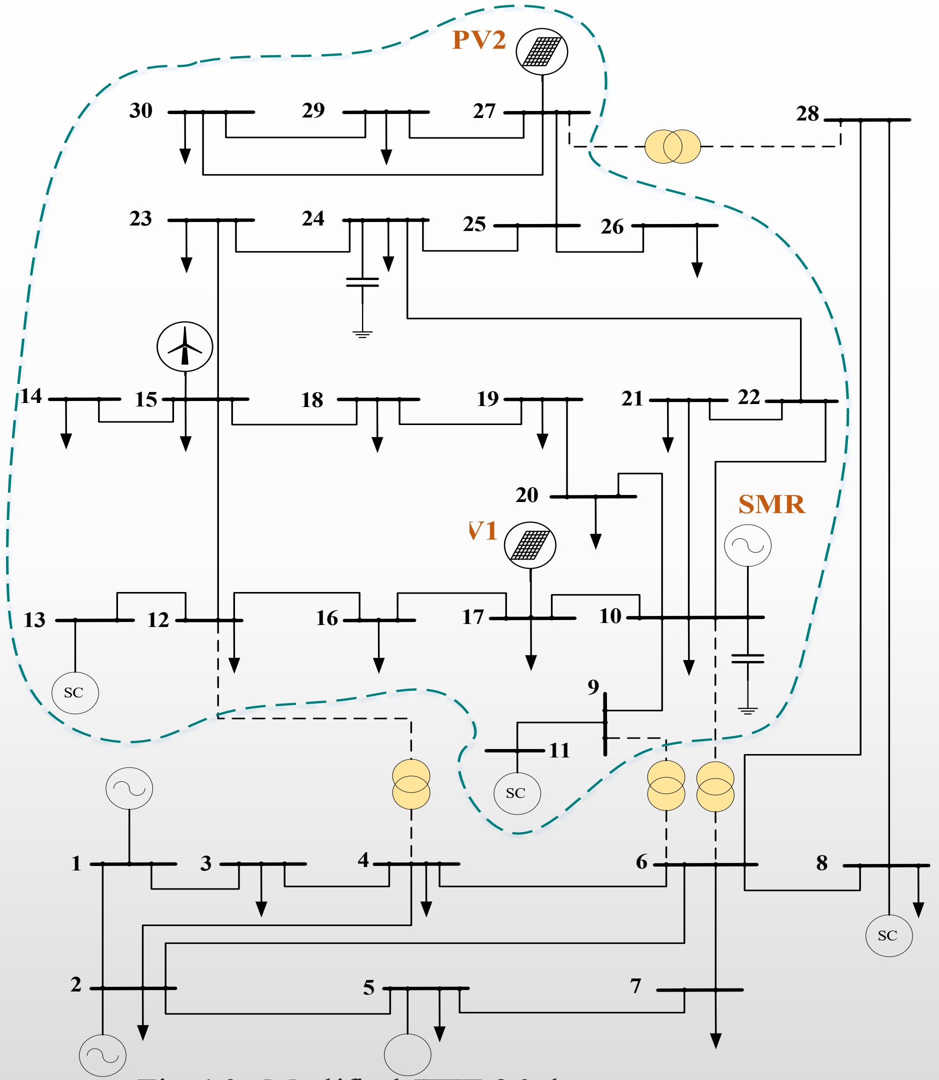
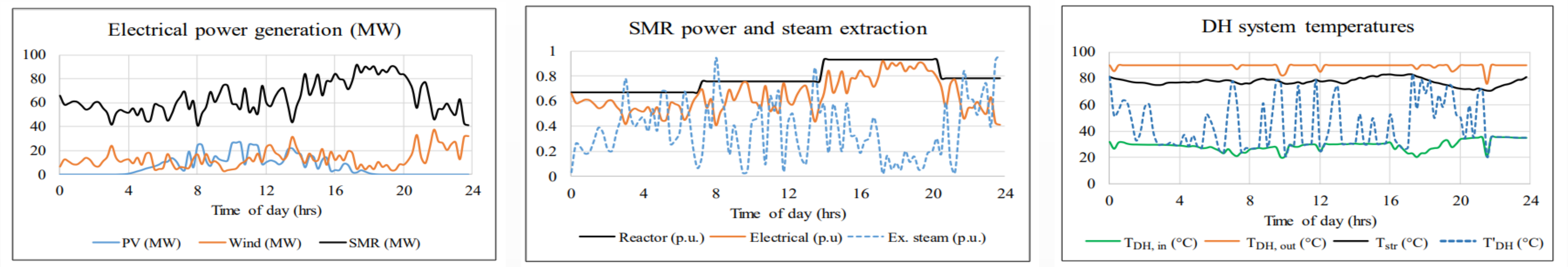


