

A Co-Simulation Approach for Real-Time Transient Analysis of Electro-Thermal System Interactions on Board of Future All-Electric Ships

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Abstract

This paper presents an approach to performing real-time co-simulation of electro-thermal coupled power systems for aiding the design of future all-electric Navy ships. The goal is to study the transient interactions between the electrical and the thermal sub-systems. The approach utilizes the existing large scale real-time simulation capabilities of electrical systems established at Florida State University on the Real Time Digital Simulator (RTDS) platform in conjunction with real-time simulation models of thermal systems from the University of South Carolina implemented on the Virtual Test Bed (VTB) platform. The paper first briefly discusses methods for linking the RTDS and the VTB models. It then describes the different modes of interactions between the electrical and the thermal sub-systems and illustrates them on realistic example cases. A simplified application scenario is analyzed. Initial results clearly illustrate the thermal runaway phenomena as long-term system instability typically not revealed by snapshot type off-line simulations. The paper concludes with an outlook on future steps to improve this approach towards higher system fidelity and level of detail represented in the thermal system.

1. INTRODUCTION

Real-time management of the closely coupled, low inertia electrical power systems of future all electric Navy ships at yet unprecedented power levels may pose one of the greatest challenges to this technology. At present, thermal plants, as well as electrical systems, are designed with substantial margins to account for transient conditions, which at present are very difficult if not impossible to predict with sufficient accuracy. This practice, which at best introduces loading factors in order to reduce the excess design margin, leads to sub-optimally designed systems. In the future, however, such conservative design methods can no longer be accepted in order to achieve the overall performance goals such as fuel efficiency and power density of the future Navy platforms [1]. Therefore, it will be necessary to better co-design the electrical and thermal systems, in particular with

respect to transient responses during dynamic events due to electrical-thermal system interactions.

Coupled thermal-electrical transient studies have traditionally only been carried out on the apparatus or, at best, at the sub-system level [2]. In order to allow such studies on the overall system level, a few challenges have to be overcome. First, a high fidelity electrical system simulation model has to be created. While improvement to the model is still ongoing, the electric system simulation model of a notional destroyer class ship reported in [3] is certainly an important precedent. The model features sufficient detail to study electrical system transients and dynamics owing to its implementation on a high performance computational platform, namely the real-time digital simulator (RTDS, [4]) that actually yields results in real time. If certain transients require smaller simulation time steps, the computationally extensive model can still be executed in a reasonably short time frame removing the real-time constraint. In contrast, no comparative thermal system simulation model of a ship cooling system exists at this time. Therefore, researchers at different universities are currently engaged in the process of developing one. Significant contributions in this direction are reported in [5] and [6]. When such a model eventually becomes available, comprehensive thermal-electrically coupled transient simulations of (notional) electric ship systems will be possible. The reason for the focus of this paper on real-time is to eventually enable augmentation of already existing electromechanical power hardware-in-the loop (PHIL) experiments [7] with appropriate thermal system co-simulations in order to fully incorporate these aspects into the PHIL concept. However, the basic approach outlined in this paper applies to non-real-time simulations as well.

In addition to the details on how to connect different real-time simulation platforms there are a number of other issues associated with coupled thermal-electrical co-simulation on a large scale, which are discussed in this paper. An illustrative example based on the notional destroyer class ship system [3] is given which demonstrates the different mechanisms by which the thermal and the electrical system interact dynamically and even lead to slow system instabilities due to thermal runaway. The paper concludes with an outlook on a more complex scenario in the direction of building the simulation of the whole ship.

