Geographically Distributed Thermo-Electric Co-Simulation of All-Electric Ship

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Abstract— **In this paper, a thermo-electric co-simulation of an all-electric ship type notional system using two geographically distributed heterogeneous real-time simulators is presented. The two real-time simulators, from RTDS and OPAL-RT, are used for modeling the electrical system and the thermal system of an all-electric ship, respectively. RTDS is located at the Center for Advanced Power Systems, Florida State University, Tallahassee, Florida, USA whereas the OPAL-RT simulator is located in the RTX-Lab at the University of Alberta, Edmonton, Canada. The two simulators separated by approximately 3500 km, exchange data through an asynchronous link over the Internet utilizing the TCP/IP and UDP protocols. The electrical model was developed using RSCAD and simulated on RTDS while the thermal model was developed using SIMULINK and simulated in the RT-LAB environment. RTDS sends the electrical power losses to the OPAL-RT simulator, which computes the temperatures of the thermal systems and sends the data back to the RTDS simulator. Simulation results indicate that despite the large physical distance between the two simulators, the co-simulation is accurate and stable. A low latency of 0.208 s was observed which is within acceptable limits for a slow system response expected from the thermal system, which has time constants in the range of seconds. Results indicate that co-simulation of different types of systems is a viable and may be a cost-effective option to perform remote hardware-in-the-loop simulation of complex multi-engineering models.**

I. Introduction

The future All-Electric-Ships (e-ship) are envisaged to have a paradigm shift in the processes of generation, transmission and utilization with an ultimate objective of using electrical power for propulsion, weapons and other purposes in addition to supplying loads to the services. This requires a power system with high efficiency, smooth control, greater flexibility, reliability and adaptability to the various needs in different circumstances. The development of high-power semiconductor based converters and variable speed drives paved the way for building such a power system in the e-ship. The combined electrical system comprising of generators, motors, power electronic converters, drives and other appliances, however, generates large amounts of heat, which requires a proper and efficient thermal-management (cooling) system. Poor thermal management may cause low efficiency and unnecessarily over engineered plants. Therefore, detailed study of both electrical and thermal system through a thermo-electric simulation is necessary at various stages of planning and design as well as during operation. However, due to the complicated physical switching processes and very fast transient period, simulation of electronic power conversion modules needs very small simulation time steps (sub-microsecond) [1]. For a thermo-electric simulation, the problem is even more complicated when thermal models with large time-constants are included in the same simulation. Thus there is a need for thermo-electric *co-simulation* where multiple tightly linked simulators are used for the entire simulation.

Co-simulation means the simulation of a complex system using two or more heterogeneous interconnected simulations where the model can be split into more than one simulator. Thermo-electric co-simulation involves the modeling of the electric power system separately from that of thermal management system. The simulations, however, are coupled in such a way that they exchange feedback signals either synchronously or asynchronously. This type of simulation is known as *distributed* simulation. The two most common distributed simulation approaches are: (1) locally distributed simulation and (2) geographically distributed simulation. Locally distributed simulation offers the advantage of simulating large complex systems by splitting the model into more than one simulator available at the same physical location while, geographically distributed simulation facilitates remote monitoring and control, non-destructive remote testing, troubleshooting of remote devices, and utilization of globally available simulation resources. It is useful when the time constants of the subsystems are very different such as the thermo-electric co-simulation in our case.

The availability of a transient simulator for modeling the dynamics in electrical and thermal systems using the same software program is very rare or close to non-existent.

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Although there are commercially available software tools such Dymola and COMSOL that can model both electrical and thermal systems simultaneously, there are still limitations related to modeling, interfacing capabilities, and the speed of simulation. On the other hand, having individual simulators for each field of engineering at the same geographic location is also unrealistic and may be unaffordable. Therefore, exploiting geographically scattered multi-engineering simulators through efficient communication links is a cost-effective alternative. Most of the advanced high-performance simulators are scattered at specific locations in the world. Some of these simulators have their own limitations with respect to modeling and simulation of multi-engineering or multi-physics systems. Using a cost-effective, widely available communication medium such as the Internet (with or without GPS synchronization) or a dedicated communication technology such as VPN (Virtual Private Network), these simulators can cooperate to perform distributed co-simulation for solving common problems. Such an approach permits the sharing of specialized computational resources and enables collaborative teamwork [2-3]. The Center for Advanced Power Systems (CAPS) at Florida State University (FSU) in the USA has previously established an advanced simulation and experimental facility with the capability of performing hardware-in-the-Loop (HIL), real-time power system simulation [4]. The main computational engine is a Real-Time Digital Simulator (RTDS), a large-scale electromagnetic transient simulator, developed by RTDS Technologies Inc. [5]. On the other hand, the Real-Time eXperimental Laboratory (RTX-Lab) at the University of Alberta (U of A) in Canada also specializes in real-time, HIL simulation and experimental research with a state-of-the-art PC-Cluster based real-time simulator built by the OPAL-RT Technologies Inc. from commercial-off-the-shelf digital hardware and software components [6]. The RTDS uses Digital Signal Processors (DSPs) and RISC processors whereas OPAL-RT simulator uses general purpose CPUs for computational nodes. By interfacing these two simulators over a long distance, using the Internet, for running a thermo-electric co-simulation, the challenges of both thermo-electric real-time co-simulation and geographically distributed simulation arise in the same scenario.