Fig 10: Modified IEEE 30-bus case system

SMR-RES Hybrid Electricity & District Heating System: Load-Following Results



(a) (b) (c)

Fig 11: Load following results for 24 hrs for electricity and district heating

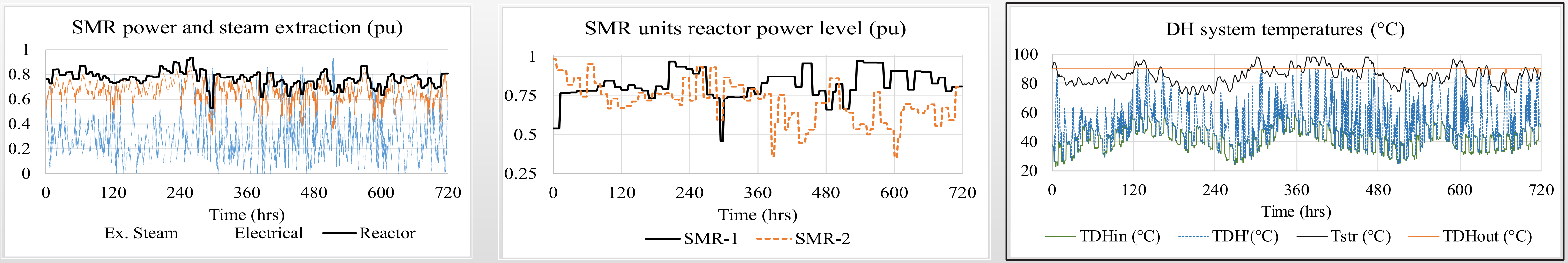


Fig 12: Load following results for one month for electricity and district heating

SMR-RES Energy System for Electricity and Hydrogen

- High-temperature steam electrolysis (HTSE) method for hydrogen generation
- HTSE as a variable electrical and thermal load
- Coarse load shaping
- Load following
- Tested in the same case system used for district heating (modified IEEE 30 bus system)