2. THERMAL-ELECTRICAL COUPLED SYSTEM SIMULATIONS

An important computational aspect of any coupled thermal-electrical transient system simulation is the vast differences between the electrical and the thermal response times. While time-domain simulations of electrical systems typically require from one to hundred microsecond time steps, those of thermodynamic system simulations range from 100 milliseconds to several tens of seconds. It would be a waste of computational resources to simulate the thermal system with the same simulation time step as the electrical system. Since the high-fidelity electrical system simulation already exists in the RTDS platform this paper explores how this RTDS model can be coupled with a thermal system simulated with vastly larger time steps. The thermal system can either be implemented on the same (RTDS) platform using its generic modeling capabilities. Or it may utilize another simulation platform which provides specific thermal modeling capability such as the Virtual Test Bed (VTB) developed at the University of South Carolina [8], which is the preferred approach proposed in this paper. Currently, a real-time version of VTB [9] has been installed at Florida State University and a first version of data connection with RTDS has been implemented.

The three major interactions between the electrical and the thermal system are due to:

- a) The electrical component losses extracted by the cooling plant,
- b) The instantaneous electrical power requirement by the cooling plant, and
- c) Variations in coolant temperature, which change the electrical characteristics of equipment (hereby altering the temperature dependent losses in the electrical system).

3. THE TWO CO-SIMULATION PLATFORMS

3.1. RTDS

A general description of the large-scale electromagnetic transient simulators developed by RTDS Technologies Inc. is provided in [4]. The algorithm employed by the simulators is based on the efficient Dommel algorithm [10], which is typically used for electromagnetic transient simulations. RTDS is designed to simulate systems in real time with time step sizes on the order of 50 μ s. For power electronics, the RTDS provides a feature to simulate such subsystems with much smaller time-steps (typically 1.5 μ s) [11]. The simulator makes use of a large number of digital signal processors (DSPs) operated in parallel, and provides digital and analog I/O ports for interfacing hardware to the simulation. The system is scalable, allowing subsystems of up to 54 electrically accessible nodes to be simulated on a single "rack", while larger systems can be simulated by

connecting together subsystems simulated on separate racks. The simulation cases are constructed, downloaded to the simulator, and monitored and controlled using a custom software suite, RSCAD. The software allows construction of cases using a graphical schematic editor, provided with libraries containing models for typical power system components such as machines, transmission lines, and power electronic components. Additionally, RSCAD provides the user with the capability to develop new components in a C-like language. Control over processor allocation and the execution order of components allows for most efficient of processor usage, which is important for large real-time simulation cases. Currently, 14 RTDS racks are installed at the real-time power systems simulation facility at CAPS [12].

3.2. VTB-RT

Besides RTDS a number of other systems for HIL simulations have already been developed, such as QNX, RTOS, and Opal-RT. However, all of them are based on proprietary solutions. In contrast, VTB-RT is completely implemented with public domain software and off-the-shelf hardware. From the software point of view, VTB-RT consists of three free software packages.

- 1) Linux is selected as the operating system of VTB-RT due to its low cost and flexibility. Different Linux distribution version have been successfully adopted
- 2) Real-Time Application Interface (RTAI) is a kernel modification and enhancement package of Linux that permits the handling of time-critical tasks.
- 3) Comedi is a library of open-source device drivers for many different data acquisition (DAQ) cards.

Based on these packages, there are three major components in the VTB-RT real-time implementation.

- 1) Real-Time Task: RTAI preempts the standard Linux kernel and handles hardware interrupts. In VTB-RT, a real-time task is generated by RTAI to manage the 8254 chip (clock generator) to generate a real time clock, which is used as the basis for defining the simulation step. This real-time task is a loadable module in Linux; it stays in the kernel-space upon being loaded.
- 2) Linux Process: A VTB-RT solver is realized by a set of standard Linux processes. In this way, it is similar to other Linux programs, such as a text editor. In each step interval, the solver takes in the system input from the analog input port of the DAQ card, solves the system state, and sends the system output through the output port. The Linux process is a user-space application program and thus has no direct communication with the real-time task.
- 3) Real-time First-In-First-Out (FIFO) buffer: Since in VTB-RT the real-time clock information has to be passed to the solver, a real-time FIFO is applied as the "bridge" between the real-time task and the Linux

process. Real-time FIFO is a unidirectional read/write buffer created by the RTAI. After the simulation starts, it continuously records the real-time clock generated by the real-time task. Simultaneously, the Linux process polls the real-time FIFO, detects the real-time clock and performs the simulation.