Geographically distributed electrical simulation using a homogeneous simulation platform such as Virtual Test Bed (VTB) has also been reported in [2-3]. However, to the best of our knowledge, the work reported herein is the first attempt where two off-the-shelf heterogeneous real-time simulators (RTDS and OPAL-RT simulators) are interfaced to perform a geographically distributed co-simulation. The main challenges of performing such a co-simulation are the requirement of proper computation engines, the large geographic distance and the availability of a cost-effective data exchange link with low communication latency.

In this paper, we demonstrate how two heterogeneous real-time simulators were interfaced over a distance of approximately 3500 km to perform a thermo-electric distributed co-simulation of an all-electric destroyer ship. The motivation behind this work was to:

1. Investigate the possibility of sharing resources to expedite the joint research projects.
2. Establish an efficient communication link for data transfer to run the co-simulation.
3. Investigate the effects of latencies on stability and accuracy of the geographically distributed simulation.
4. Identify potential solutions for minimizing latencies.
5. Performing remotely controlled simulation and troubleshooting.

The paper is organized as follows: Section II provides a brief description of the power system and thermal system of the e-ship and Section III discusses the architecture and hardware details of both simulators and their interfacing and communication. Section IV discusses the communication latency observed while a loop-back simulation was run between the two simulators and Section V describes the modeling of power system and thermal management system. Results are given in Section VI followed by conclusion in Section VII.

II. Power and thermal management Systems of All-Electric-Ship

A. *Power system of all-electric-ship*

The architecture of the e-ship is based on the concept of the Integrated Power System (IPS) of a notional destroyer ship [7]. The outline of this concept is depicted in Fig. 1 which shows a power generation system, load center and a ship propulsion system. A 4.16 kV Medium Voltage (MV) ring bus is powered by two 36 MW main gas turbine-driven synchronous generators (MTG 1 and MTG 2) and two 4 MW auxiliary gas turbine generators (ATG 1 and ATG 2). The MV subsystem supplies power to two 36.5 MW propulsion motors via variable speed drives. In the present study, a single AC-DC power conversion module number 4 (PCM 4) rectifies 4.16 kV AC to 1 kV DC for powering port and starboard DC buses. The longitudinal DC buses feed 1 kV DC power to zonal load centers in the ship. Only one of the load center zones is considered for this case study. At the zonal level, port and starboard DC-DC conversion modules number 1 (PCM 1) step the DC bus voltage down from 1 kV to 800 V. These converters simultaneously feed an 800 VDC bus through auctioneering diodes, which perform continuous current sharing between the port and starboard PCM 1s in the zone. Some DC load equipment operates directly from this bus. AC loads are supplied through a DC-AC inverter (PCM 2) that converts 800 V DC to 120/208 V AC or 450 V AC.

B. *Thermal management system of all-electric-ship*

In general, the thermal management system of an all-electric ship consists of cooling fluids such as chilled water, chilled air or seawater based heat exchangers and heat sinks, all controlled by a system level process control. The heat exchangers use seawater and freshwater loops for cooling the heat sink plates.

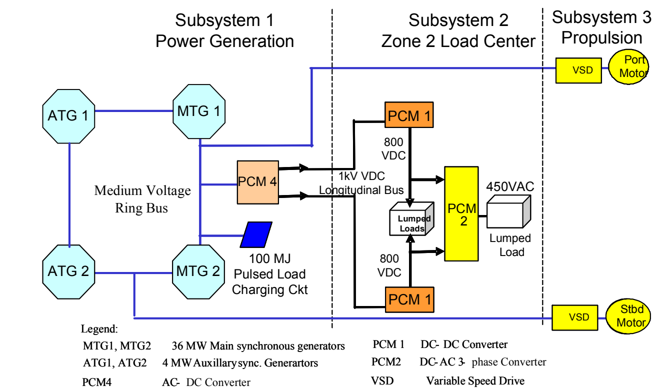

Figure 1. Notional architecture of electric power system of an e-ship

Seawater passes through a plate and frame to the heat exchanger where freshwater exchanges heat and becomes cool before re-circulated in the loop. This process starts by drawing seawater from the sea and pumped through the heat exchanger. At the same time, fresh water is pumped through the hot power devices to absorb their heat. The hot freshwater is then carried to the heat exchanger where the heat is dumped into the seawater and ejected from the ship into the sea. In some cases, metallic heat-sinks are used to remove the heat through natural air cooling or force-air cooling methods.