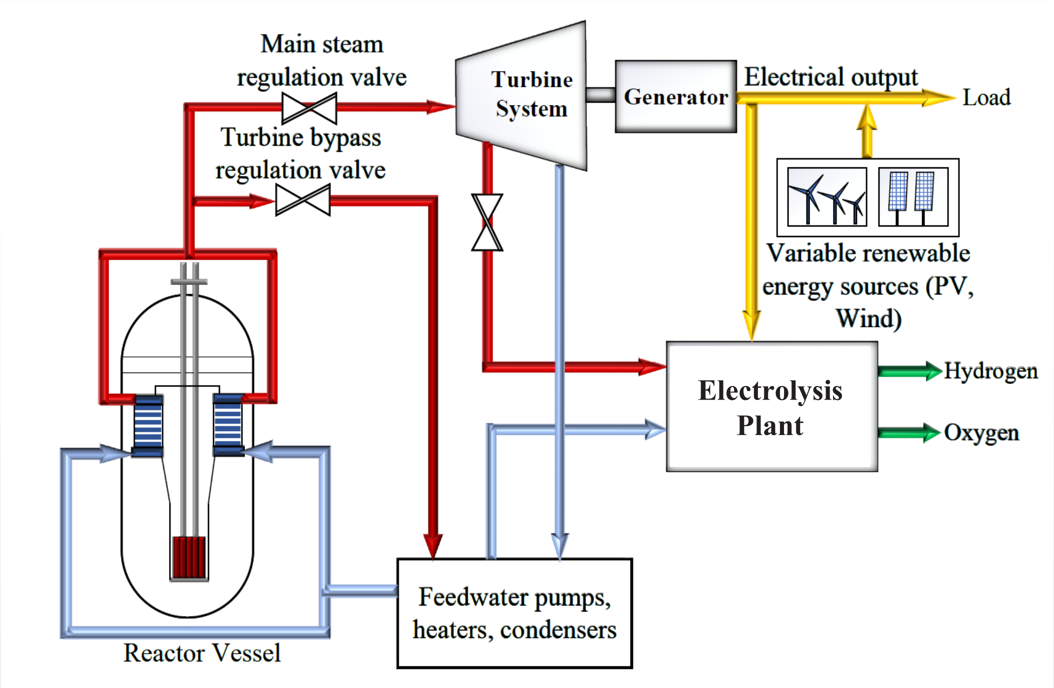


Fig 13: Schematic of SMR for electricity and hydrogen generation

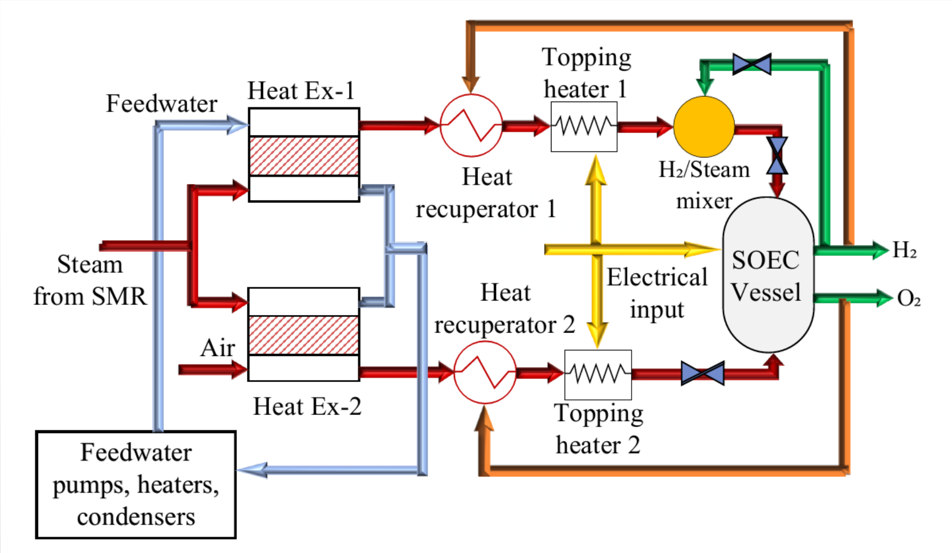
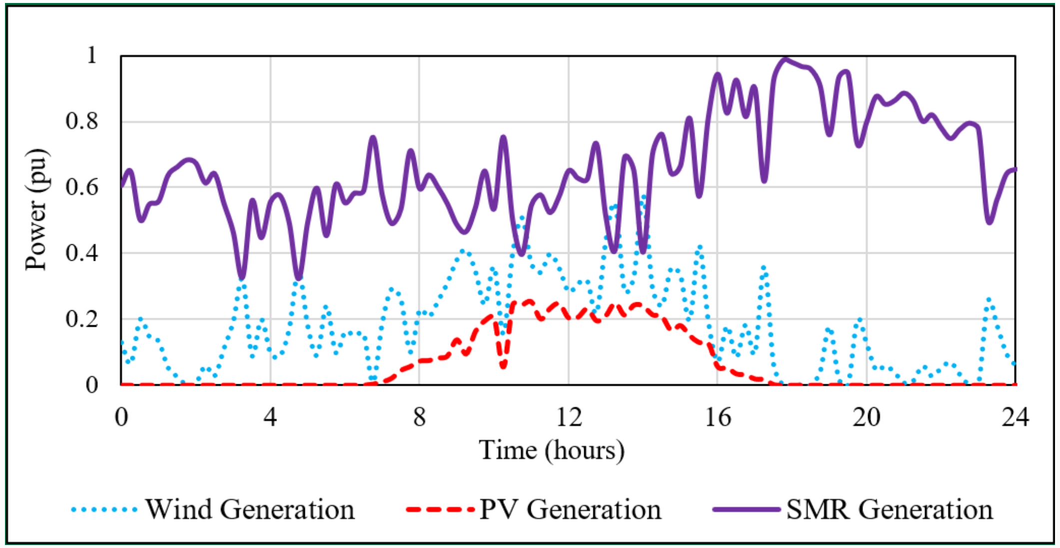
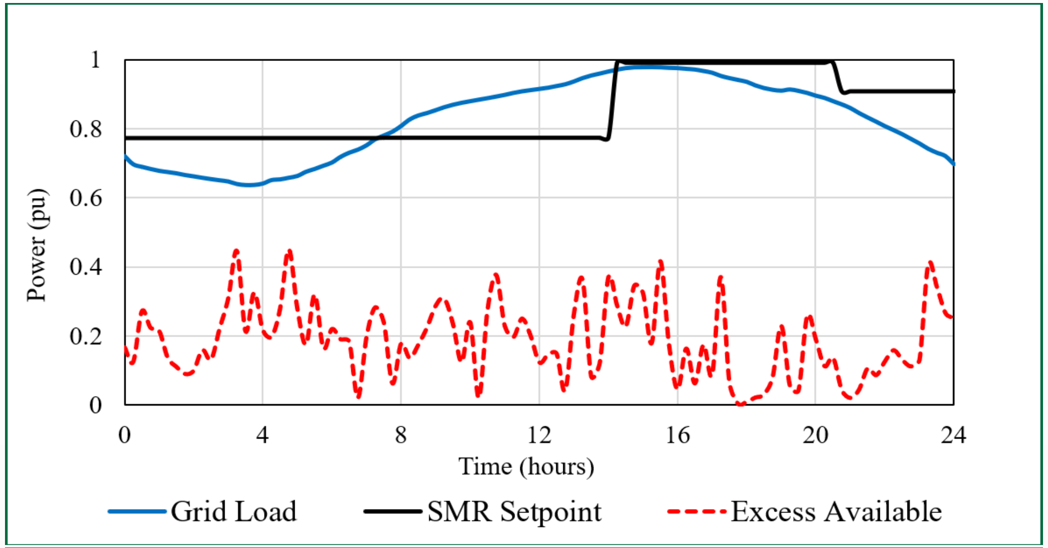


