Electricity and Water Do Mix: Interdependent Electric and Water Infrastructure Modeling, Optimization and Control

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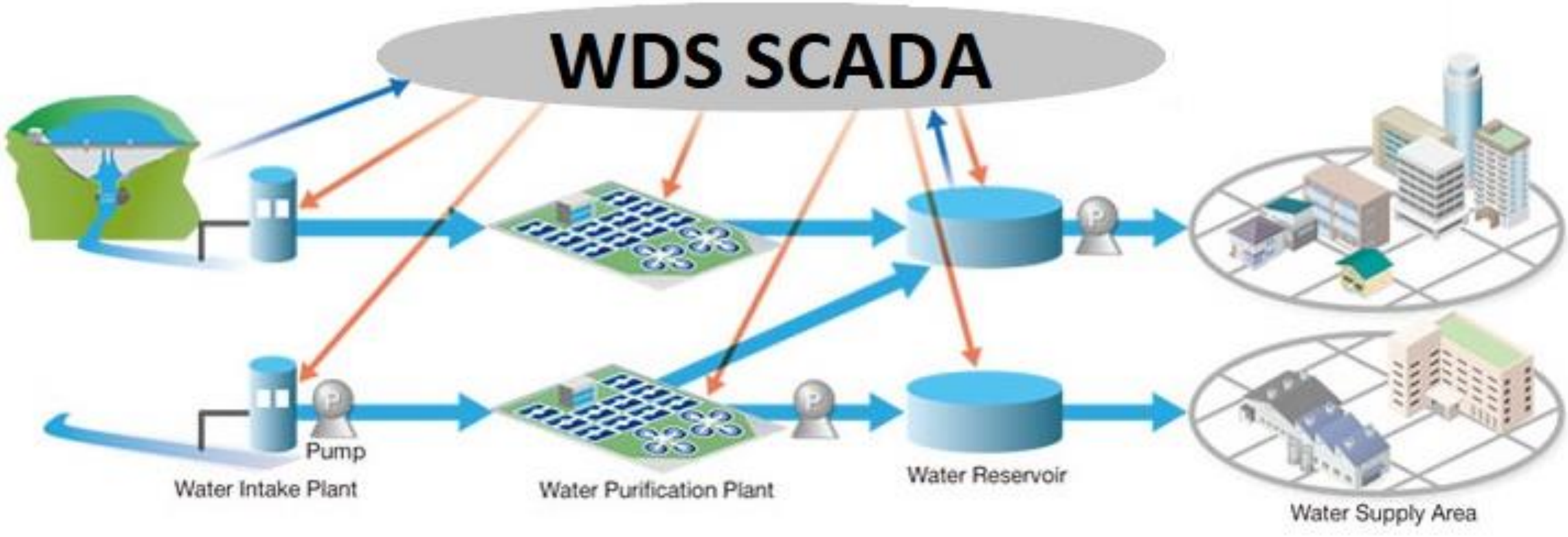
Background

- This presentation reports on work conducted on a NSF CRISP (Critical Resilient Interdependent Infrastructure Systems and Processes) Type 2 project
- The team involved in the work include:
  - Larry Mays – Prof. Environmental Engg (Water Systems)
  - Junshan Zhang – Prof. ECEE (Middleware)
  - Sau Kwan – Prof. Psychology (Surveys and load models)
  - Vijay Vittal – Prof. ECEE (Power Systems)
  - Scott Zuloaga – PhD Student
  - Puneet Khatavkar – PhD Student
  - Beibei Liu – MS Student