III. Configurations of RTDS and OPAL-RT Simulators

RTDS and OPAL-RT are two well known simulators available in the industry for performing real-time electromagnetic transient simulations of large networks. A short description of the respective systems at FSU and U of A is given in the following sections followed by detailed explanations of the co-simulation setup at each facility.

A. RTDS simulator overview at CAPS-FSU

The RTDS is designed to simulate systems in real-time with time step sizes on the order of 50 μs. For power electronics, the RTDS provides a feature to simulate such subsystems with smaller time-steps (typically around 2 μs) [8]. The simulator at CAPS has 330 Analog Devices ADSP21062 (SHARC) digital signal processors and 50 RISC processors (IBM PPC750CXe and IBM PPC750GX), 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*. There are 14 RTDS *racks* installed at the real-time power systems simulation facility at CAPS, and a more complete description can be found in. 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, the software provides the user with the capability to develop new components. Control over processor allocation and the execution order of components is also provided through the software. A more complete description of this installation can be found in [9] and [10].

B. OPAL-RT simulator overview at RTX-LAB (U of A)

The RTX-Lab real-time simulator is built from commercial-off-the-shelf components such as general purpose CPU based high speed computers as the main computation engine, standard computers for model development and GUI, FPGA based I/Os for external communication and gigabit Ethernet network for communication between computers. The main computation nodes, known as the *Targets* are comprised of dual Intel Xeon processor based 3.0 GHz computers and a separate set of PCs, known as the *Hosts,* are comprised of 3.0 GHz Pentium IV processor based computers. The *Target* computer facilitates the connection of external hardware through the FPGA-based I/O ports and a data transfer link between the *Host* and the *Target* through a gigabit Ethernet link. External hardware devices can be interfaced with the real-time simulator to perform hardware-in-the-loop simulation.

The *Target* computer runs on a Linux based real-time operating system which offers eXtra High Performance (XHP) mode operation through CPU shielding where one CPU is dedicated for the simulation while the other CPU is responsible for running the OS and other jobs such as interrupt handling, writing to the disk and I/O operations. The *Host* computer runs on Windows XP on which a real-time interfacing software RT-LAB [11] is installed to perform the co-ordination of all the hardware involved in the simulation. Further details about the hardware, software, modeling and various communication techniques used in the RTX-Lab real-time simulator are available in [6].

C. Co- simulation setup at CAPS-FSU

In traditional HIL simulations, the high-speed analog input and analog output ports of the RTDS are essential for synchronizing the software simulation with physical power system elements, such as protection relays, motor drive controllers, and sensors for voltages and currents. Previous co-simulations have been run with the RTDS which used analog signals for data interchange [12], but a computer network-based co-simulation would not use analog signaling. In computer network co-simulations, a sub-sampled data set must be selected for transfer from and to a remote simulation, since continuous network streaming of all data points is not feasible.

As shown in Fig. 2, digital I/O ports on the RTDS are used to transfer data between the RTDS and two microcontrollers using a time-division multiplexing (TDM) scheme. The microcontrollers are Rabbit RCM3200, with Ethernet, TCP/IP, and ModbusTCP support, and custom C software was developed at CAPS-FSU to support the TDM transfer and data buffering. One microcontroller unit is dedicated for

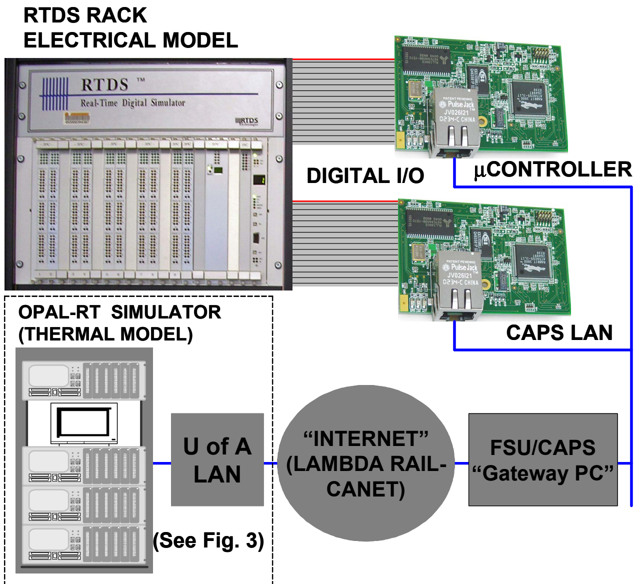

Figure 2. Hardware setup at CAPS-FSU for geographically distributed co-smulation

input and one for output. The microcontrollers are both Modbus slaves (servers) for an intermediate gateway computer, but could also support a utility SCADA system.

