Power System Control

Norbert Doerry

November 9, 2025 (rev A)

1. Introduction

As stated by Doerry (2007):

> "The primary aim of the design of a shipboard electric power system has traditionally been survivability and continuity of the electrical power supply. Survivability relates to the ability of the power system, when damaged by a threat, to support the ship's ability to continue its missions. Power continuity relates to the ability of the power system to reliably provide power to ship systems under normal operations."

The design of the electrical power control system should first and foremost focus on accomplishing this aim.

Within many of the standards, continuity of the electrical power supply is addressed through quality of service.

Most large ships employ a digitally based machinery control system that incorporates an electrical power control system. These control systems employ both a physical architecture which details the physical control equipment and how they are interconnected, as well as a logical architecture that describes how functions are allocated to different levels (or layers) of the electrical power control system.

Most digital control systems are designed based on the concept of time scale separation. Control loops and actions that must occur rapidly occur at the lowest levels as part of hardware, or directly controlling hardware. Control loops in progressively higher layers of the logical architecture have characteristic times that are progressively longer. The concept of a characteristic time is major determinate of which control layer a function must be allocated to in order to have acceptable system performance.

Cybersecurity requirements are continuously evolving and impacting the selection of control hardware, architectures, and algorithms.

Older ships and some modern less complex ships still employ point-to-point connectivity between controllers and controlled devices. This document does not address these systems.

2. Power system physical control architectures

2.1. Information model

DPC 202-1 defines an information model for shipboard machinery control systems to include electrical power control systems.

2.1.1. Presentation Layer.

The graphical user interface for interacting with the user. Resides within the human-machine interface (HMI)

2.1.2. Information Layer.

Implementation of data centric logic, such as information and alarm processing, transfer of control logic, managing historical and other data, etc. Resides in the HMI.

2.1.3. Network Layer

Transmission of data among the other layers. The network is usually dedicated to machinery control system data. The network may be partitioned into subnetworks for each zone or machinery room; these subnetworks are usually interconnected at the total ship level.

Dedicated field device networks, not directly connected to the total ship network, may also be employed to connect controllers at the control layer with field devices at the field device layer.

2.1.4. Control Layer

The digital implementation of controls based on sensor data, operator input, and configuration data provided by other layers; the physical implementation of controls is done via communications with field devices. The control layer can be implemented as an integral part of an electrical system component (such as a generator set), or as a part of a stand-alone controller.

2.1.5. Field Device Layer

The field device layer is the interface between the digital control environment and physical hardware. The field device layer includes such items as tank level indicators, valve actuators, motor controllers, etc.

2.2. Hardware

DPC 202-1 identifies five hardware elements of a machinery control system: Field device, Input/Output Unit, Controller, Network and Human Machine Interface. Figure 1 depicts the relationships among these elements in a typical digital machinery control system implementation.

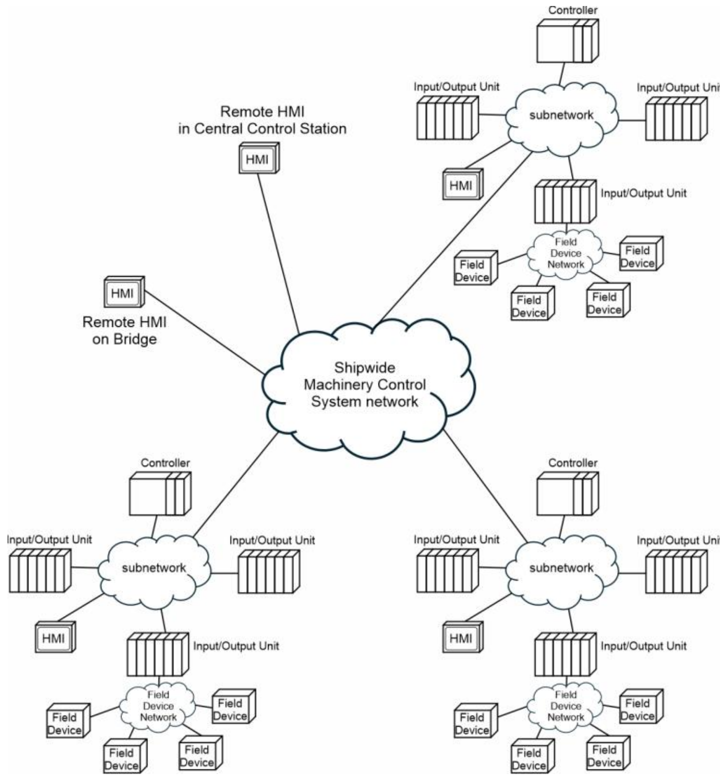

Figure 1: Digital machinery control system physical architecture

2.2.1. Field Device

A field device converts digital commands to physical actuators and measurements of the physical environment to digital data. Field devices typically communicate with Input/Output Units, and possibly with other field devices. A field device may be a stand-alone component, or could be embedded in equipment such as a switchboard, generator set or power converter.