4. CO-SIMULATION ISSUES

Co-simulation is a useful technique to overcome the limitation of any single simulation platform. The implementation of a co-simulation strategy involves a series of challenges, which are described briefly below and discussed with respect to the applications provided in this paper.

4.1. Synchronization Between the Solvers

Since RTDS is a dedicated real-time simulator, it cannot “wait” longer than the specified time-step for any other simulation processes to finish its task. Therefore, a co-simulation platform has to obey the real-time constraint each time step. Synchronization between the RTDS and the VTB-RT relies on the individual real-time clocks of each process. At present, no special provision is implemented to actually assure such synchronization over longer simulation times. Because of the naturally large separation of time constant between electrical and thermal system any possible jittering in data transfer between the two simulations is considered a minor issue. However, more detailed analysis of possible negative effects due to such jitters should be investigated in the future.

4.2. Protocol for Data Exchange

RTDS is based on custom hardware dedicated to high-performance real-time simulations and thus is equipped with specialized and proprietary DAQ hardware for massive analog I/O capability. In contrast, VTB-RT can operate with any DAQ card supported by the Comedi library. Since RTDS at present does not well support digital-to-digital connections to third party simulation or control processes (i.e. over ETHERNET or similar protocols) it was decided to utilize an analog connection between the RTDS and the VTB-RT. For the current installation VTB-RT is equipped with a National Instruments (NI 6014) card, which could receive up to 16 analog inputs from RTDS and provide back two analog outputs to the RTDS. It is technically possible to provide more I/O by adding NI cards to the PCI bus of the VTB-RT computer. Due to the simplicity of the thermal system considering for the first simulation scenario, only two inputs from the RTDS (the total heat load and the motor voltage for the pump of the primary cooling loop) and two outputs (the heat sink temperature and the current drawn by

the pump motor) are exchanged between the two simulation processes. In the future, however, a digital-to-digital connection between the electrical and the thermal simulation is envisioned for simulating larger systems.

4.3. Simulation Stability

Two distinctively different stability issues have to be addressed when conducting co-simulations between electrical and thermal transient simulation platforms. The first one is to avoid instabilities due to the inherent time delay caused by the co-simulation interface itself. In the present case, a total maximum (round trip) time delay of

$$\Delta t_{MAX} = 2(dt_{EL} + dt_{TH}) \quad (1)$$

is anticipated, where dt_{EL} and dt_{TH} signifies the simulation time steps in the electrical (RTDS) and the thermal (VTB) simulation, respectively. Since the electrical system simulation typically requires at least two orders of magnitude smaller simulation time steps, the thermal simulation essentially governs the interface time delay. Choosing dt_{TH} significantly smaller than the smallest time constant of any transient governed by the electrical-thermal system interactions ensures that the interface remains transparent with respect to the stability of the simulation. In the present example, $dt_{EL} = 50 \mu s$ and $dt_{TH} = 4 ms$ was chosen. The thermal simulation time step was actually governed by the pump motor model.

The second aspect is to ensure stability of the models and their respective solvers. In the present case, each of the thermal component models, which were developed at USC, were evaluated with respect to their performance on the fixed time step solver employed in the VTB-RT simulation. The same was done for any custom developed models implemented on the RTDS.

Finally, instabilities can still arise after all the above criteria have been fulfilled as illustrated in the example that is given later in the paper. However, such instabilities must not be confused with simulation instabilities since they are a direct result from the interactions between the electrical and the thermal system.