D. *Co-Simulation setup at U of A*

Similar to the RTDS, where sub-systems are simulated simultaneously on different *rack*s, the default hardware setup at the RTX-Lab was suitable for locally distributed real-time simulation where models can be split into multiple *Targets* linked to each other through various communication links such as the Gigabit Ethernet, Infiniband link and signal wire. For geographically distributed simulation, a communication link was required for exchanging data between the two simulators over such a long distance. Among the available cost-effective options, the publicly available Internet was used as the backbone of the communication link between the two simulators. The high speed Internet backbones used for interconnecting research networks in the United States and Canada (Florida Lambda Rail, National Lambda Rail, and CANET), provide high-throughput, low-latency communication.

Fig. 3 illustrates the hardware setup at the RTX-Lab where *Target* node 1 is used as the main computation engine and *Host* 1 is used to prepare the model using SIMULINK and RT-LAB. The Host is connected to two network switches using two Network Interface Cards (NIC1 and NIC2) installed on it. NIC1 communicates with the Target and NIC2 communicates with the external world Internet (WAN) through the HP switch and the Sonic Firewall. The main requirement of NIC2 link is to acquire the RT-LAB license from the license manager running on a separate computer. A router is added and configured to link the *Target*s to the WAN so that simulation results can be sent directly to any remote computer such as the gateway server located at the

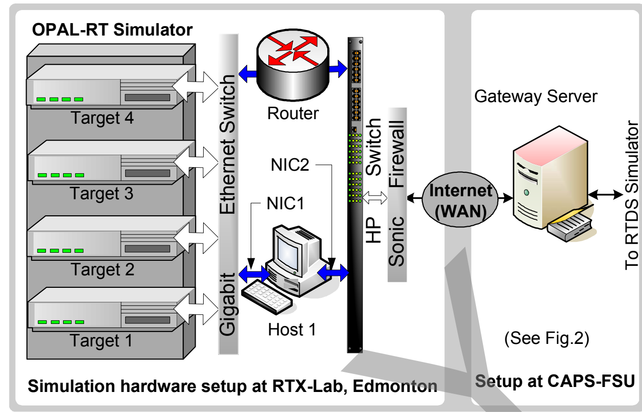

Figure 3. Hardware setup at the RTX-Lab (U of A) for geographically distributed co-simulation.

CAPS-FSU. In addition to the operating systems (Windows and Linux) required for both *Hosts* and *Targets*, the *Host* computer also needs Simulink and RT-LAB software which were basically used to create, compile and load the model into the *Target*. A client communicator program, developed in C was embedded with the Simulink model which allows the *Target* to send data over the Internet to a predefined remote server with a fixed IP address and to receive data from the remote server.

E. *Server-Client communication*

A gateway computer (S*erver)* at CAPS-FSU was dedicated for TCP-based data transfer, using custom networking software developed in Microsoft Visual C++. This gateway program connects to both ModbusTCP slaves, and waits for a connection from the remote simulation on the OPAL-RT system (*Client*). After the remote connection is established, the gateway waits for a transfer of a data set from the OPAL-RT system, and then replies to the remote system with a data set from the RTDS. The gateway program must also communicate with the two ModbusTCP microcontrollers, sending data to one, and receiving from the other. In turn, the microcontrollers communicate with the RTDS via the TDM digital I/O scheme. The process is repeated, with the OPAL-RT system initiating each two-way data transfer. The current data set is a set of 32 floating point values in each direction.

IV. Latency Investigation: A Loop-Back Study

To determine the communication latency between the two simulators, a loop-back test system was designed and tested on the geographically distributed simulation system. In the loop-back test, a low frequency sine wave (0.1 Hz) was generated on the RTX-Lab simulator and sent to the RTDS simulator. The RTDS simulator received discrete data points of the sine wave, while sending back the current data point to the OPAL-RT simulator. The signal was then re-collected and the latency was measured at the RTX-Lab. Fig. 4 shows the model prepared in RT-LAB environment where the sine wave was sent through the "Asynchronous Send" block to the remote server located at CAPS-FSU. Similarly, another block known as "Asynchronous Rec" was used to collect the data

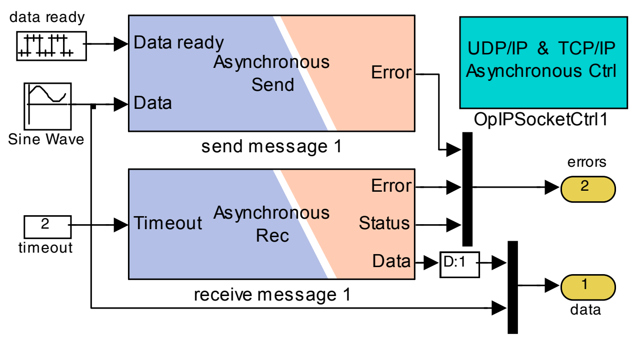

Figure 4. Loop-back test model developed in Simulink within the RT-LAB environment