2.2.2. Input/Output Unit

The Input/Output Unit interfaces with both the field devices and the controller. The Input/Output units can perform data translation, signal conditioning, and basic signal processing, but are not intended to implement control algorithms. An Input/Output Unit may be a standalone component that is part of the machinery control system, or could be embedded in equipment such as a switchboard, generator set or power converter.

2.2.3. Controller

A controller is typically implemented as a Programmable Logic Controller (PLC) or Control Processor. The controller executes control algorithms based on signals form Input/Output units, other controllers, and HMIs. The digital control algorithm outputs are communicated to the applicable Input/Output units for implementation. Each subnetwork generally has one or more controllers. A controller may be a stand-alone component that is part of the machinery control system, or could be embedded in equipment such as a switchboard, generator set or power converter.

2.2.4. Network

Separate networks are typically employed to connect components in different levels of the control system. The lowest level includes field devices and input/output units which are connected via a field device network. The next level includes input/output units, HMIs and controllers that connect via a subnetwork. The final level interconnects the subnetworks, includes HMIs, and may include additional controllers.

2.2.5. Human-Machine Interfaces

Figure 2: USS Forrest Sherman (DDG 98) Electric Plant Control Console (U.S. Navy Photo)

Figure 3: USS Goldsborough (DDG 20) Ship Service Switchboard (Public Domain)

HMIs exist both in central control stations as depicted in Figure 2; or can be local control stations such as at a switchboard as depicted in Figure 3. The primary purpose of the HMI is to provide the operator with situational awareness of the operation of the electrical power system and to provide a means for the operator to configure or provide control set points for the electrical power system.

2.3. Topologies

Multiple topologies are applicable to the field device network, subnetwork, and the shipwide machinery control system network depicted in Figure 1. The choice of topology is usually based on cost, reliability, and survivability.

2.3.1. Point to Point

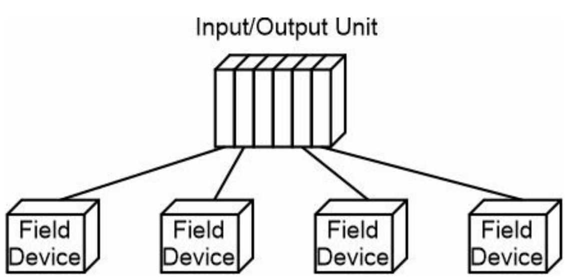

Figure 4: Point to point topology

Figure 4 depicts a point to point topology implementation of a field device network; each field device has a direct hard-wired connection to the Input/Output Unit. A point to point topology is typically restricted to the field device network. A point to point topology may be desirable if multiple interface types are required for the various field devices.

2.3.2. Star

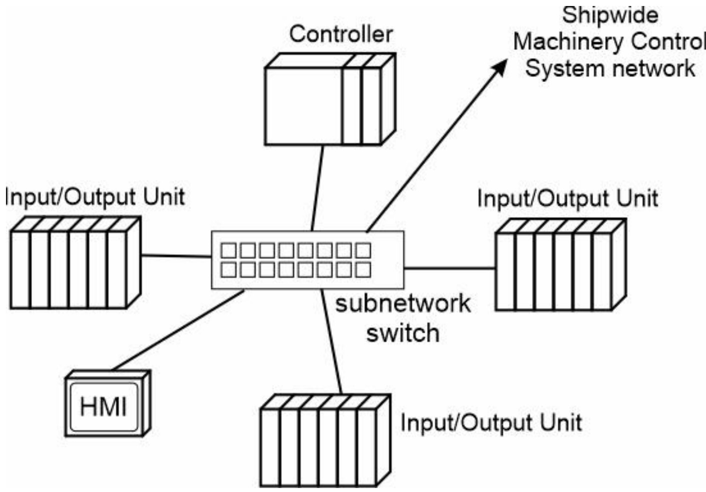

Figure 5: Star topology

Figure 5 depicts a star topology implemented on a subnetwork. Each device connects to a network (subnetwork) switch using the same network interface type. The network switch is a single point-of-failure; it should have extremely high reliability. From a cybersecurity perspective, the connection to the shipwide machinery control system network may be shut off if needed; the subnetwork should be able to operate separately as an enclave.