5. SIMPLE SIMULATION SCENARIO WITH A SINGLE THERMAL LOOP

A simple simulation scenario has been fully implemented and partially tested using the platform described above. This section first describes the electrical and thermal plants separately and then discusses how the two systems are initialized and finally linked in this RTDS-VTB co-simulation approach.

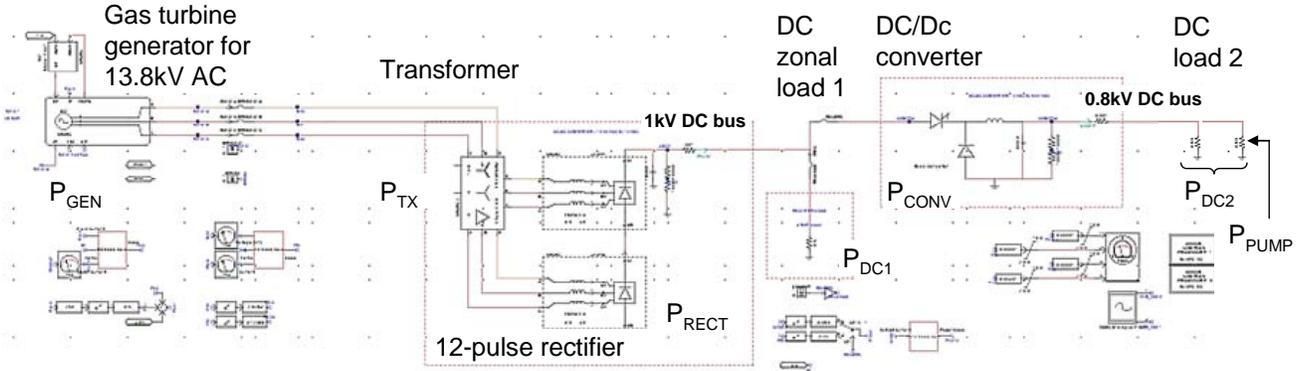


Figure 1: The electrical system adopted for the tests

5.1. The electrical system

The electrical subsystem, as depicted in Figure 1, is a subset of the notional destroyer class integrated power system simulation model described in [13]. It is composed of the following components:

A 40 MVA synchronous gas turbine generator provides power to a simplified DC zonal system, comprised of a 12-pulse thyristor controlled rectifier, which supports a 1 kV DC distribution bus that powers a DC/DC converter and feeds a DC zone load. The zone powered by the DC/DC converter contains two more DC loads: a dedicated load (R_{PUMP}) representing the power demand by the cooling plant and another generic load (i.e. other ship service loads). All these loads are controllable through sliders in the RTDS runtime environment. In addition, the value of R_{PUMP} is controlled by the following expression

$$R_{PUMP} = \frac{V_{DC2}^2}{P_{PUMP}} = \frac{V_{DC2}^2}{V_{MOT} \cdot I_{MOT}}, \quad (2)$$

with $V_{DC2} = 0.8$ kV being the DC zonal voltage, to represent the instantaneous power demand P_{PUMP} caused by pump powering the primary or freshwater cooling loop. The power demand by the secondary or seawater cooling loop is neglected for simplicity.

5.2. The thermal system

Figure 2 illustrates the VTB schematic of the thermal subsystem. It is comprised of a single freshwater cooling loop, which, in this simplified example, receives the total heat load

$$P_{TOT} = P_{GEN} + P_{PUMP} + P_{TX} + P_{RECT} + P_{DC1} + P_{CONV} + P_{DC2}, \quad (3)$$

from the electrical system as the sum of the individual losses from each electrical component (see also Figure 1). For this example, these losses are computed from their respective instantaneous component through power values through loss multiplication with loss coefficients between

1% and 6%. In particular, P_{DC2} is assigned 6% of the total power supplied by the DC/DC converter. Hence it includes the losses assumed in the cooling plant pump. P_{TOT} is scaled appropriately in the RTDS to allow data transfer via the analog link. In the VTB-RT environment it is scaled back to its original value and passed into the heat sink model as an electrical current injection, the current representation of a heat injection in VTB-RT. The current source is implemented through a high voltage source with a large series impedance.