Background

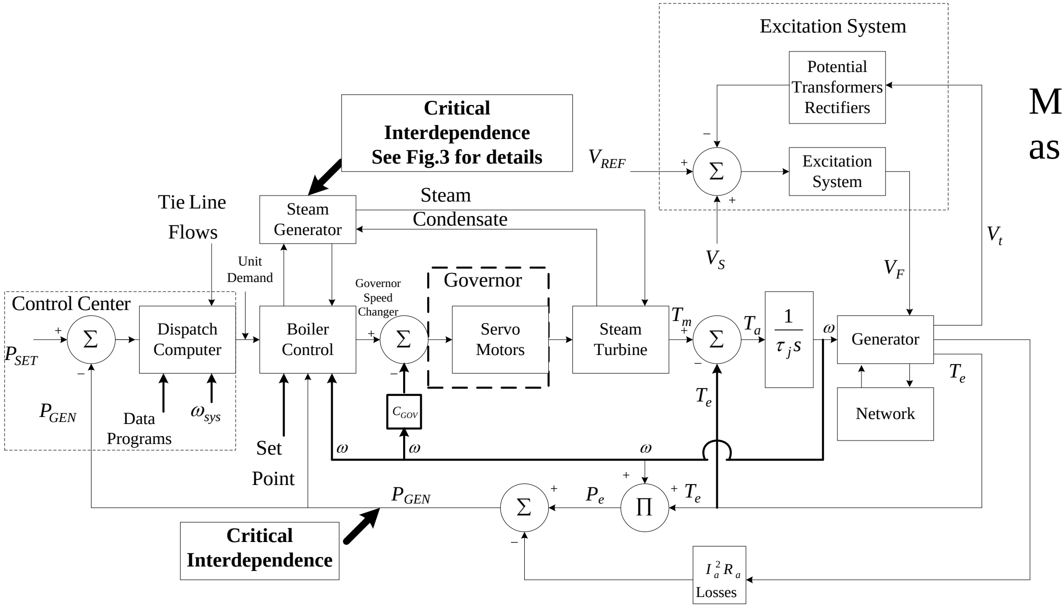
- Thermo-electric generation and the water delivery system are two critical national infrastructures which are interdependent
- Both these systems are highly automated in terms of operation and control, facilitated by a supervisory control and data acquisition (SCADA) system
- The SCADA systems of the two infrastructures operate independently and do not share information or common observability/control capabilities
- This project has developed a sophisticated mathematical model of the interdependent systems and formulated a tool to simulate the two interdependent systems to examine impacts of mega droughts and contingencies

Water-Energy Nexus



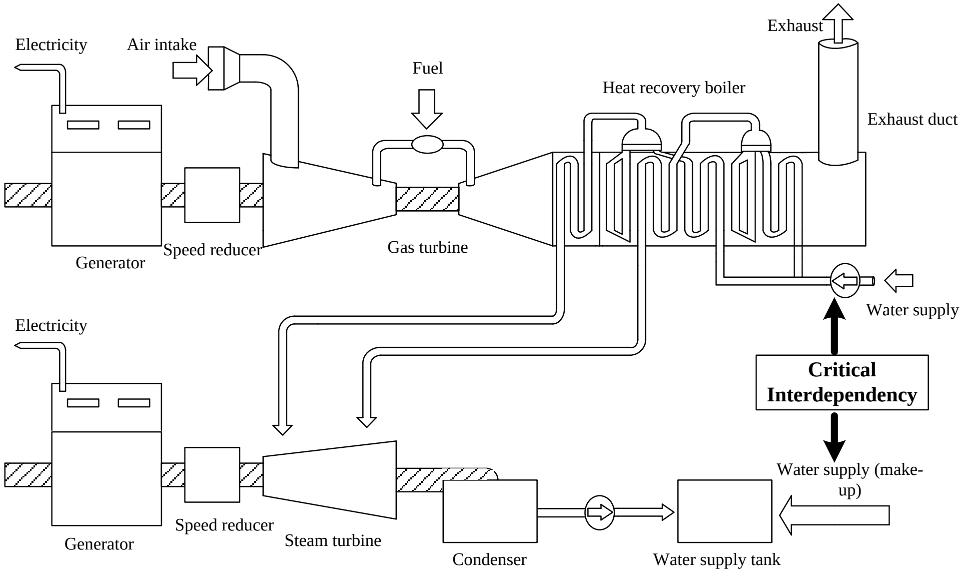
Water Distribution System (WDS) Overview