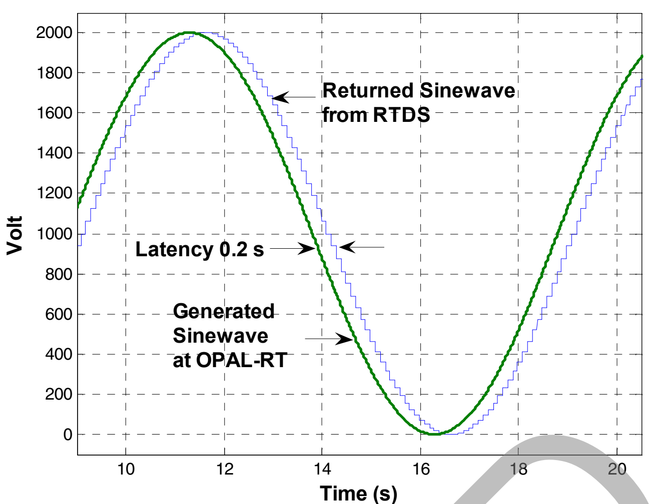

Figure 5. Generated and returned sine wave of 0.1 Hz recorded at RTX-Lab real-time simulator

sent by the remote server. Behind both of these blocks, s-functions, written in C language, were used to establish the communication link between the *Target* node and the remote gateway computer (server). A separate block named "UDP/IP & TCP/IP Asynchronous Control" was used to assign the desired protocol along with the IP address of the remote server. This block was also used to load the client program for the simulation. The generated sine wave and the received sine wave were then compared for accuracy and latency of the received signal.

Fig. 5 shows both the original transmitted sine wave and the returned sine wave from RTDS setup which were captured in the RTX-Lab. A time-step of 1ms was used for the test simulation. The continuous sine wave is the one generated at the *Target* of the RTX-Lab simulator and sent to the RTDS simulator while the discrete sine-wave is the one returned from the RTDS simulator. The latency, which is defined as the time difference between the two sine waves depends on many factors such as the Internet speed, distance, server speed, the LAN congestion and others. Results obtained from the loop-back test show a maximum latency of 0.208 s for both transmitting and receiving the data including all the interfacing and communication delays. This latency translates to 0.126 radians for the 0.1 Hz sine wave. As the hardware remains same, the factors that could influence the latency are the Internet speed and the LAN congestion. Therefore, the latency was investigated at different times of the day expecting that these factors may influence the latency at different times of the day. However, no significant difference was observed and this is mainly due to the very high-throughput Lambdarail-CANNET network between the two universities.

V. System Modeling and Thermo-Electric Co-Simulation

A. *Modeling of a shipboard power system at CAPS, FSU using RTDS*

A large-scale model of a notional destroyer-class electric ship system was developed at CAPS for real-time simulation studies and hardware-in-the-loop experiments. The model implementation details are described here, again referring to Fig. 1.

- A DQ-axis synchronous machine model with a voltage regulator/exciter, prime mover, and governor represents the main and auxiliary generators. An aero-derivative gas turbine model is employed that includes details of the governor, combustion chamber, and exhaust gas temperature measurement time constants. The voltage regulator is a generic model employing PI control. A load sharing routine monitors the real and reactive powers supplied by each generator and provides control signals to equally divide the loads between connected generators as a fraction of each generator's capacity.
- A DQ-axis induction motor model represents the propulsion motors. The motor drives are back-to-back, two-level, GTO bridges with front-end PWM control switching at 1 kHz. The motors employ vector control and active damping is used in the drive front-end controls to complement passive filtering in minimizing drive harmonic distortion. All power conversion modules are modeled as ideal switching devices. The PCM 4 rectifier is a 12-pulse thyristor-driven modules with PI voltage control. PCM 1 DC buck converters switch at 1 kHz and employ proportional-integral (PI) voltage control. The PCM 2 inverter is a sinusoidal PWM GTO module with current and voltage control, executing on the high-speed RISC processor with a simulation time step of less than 2 µs. Ship's service loads are represented in the RTDS E-ship model as lumped load categories at the 800 VDC bus level.
- As it is important to accurately model the behavior of the propulsion motors and drives, the load torque applied to the motors from the propellers must also be modeled to a reasonable degree of accuracy in order to assess the effect of ship maneuvers on the power system. The hydrodynamic model of the ship accounts for the inertia of the propeller and entrained water, the torque exerted on the motors by the propellers and the thrust exerted on the ship by the propellers as functions of the ship speed

and propeller speeds, and the hydrodynamic resistance of the ship as a function of the ship speed. The model restricts the simulation to one-dimensional motion of the ship, but allows for both positive and negative values of the ship speed and angular velocities of the propellers. It should be noted that the required computational resources could be significantly reduced by employing averaged models for many of the above model components. However, the large number of thermal loads in a future naval combatant must be modeled in sufficient detail to ensure against negative and unforeseen effects such as thermal runaway during cold start.