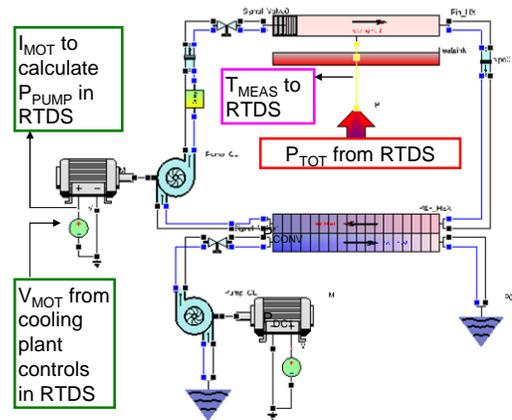


Figure 2: The thermal subsystem adopted for the tests

At present, no temperature effects are modeled in the electrical system. The temperature T_{MEAS} , measured at the heat sink as an equivalent voltage, is transferred to the RTDS only for real time monitoring and plotting. Eventually, the effect of individual component temperatures on their electrical characteristics will be taken into account by augmenting the electrical component models in RTDS accordingly.

The heat sink is thermally coupled to a heat exchanger through which an electrically powered pump maintains the flow of coolant. A second heat exchanger provides a sink

for the heats of the primary cooling loop to the seawater. Table 1 provides a summary of the exchanged signals in the co-simulation.

Table 1 - Summary of Co-Simulation Signal Exchange

Signal Description	Signal Name	Signal Units	Signal Flow
Total Heat Loss	P_{TOT}	kW	From RTDS to VTB-RT
Pump Motor Terminal Voltage	V_{MOT}	V	From RTDS to VTB-RT
Heat sink Temperature	T_{MEAS}	°C	From VTB-RT to RTDS
Pump Motor Armature Current	I_{MOT}	A	From VTB-RT to RTDS

5.3. The control systems and simulation start-up

In order for this simulation to perform well under transient conditions, simple control systems for the generator (governor and voltage control), the rectifier (DC bus voltage control), the DC/DC converter (DC zonal voltage control) and the thermal plant (heat sink temperature control) were implemented. For simplicity, and because no easy real time access to controllable parameters in VTB-RT was available, all the controls were implemented on the RTDS. The thermal plant control is a simple proportional-integral (PI) controller, which tries to maintain a user defined reference value for T_{MEAS} by adjusting the voltage of the motor V_{MOT} that drives the primary cooling loop pump in the VTB-RT case. The controller was tuned (without any feedback from or to the electrical system) to provide an acceptably fast thermal plant response while keeping the transients on the motor voltage reasonably low.

In order to start up the co-simulation case, the electrical system simulation in RTDS is started first, allowing initialization transients to settle out without feedback of P_{PUMP} from the thermal system. Then, the thermal simulation is started in VTB-RT allowing the thermal system to settle into a steady state in open loop control with a constant value P_{TOT} and V_{MOT} sent from the RTDS case. Then, the PI cooling plant controller is engaged. Next, the true electrical system losses are sent to the VTB-RT case and, finally, the feedback of P_{PUMP} is activated. At this stage, two of the three fundamental electrical-thermal system interactions are represented in the co-simulation.