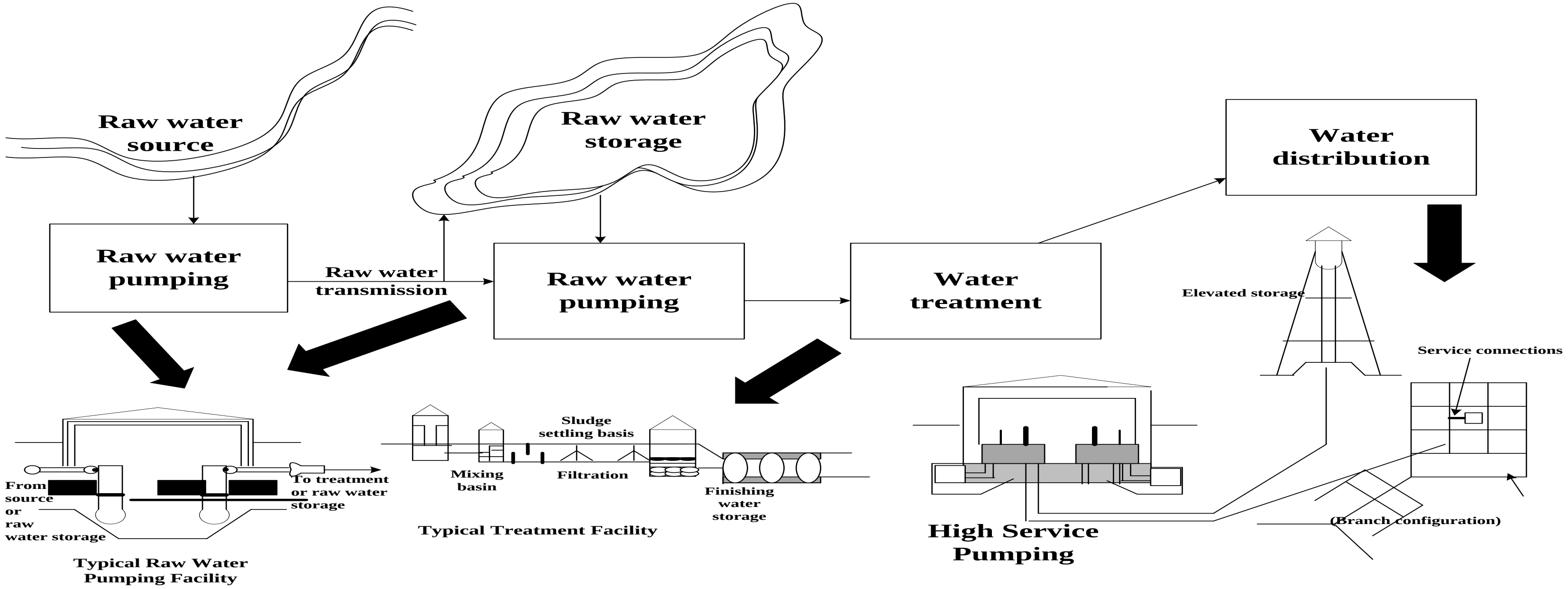
(Modified from: Water Supply System Operation, Hitachi)