B. Modeling of thermal system at RTX-Lab, (U of A) using Simulink and RT-LAB

For this geographically distributed thermo-electric co-simulation, two types of cooling mechanisms were modeled. The first model is a naturally cooled heat-sink while the second model is both naturally cooled and water-cooled heat-sink with a pipe at the center of the heat-sink through which water is passed. The water flow rate is maintained such that the outlet temperature of the water reaches the body temperature of the heat-sink. As shown in Fig. 6, we considered a heat-sink with a dimension of w x l x d, where, w is the width, l is the length and d is the depth of the heat-sink. For the sake of simplicity, neglecting the variation of temperature stress in the space domain, the thermal equilibrium equation that can best express the heat-sink process is given as [13],

$$\rho_c c_c V_c \frac{d[T_c(t)]}{dt} = Q(t) - \sum_{i=1}^{m} h_c A_c [T_c(t) - T_a(t)] - \sum_{i=1}^{m} \sigma \varepsilon A_c [T_c^4(t) - T_a^{\,4}(t)] \quad (1)$$

where, ρ_c is the density of the heat-sink material, c_c is the specific heat and V_c is the volume of the heat-sink. $Q(t)$ is the heat input in Watt and $d[T_c(t)]$ is the change in temperature with respect to its previous time-step. σ is the emissivity, ε is the Stefan-Boltzman constant [5.67 x 10^{-8} J/(s-m^{2}-K^{4})] for radiation and A_c is the surface area from where heat - convection and radiation takes place. h_c is the convection-coefficient which is temperature dependent and varies non-linearly with temperature. However, for the heat-sink with water cooling system, the dynamics can be expressed as

$$\rho_c c_c V_c \frac{d[T_c(t)]}{dt} = Q(t) - \sum_{i=1}^{m} h_c A_c [T_c(t) - T_a(t)] - \sum_{i=1}^{m} \sigma \varepsilon A_c [T_c^4(t) - T_a^{\,4}(t)] - \rho_w v_w c_w A_w \frac{[T_{out}(t) - T_{in}(t)]}{2} \quad (2)$$

where, ρ_w is the density, c_w is the specific heat and v_w is the velocity of water, A_w is the cross sectional area of the pipe and T_{out} and T_{in} are the outlet and inlet temperature of water.

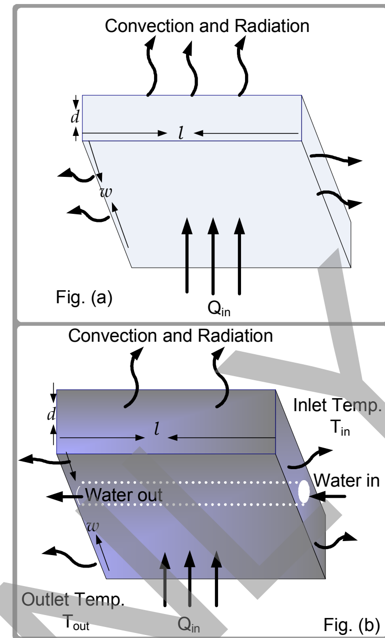

Figure 6. Heat sinks and their heat transfer mechanisms

These equations are differential-algebraic in nature, and to model them in Simulink, few assumptions were made so as to avoid non-linear iterative solutions. For example, instead of the current temperature $T_c(t)$, the temperature of the previous time-step, $T_c(t\text{-}\Delta t)$, was used for calculating the heat-loss due to the radiation and convection. This assumption is expected to have very little impact on the accuracy as the change in temperature of the solid mass in a time-step of 1 ms is very small. The thermal model developed using Simulink within the RT-LAB environment is shown in Fig. 7. Similar to the loop-back test model, the two main blocks "Asynchronous Send" and "Asynchronous Rec" were used to send and receive simulation data to and from the RTDS, respectively. Eleven data ports were used to receive *bit_data* and ten inputs from the RTDS model. Ten output data ports were used to send *bit_data* (set to 0) and nine calculated temperatures $T_c(t)$ to the RTDS model. *Bit_data* was used to operate switches by sending 1 or 0 from one model to another model. The Simulink thermal subsystems, inserted between the "Asynchronous Send" and "Asynchronous Rec" blocks take in "kW Loss" as inputs and produce "Temperatures" as output. Some of the subsystems are modeled as water-cooled heat-sink and the rest are naturally cooled heat-sinks. All the input and output data were monitored on a *Host* computer.