The star topology is applicable to field device networks, subnetworks, and the shipwide machinery control system network.

2.3.3. Dual Star

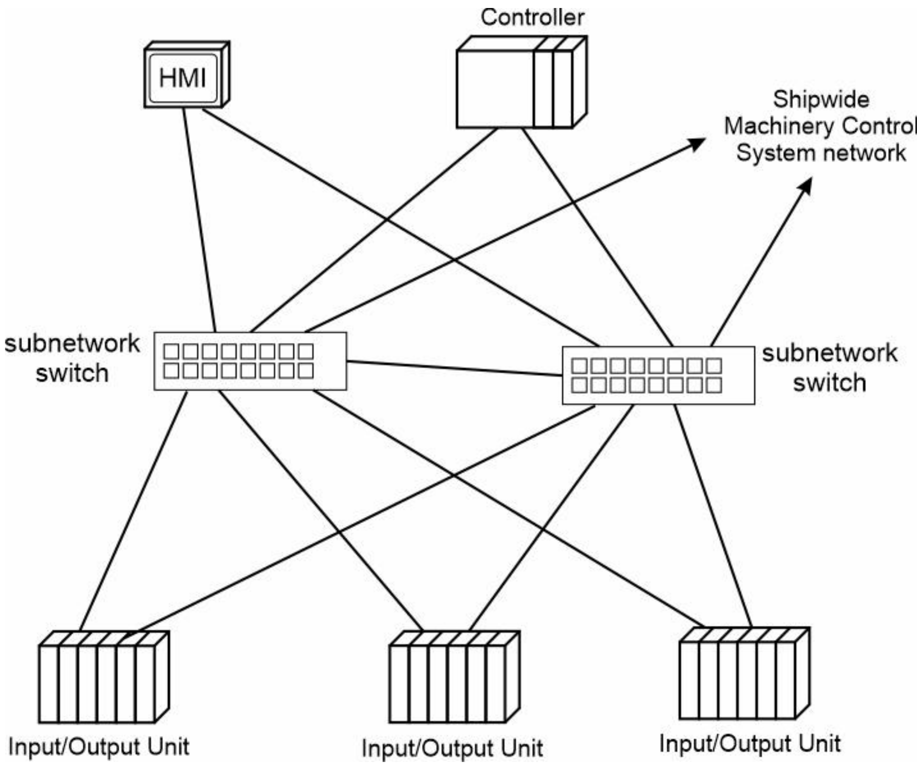

Figure 6: Dual star topology

Figure 6 depicts a dual star topology implementation of a subnetwork. Each device connects to two independent subnetwork switches which in turn connect to the shipwide machinery control system network. Because of the two subnetwork switches, the dual star topology is much more reliable and survivable than the star topology. The cost however, is substantially more.

The dual star topology is applicable to field device networks, subnetworks, and the shipwide machinery control system network.

2.3.4. Ring

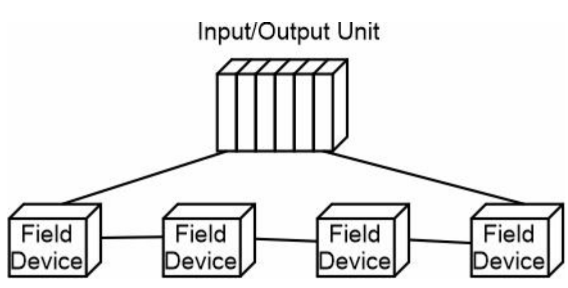

Figure 7: Ring bus topology

Figure 7 depicts a ring bus for a field device network. Each field device communicates all data traffic, including its own, to two neighbors. The field devices are connected in a daisy-chain that begins and ends with the Input/Output unit. A ring bus can tolerate loss of a single connection; the loss of two or more connections will result in at least one device losing connectivity. If the field devices are not too far apart, a ring bus may require less cable, and thus cost less, than other topologies. Unlike a star or dual star topology, a ring bus does not require a subnetwork switch.