Fig 14: High temperature steam electrolysis for hydrogen generation

SMR-RES Energy System for Electricity and Hydrogen: Load-Following Results





Description	Values
Rated capacity	16 MWe
Minimum demand	1.60 MWe and 1.54 MWth
Steam utilization factor	80%
Hydrogen mixed in cathode stream	10 mol%
Average input flow rate (cathode)	0.73 kg/sec
Average H_2 production rate	0.06 kg/sec
Average O_2 production rate	0.46 kg/sec

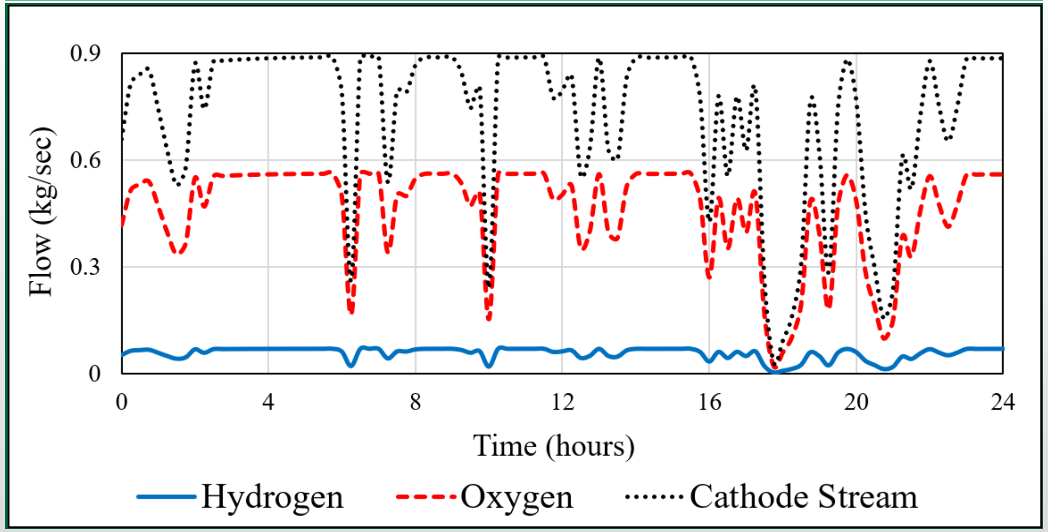


Fig 15: Load following results for electricity and hydrogen

Load-generation balance in microgrid

- Microgrid with distributed generation, load, and electrolyser

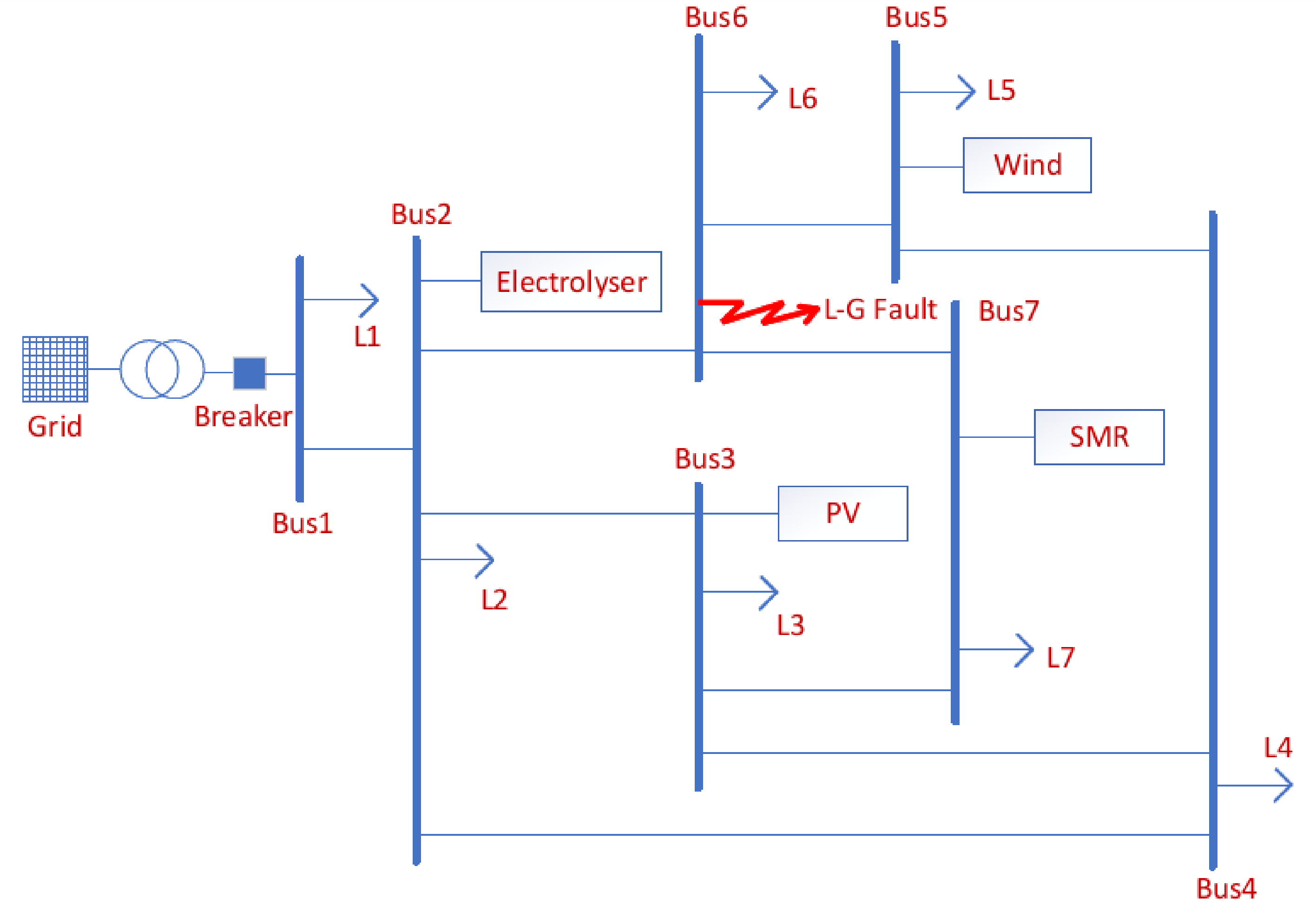


Fig 16: A simple microgrid layout

Load-generation balance in microgrid

- Normal operation of microgrid when connected to utility grid
- Islanded operation
- Islanded operation with fault in Bus-6

	Normal Operation		Islanded operation	
	Without electrolyser	**With electrolyser**	**Without application of fault**	**With application of fault**
Grid (138 kV)	0.66 MW	2.37 MW	-	-
DGs (13.2 kV)	6.72 MW	6.7 MW	6.217 MW	4.71 MW
Loads (13.2 kV)	7.15 MW	7.09 MW	4.67 MW	3.09 MW
Electrolyser (13.2 kV)	-	1.97 MW	1.7 MW	1.88 MW