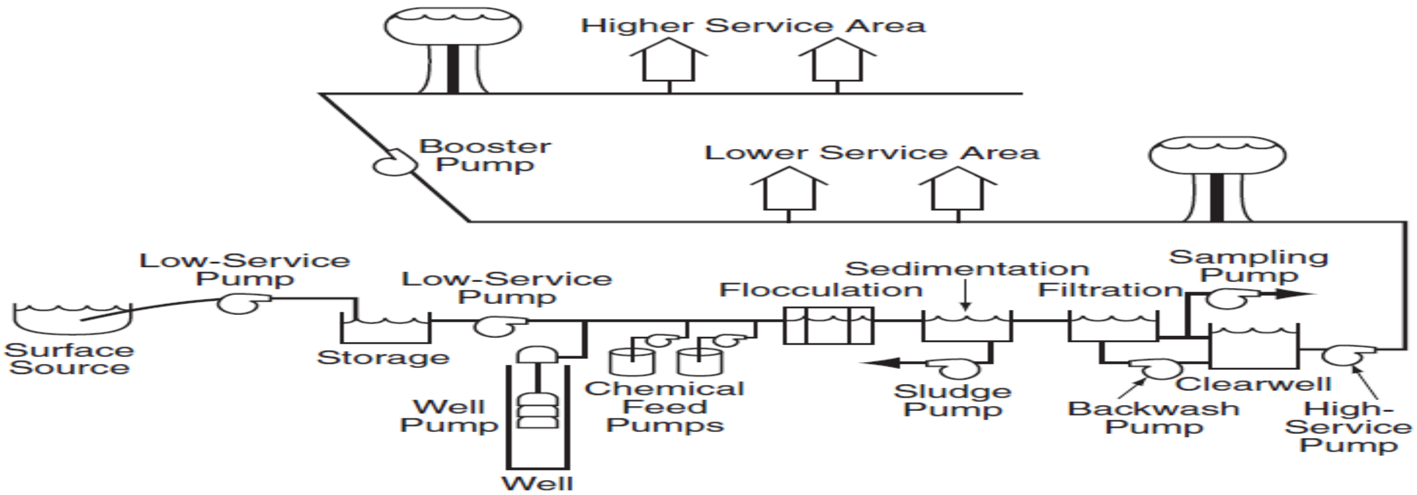
Model of thermal generation unit with associated controls

Details of the thermal cycle





Functional components of a water utility



Uses of electric pumps in a water supply system

Canal Gate leading to storage

100 cfs raw water pump

Twin Peaks Pumping Station (NW of Tuscon, AZ):
6 units, 621 cfs total, 8100 hp ≈ 6.04 MW

Water Energy Nexus Events

Inherently dry climate, increased risk of future mega-droughts

[illegible]

B. I. Cook, T. R. Ault, and J. E. Smerdon, "Unprecedented 21st century drought risk in the American Southwest and Central Plains," *Sci. Adv.*, vol. 1, no. 1, pp. 1–8, 2015