6. SIMULATION RESULTS

While the full extent of the system interactions of this simple test case have not yet been explored exhaustively this sections provides illustrative examples of typical system

responses. Starting from a steady state operating point an electrical transient was introduced by increasing the generic DC zonal load on the 1 kV bus from 0.9 MW to 1.25 MW. The initial transient system response is illustrated in Figure 3. The sudden increase in power loss of the electrical components upstream and including P_{DC1} causes the initial increase in heat sink temperature. Simultaneously, the cooling plant power demand increases as the thermal system tries to maintain the set point temperature of 70°C. The additional increase in power losses can be seen very well in Figure 3 where the total electrical heat load apparently finally settles at 400 kW. However, a much longer observation window reveals system instability due to the limited cooling capacity of the thermal plant during this system event. Figure 4 depicts a record over 75 seconds which clearly shows the thermal runaway. It ultimately caused the thermal simulation to stop due to a time step error as the temperature went out of bounds approximately 10 seconds after the end of the record shown in Figure 4. It is important to note that for such a load change this instability only occurs for a set point temperature of less or equal 70°C. Finally, Figure 5 shows the system response without the feedback of P_{PUMP} . Not only is the initial temperature rise slightly smaller, but also the system instability is not visible as expected.

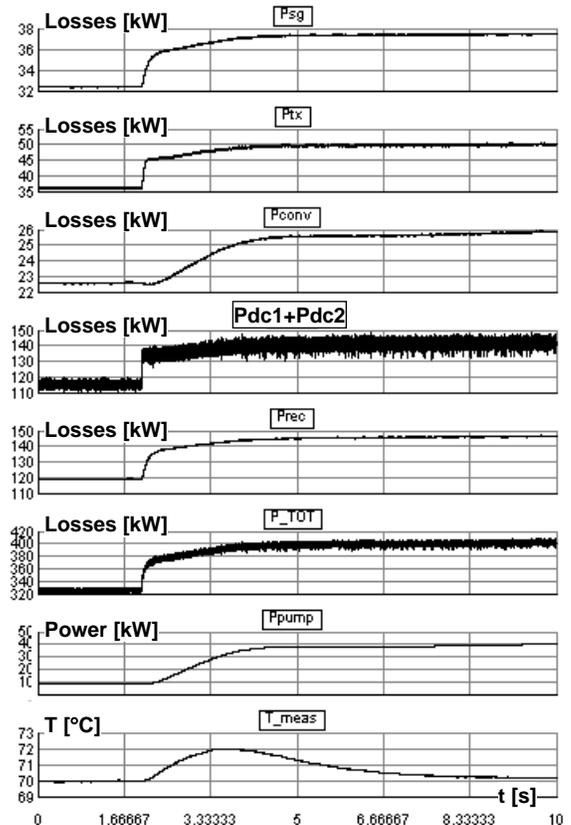


Figure 3: Initial system response to electrical transient

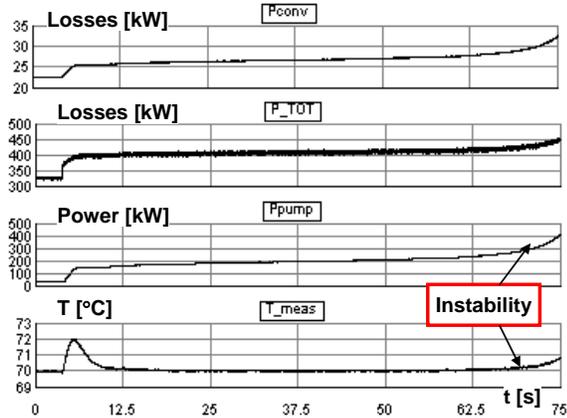


Figure 4: Long term response showing thermal runaway

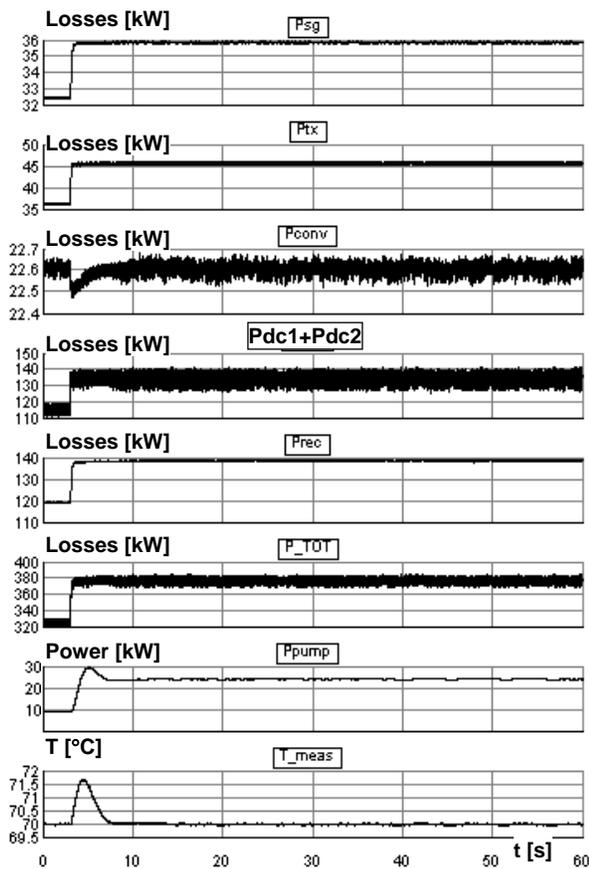


Figure 5: Long term response without pump power feedback from the thermal system

7. FUTURE DEVELOPMENTS