VI. Thermo-Electric Co-simulation Results

To study the temperature response of the thermo-electric co-simulation, the ship speed was changed several times at regular intervals in the RTDS model. The change in speed changed the power losses in various parts of the electric

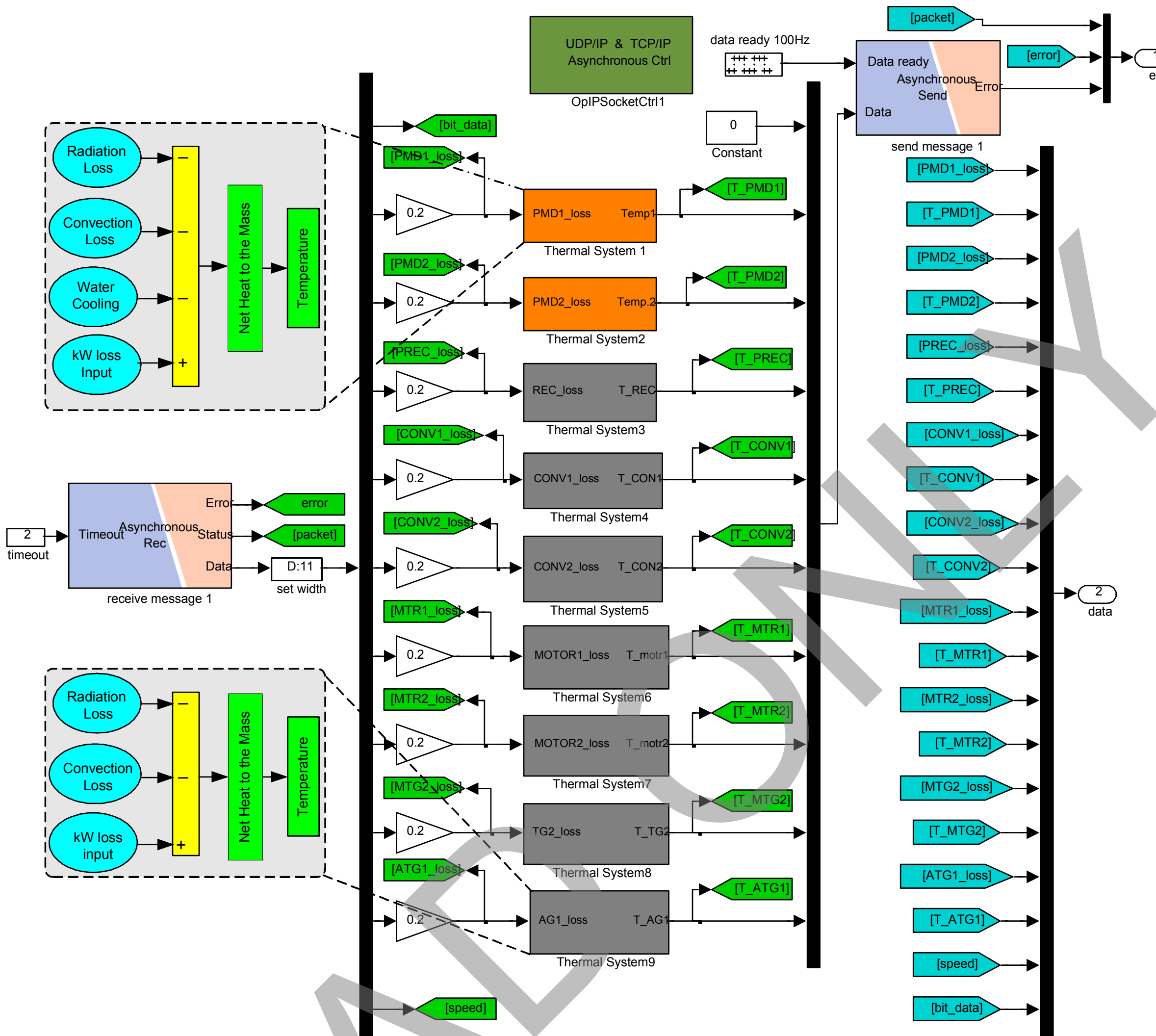

Fig.ure 7. Thermal model implementations in SIMULINK within the RT-LAB environment

system. These power losses were sent to the OPAL-RT simulator through the established communication link. The thermal model in the OPAL-RT simulator received that data as input and calculated the temperature of each heat-sink. All the temperature data were then sent to the RTDS model where they were used for generating control signals to take further actions. The power loss signals that were supplied by the RTDS model were from Propulsion Motor Drive 1 (PMD1), Propulsion Motor Drive 2 (PMD2), Rectifier (PREC), DC-DC Converter 1 (PCONV1), DC-DC Converter 2 (PCONV2), Propulsion Motor 1 (PMTR1), Propulsion Motor 2 (PMTR2), Main Turbine Generator 2 (PMTG2) and Auxiliary Turbine generator 1 (PATG1).