Water usage in thermal plants

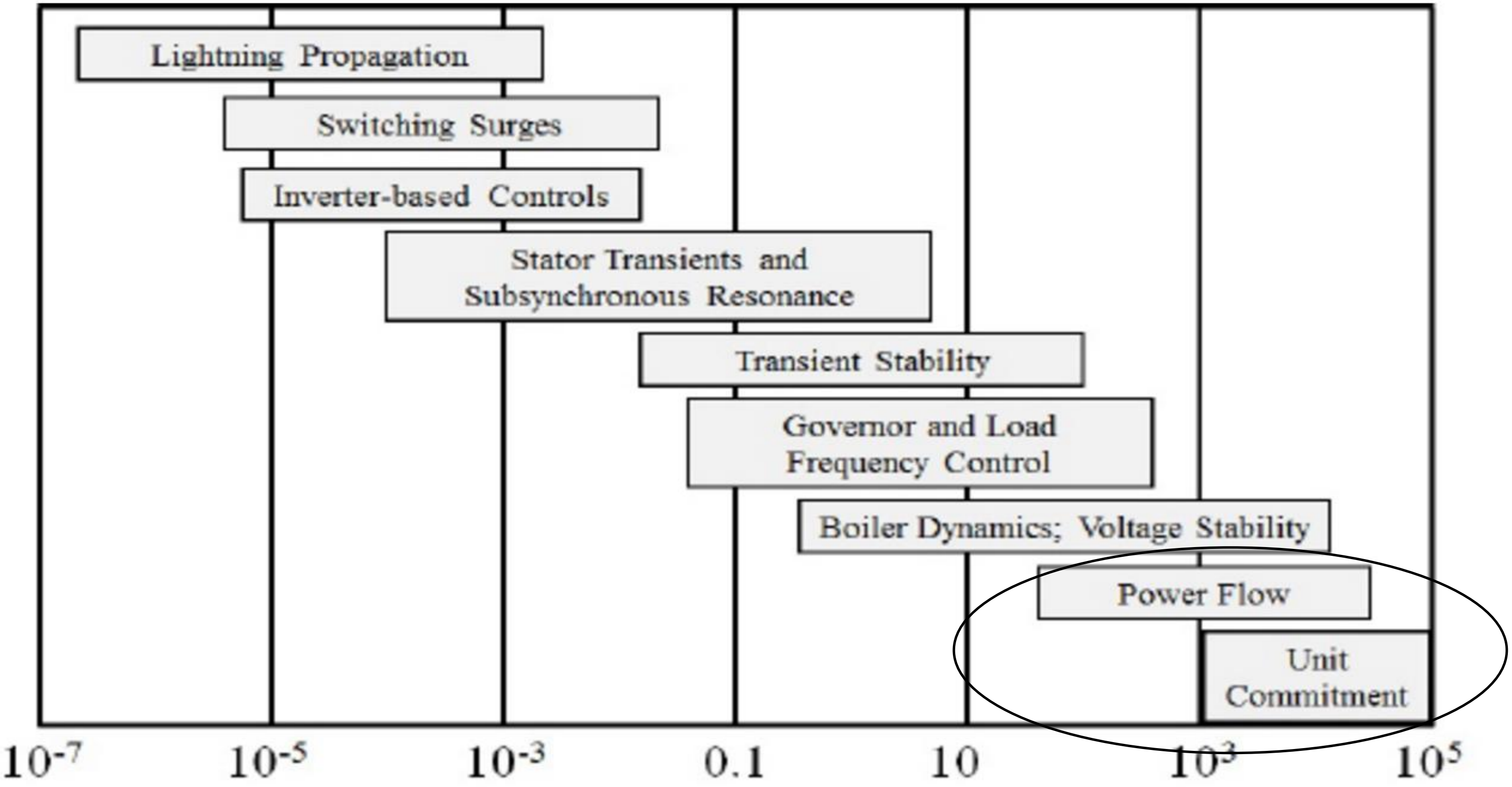
- Electric utilities have meticulous records of cooling water usage for each plant during different seasons and at different temperatures
- This allows utilities to determine accurate annual characterization of cooling water requirement for different thermal prime mover fuel types
- This information along with the plant's total annual energy output are used to determine an averaged cooling water requirement rate in **gallons/MW-hr**
- Each thermal plant is supplied by two independent cooling water sources for redundancy
- Each thermal plant has onsite storage for at least 15 days
- Hence, the water usage vs power output dynamics is a slow time-scale phenomenon and can be approximated by a steady-state model

Electric energy usage in water delivery and treatment systems

- Electricity is used to run the pumps used in the water delivery and treatment systems (WDSs)
- The WDSs also have exhaustive data on the demand for water, the architecture and layout of the WDS and based on this can generate optimized pump schedules
- Knowing the rating of the pumps and the flow rates associated with delivery and treatment, the pump efficiency curves are utilized to determine the electric power requirements over any given interval of time
- Pump schedules can then be optimized to minimize energy consumption

Interdependent mathematical model

- Given this fundamental understanding, the level of detail needed for modeling the two systems clearly depends on the time scales being represented
- Figure 6 on the next slide shows the phenomenon of interest in power systems and the associated time scales
- The phenomenon at each time scale requires a certain degree of modeling accuracy together with the representation of the requisite controls
- For the power system this could range from detailed electromagnetic transient analysis model to a simple dc power flow



(Pai, 2006. modified by Overbye)