As next stage of this project we are planning to enhance the level of detail represented in the thermal plant, such as representing separate heat exchangers for each major electrical component in the system as illustrated in Figure 6. As a result, analysis of a multi-loop temperature control will be possible. The control of the thermal plant should then be

incorporated in the VTB-RT environment. In particular, the focus will be on considering the characteristics of power electronics equipment in the future All Electrical Ship system.

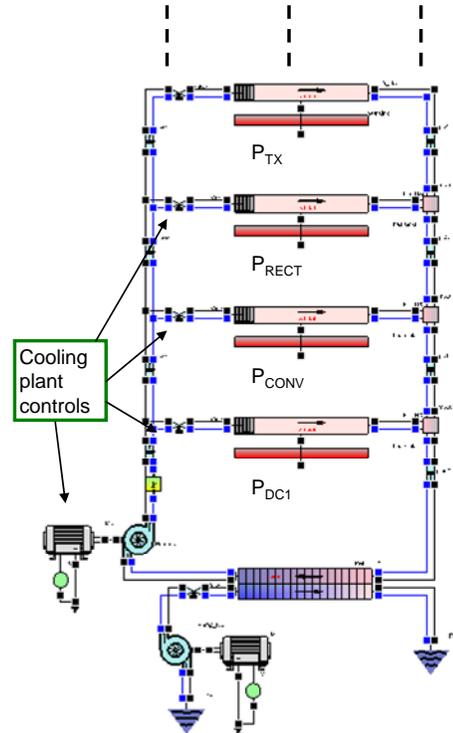


Figure 6: The second stage of complexity: multi-loop thermal control

8. CONCLUSION

This paper presented an experimental activity in the field of electro-thermal simulation. The main goal of this research is to assess dynamic issues in a complex system such as an All-Electric Ship. While the initial example case is highly simplified representation of such a system, it did reveal a significant insight into the thermal runaway problem due to the inherently continuous simulation of the two real time simulators. Such an event is entirely possible on a real system if a lack of transient analysis yields insufficient margins in the co-design of the electro-thermal system or results in inadequate settings of thermal control systems.

In the future, the plan is to expand this effort to:

- Increase the fidelity and level of detail of the thermal plant in the goal of a notional ship co-simulation
- Incorporate more realistically sophisticated thermal plant control systems
- Developing a digital-digital connection between the RTDS and the VTB-RT.

Furthermore, it is expected that eventually coupled electrical-thermal co-simulations such as the ones outlined in this paper will significantly augment the fidelity of future

controller and power hardware-in-the loop experiments as well as reconfiguration and survivability studies.

9. ACKNOWLEDGMENTS

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