Fig. 8 shows the simulation results of an illustrative maneuver where the speed of the ship was consecutively changed between 25 nautical miles per hour (knots) and 29 knots at an interval of 100 s. It is found that with the increase of ship-speed, the power loss in the propulsion motor drives increases. The maximum power loss from PMD1 reaches a value of 3.6MW (approximately 10% of the installed power) which leads to a corresponding maximum temperature of 53°C. Similarly, the minimum power loss was found to be 2.3 MW which brought down the temperature of the heat-sink to 46°C. Similar results were observed for PMD2 as well. During each change of ship speed, a small transient overshoot in power loss was observed which stabilized within a few seconds. Similar transient overshoots were observed in the results of the propulsion motors and the turbine-generator systems. As expected, almost no impact was seen on the power losses of the ship service rectifiers and converters. They would only see a change in power and hence a change in losses if power demand on those units would change because of the simulated maneuver. For example, in a more realistic simulation the power for the cooling water pumps may change as the heat load on the thermal system increases. But none of these more complex interactions was modeled in this illustrative example. As a result, there was no change in the temperature of the heat-sinks attached to these devices except during initialization. Fig. 9 shows such immunity of the rectifier and converter systems.

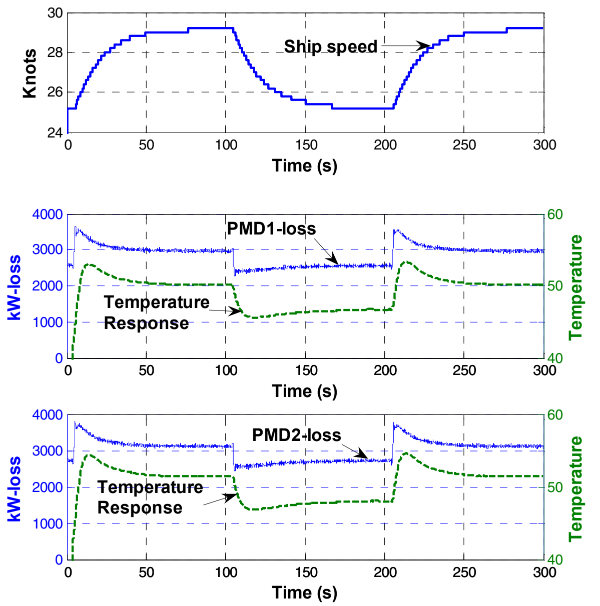

Figure 8. Transient response of power losses and temperature change for propulsion motor drives when ship speed is changed

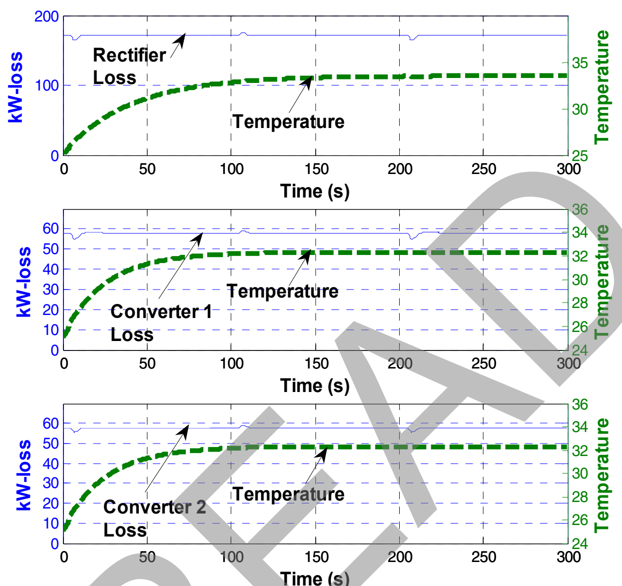

Figure 9. Transient response of power losses and temperatures for ship service rectifier and converters when ship speed is changed

VII. Conclusions

Thermo-electric co-simulation of an e-ship using cost-effective resources and accurate modeling technique is a significant challenge. In this paper, the viability of remote co-simulation using publicly available Internet while maintaining acceptable accuracy has been demonstrated. Two powerful real-time simulators RTDS and OPAL-RT were interfaced through the Internet and other custom hardware to perform this study. A model of e-ship was developed using RSCAD in the RTDS environment while the thermal model was developed in Simulink in the RT-LAB environment. Due to the in-compatibility of commercial thermal modeling software, heat-sink based thermal models were used for this study. However, future research will concentrate on more accurate and efficient custom developed dynamic thermal models. The accuracy of the thermo-electric co-simulation results was validated by running an off-line simulation locally using Simulink. The simulation was stable and the use of TCP/IP protocol ensured minimum data loss. Any data loss which may exist, however, hardly influenced the simulation results as the thermal system response was slow. As this study successfully performed the distributed co-simulation of two different systems with different time-constants, we believe that distributed co-simulation for various systems can be further extended to hardware-in-the-loop simulation to allow remote control and testing of critical hardware.

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