Fig. 6 Diagram of power system phenomena time scales

Power system model

- Given that each thermoelectric generating station has at least two separate sources of water and finite amount of onsite storage → fast dynamics associated with the power system do not play a critical role in capturing the interdependency between the two systems
- Hence, the power system is represented by a series of static power flows with the appropriate optimized unit commitment (UC) of generating units based on anticipated operating conditions in the short-term horizon

Power system model

- At each time interval of analysis an optimal power flow (OPF) formulated in conjunction with the water delivery pump demands and the electric power system load demand constraints is solved to obtain the schedule plant output
- The power system ED which is a non-convex, nonlinear problem involves a modified version of the so called combined economic and environmental dispatch which replaces the commonly used metric for emissions cost with one for an operational water cost

WDS model

- Decisions regarding pump operations made on an hourly basis
- Hydraulic analysis performed by solving continuity equations at each node and energy equations around the pipe loops and from storage tanks and reservoirs in the network
- Output of hydraulic analysis includes:
  - Pressures at nodes
  - Water quality concentrations at nodes
  - Flows in links
  - Storage tank levels

WDS model

- The key objective of optimizing the operations of the WDS under limited availability of energy is an attempt to satisfy the required levels of demands at various locations while also meeting pressure requirements of the system

Some specifics of the mathematical formulation

Power System:

SCUC – Security constrained unit commitment

Min {Operating costs related to generation for period of study (piece-wise linear incremental cost) and cost related to no-load operation and unit startup}

Determine the combination of units for desired period of operation which, when operated, minimize the total operating costs

Various constraints included: power output, reserves, line flows, nodal power balance, ramp rate, minimum up and down time

n-1 generation and transmission contingencies

Some specifics of the mathematical formulation

Power System:

CEED – Combined economic and environmental dispatch

Min {Operating cost due to generation and cooling water cost}

Various constraints included: power flow constraints, generation limits, outputs of units committed and not committed, pump power demands

Some specifics of the mathematical formulation

WDS – Model represented using EPA’s open source software EPANET

1. Obtain electrical energy input from power system
2. Receive latest information on status of pumps, tank levels, status of valves, and flows in and out of the system from the SCADA system
3. Update WDS input using SCADA data
4. Run WDS optimization model to determine actual pump demand pattern and pump operation schedule that can be met using available electrical energy input
5. Implement the optimal pump schedule over the next one hour

Some specifics of the mathematical formulation

WDS – Min{Difference between demands required and demands supplied}

Various constraints associated with:

Flow distribution throughout the network – conservation of mass at each node, conservation of energy in each pipe