The ring bus topology is applicable to field device networks and subnetworks. It generally is not used for the shipwide machinery control system network.

2.3.5. Dual Ring

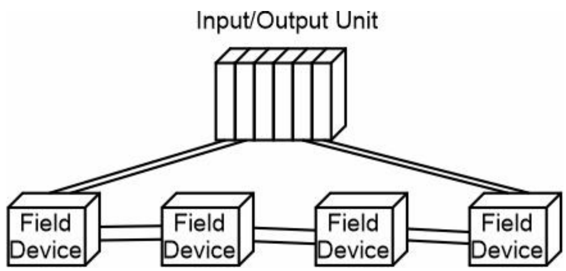

Figure 8: Dual ring bus topology

Figure 8 depicts a dual ring bus for a field device network. Each field device communicates all data traffic, including its own, to two neighbors using redundant connections. The field devices are connected in a daisy-chain that begins and ends with the Input/Output unit. A dual ring bus can tolerate the loss of multiple connections without a device losing connectivity. The amount of cabling is double that of the ring bus topology and is likely to be more expensive.

The dual ring bus topology is applicable to field device networks and subnetworks. It generally is not used for the shipwide machinery control system network.

2.3.6. Mesh

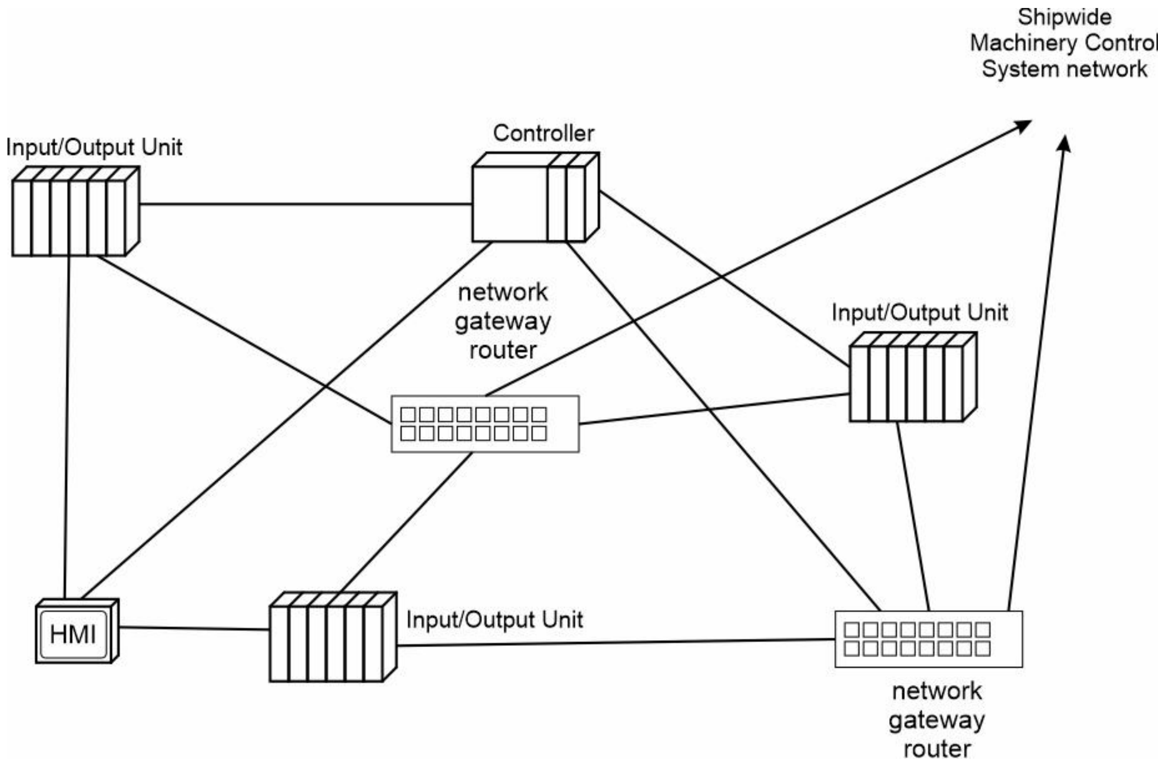

Figure 9: Mesh topology

Figure 9 depicts a mesh topology implementation of a subnetwork. Each device connects to multiple other devices. Typically, two or more network gateway routers connect to the shipwide machinery control system network. Data can be routed through multiple paths between any two devices. Mesh networks can be very reliable and survivable.