Steady state values for electrolyser				
Hydrogen gen (mol/sec)	-	4.28	3.83	4.13
Oxygen gen (mol/sec)	-	2.14	1.91	2.06
Water in (mol/sec)	-	9.618	9.61	9.61
Current (kA)	-	12.92	11.56	12.47
Voltage (kV)	-	0.15	0.147	0.15
Power consumed (MW)	-	1.97	1.7	1.88
			Loads L1 and L2 shed even before application of fault, not enough generation	Load L3 and L4 also shed in addition to L1 and L2

Conclusions

- Developed SMR dynamic model to incorporate reactor dynamics in power system simulation (in PSS/E; RTDS).

- SMR-RES hybrid energy system for electricity and district heating (DH) (in RTDS; Currently working on RTDS Models)
  - Modeled integrated energy system with cogenerating SMR, DH system, thermal energy storage, wind and PV to analyse the flexible operation

- SMR-RES hybrid energy system for electricity and hydrogen generation (in PSS/E, RTDS)
  - Modeled integrated energy system with cogenerating SMR, HTSE system, wind and PV to analyse the flexible operation while generating electricity and hydrogen

- Load generation balance analysis of a sample microgrid system incorporating DGs and electrolyser for hydrogen generation (in PSS/E, RTDS)


Thank you!