Height of water stored in tank and bounds on level of water storage

Water quality constraints

Lower and upper bounds on pump operation

Pump switching constraints

Pump power requirements

Nodal pressure head bounds

Interdependent systems simulation engine

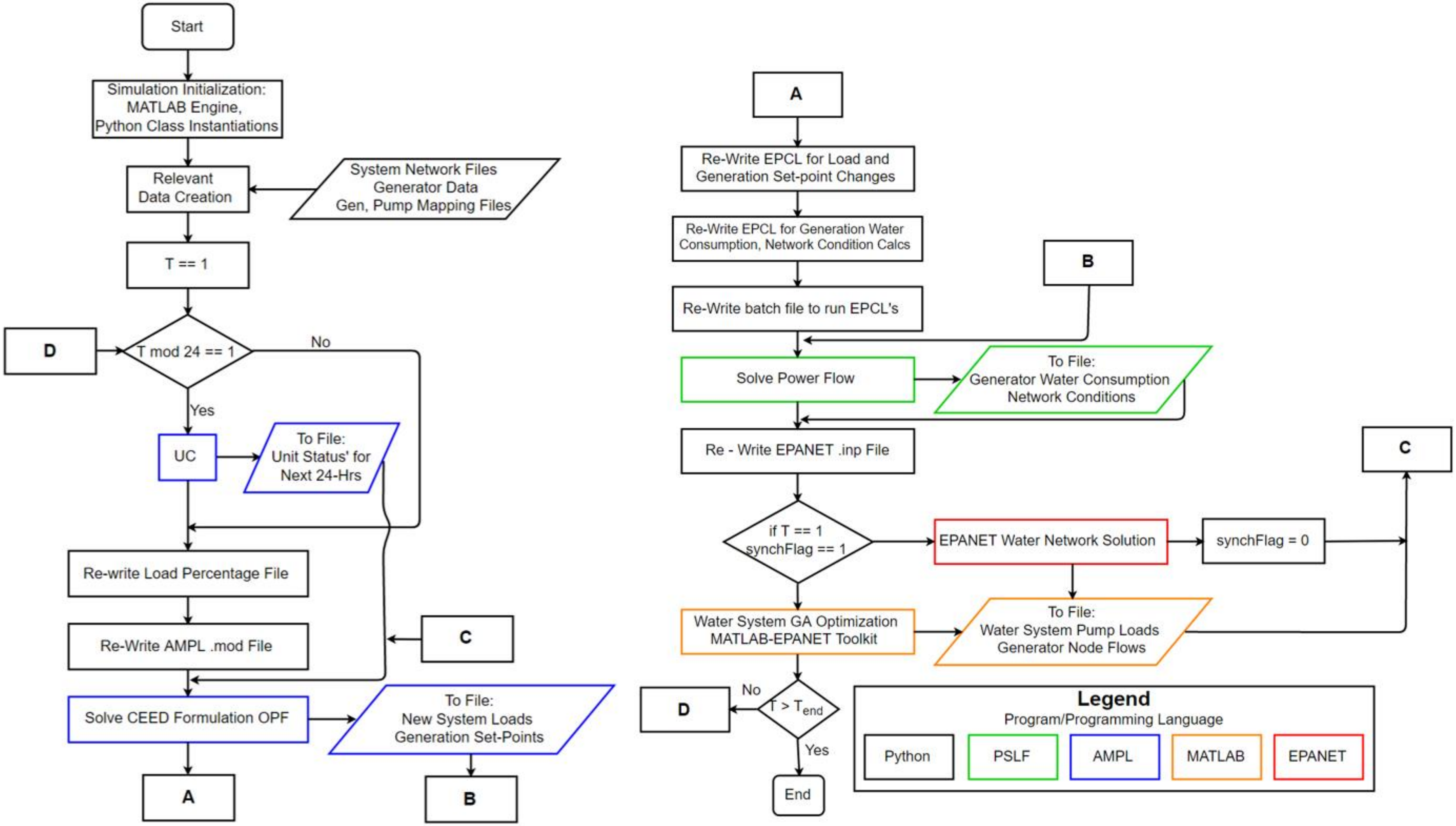


Fig. 7 Overview of simulation engine

Water System – Power System Simulation: Interactions

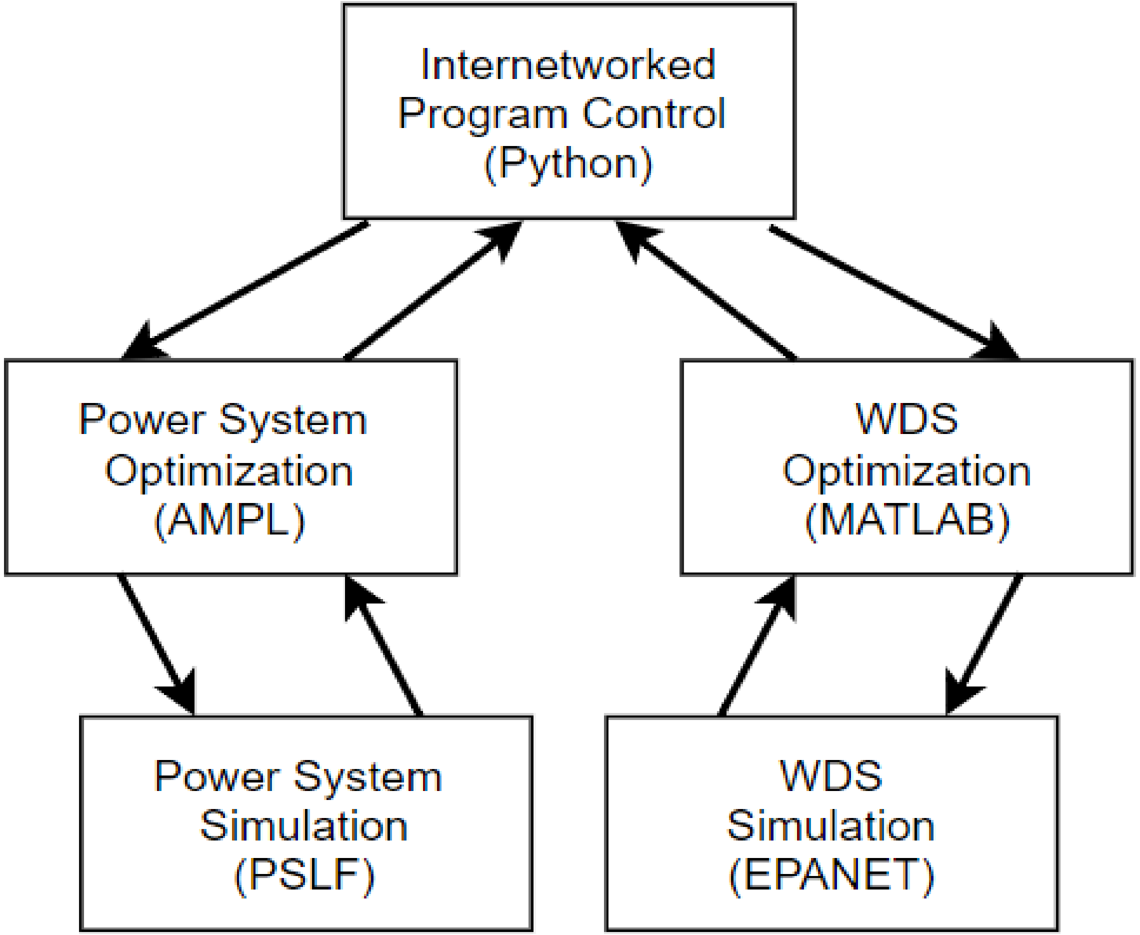


Fig. 8 Interaction between simulation tools

Conclusions

- The interdependent modeling of the electric and water delivery systems provide new insights into the impacts of disruptions on the two systems
- It is known that severe drought conditions lead to derating of electric power plants with no industry-wide established procedure to do so
- The scheme developed based on the level of water storage at the power plants and availability to incorporate a systematic procedure to derate thermo-electric plants illustrates the advantage of the interdependent model and simulation
- Disruptions in electric service also affects water supply to customers as shown by the demands not being met at certain time intervals

References

- S. Zuloaga, P. Khatavkar, L. W. Mays, and V. Vittal, "Interdependent electric and water infrastructure modeling, optimization and control," *IET Energy Syst. Integr. J.*, vol. 2, no. 1, pp. 9–21, March, 2020.
- S. Zuloaga, P. Khatavkar, L. W. Mays, and V. Vittal, "Resilience of Cyber-Enabled Electrical Energy and Water Distribution Systems Considering Infrastructural Robustness Under Conditions of Limited Water and/or Energy Availability," *IEEE Trans. Eng. Manag.*, in press/Early Access Available, pp. 1–17, Sep. 2019.
- P. Khatavkar and L. W. Mays, "Model for real-time operations of water distribution systems under limited electrical power availability with consideration of water quality," *J. Water Resour. Plan. Manag.*, vol. 144, no. 11, pp. 1-8, 2018.