In a full mesh topology, every device connects to every other device. While feasible in networks with a small number of devices, the total number of required connections grows very quickly as the number of devices increases $\left(n \times \frac{n-1}{2}\right)$. A full mesh network is usually too expensive to implement.

The mesh topology is applicable to field device networks, subnetworks, and the shipwide machinery control system network.

3. Time scale separation

Time scale separation is a technique for partitioning the analysis and control of systems with dynamics that are of very different time scales. Take for example, a parameter that is the sum of three dynamic variables:

$$x(t) = y_1(t) + y_2(t) + y_3(t)$$

Where:

$$\frac{dy_1(t)}{dt} = -\frac{1}{\tau_1} y_1(t) \quad , \quad y_1(0) = 100$$

$$\frac{dy_2(t)}{dt} = -\frac{1}{\tau_1} y_2(t) \quad , \quad y_2(0) = 200$$

$$\frac{dy_3(t)}{dt} = -\frac{1}{\tau_1} y_3(t) \quad , \quad y_3(0) = 400$$

Solving

$$y_1(t) = 100e^{-\frac{t}{\tau_1}}$$

$$y_2(t) = 200e^{-\frac{t}{\tau_2}}$$

$$y_3(t) = 400e^{-\frac{t}{\tau_3}}$$

$$x(t) = 100e^{-\frac{t}{\tau_1}} + 200e^{-\frac{t}{\tau_2}} + 400e^{-\frac{t}{\tau_3}}$$

If the time scale of interest is τ_0 and

$$\tau_0 \gg \tau_1$$

$$\tau_0 \approx \tau_2$$

$$\tau_0 \ll \tau_3$$

Then we can assume that $y_1(t)$ has reached its steady-state value and can be set to its limit as *t* approaches infinity:

$$y_1(t) \approx y_1(\infty) = 0$$

And $y_3(t)$ can be assumed to be near its initial value and can be set to its initial condition:

$$y_3(t) \approx y_3(0) = 400$$

This leaves $y_2(t)$ as the only dynamic of interest …

$$x(t) \approx 200e^{-\frac{t}{\tau_2}} + 400$$

For an initial case, if $\tau_1 = .001\ s$, $\tau_2 = 1\ s$, and $\tau_3 = 1000\ s$ and the time scale of interest is 1 second, then the graphs for $y_1(t)$, $y_2(t)$, and $y_3(t)$ are shown in Figure 10. As expected, $y_1(t)$ is near its steady-state value over the time scale of interest and $y_3(t)$ is near its initial value. The resulting values for $x(t)$ and $y_2(t)$ + 400 are shown in Figure 11. At the time scale of interest, only the dynamics associated with $y_2(t)$ need be considered.

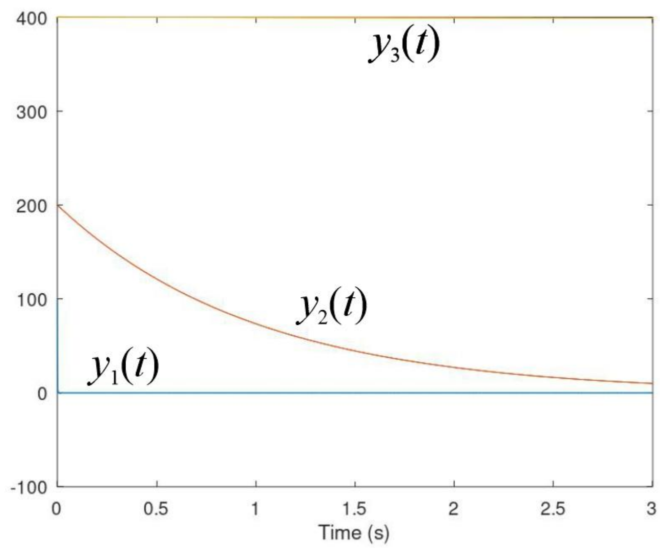

Figure 10: Values of y_1, y_2, and y_3 for initial case.

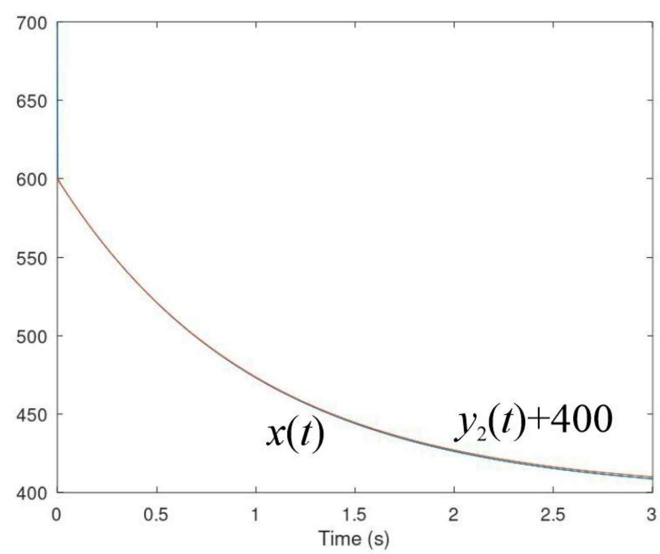

Figure 11: Values of $x(t)$ and $y_2(t)$+400 for initial case

For a second case we will narrow the gap between the time scales, if $\tau_1 = .1\ s$, $\tau_2 = 1\ s$, and $\tau_3 = 10\ s$ and the time scale of interest is still 1 second, then the graphs for $y_1(t)$, $y_2(t)$, and $y_3(t)$ are shown in Figure 12. As expected, $y_1(t)$ deviates its steady-state value over the beginning of the time scale of interest and $y_3(t)$ deviates from its initial value. The resulting values for $x(t)$ and $y_2(t) + 400$ are shown in Figure 13. At the time scale of interest, the dynamics associated with $y_2(t)$ influence $x(t)$ the most, but $y_1(t)$ and $y_3(t)$ also influence $x(t)$ to a lesser degree.

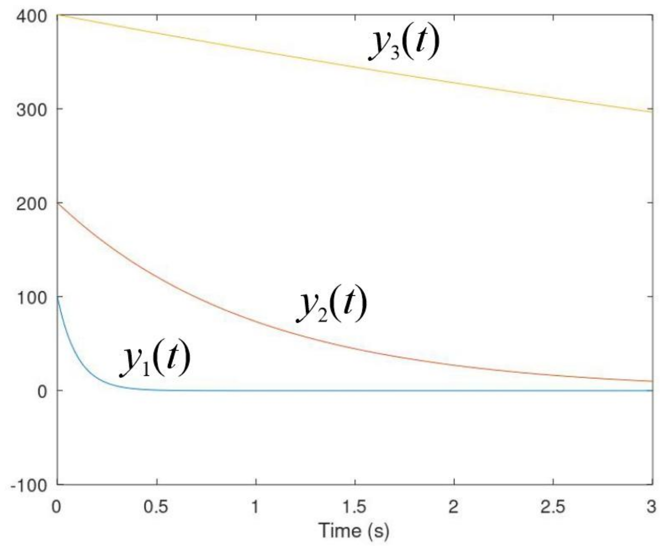

Figure 12: : Values of y_1, y_2, and y_3 for second case.

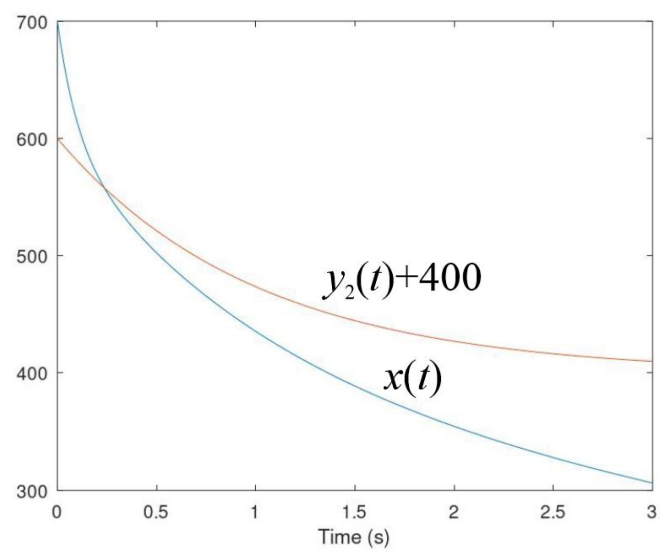

Figure 13: Values of $x(t)$ and $y_2(t)$+400 for second case

As shown in Figure 13, one order of magnitude difference in time constants results in some coupling of the terms of $x(t)$. In general, two or more orders of magnitude difference in time constants is desirable, but not always achievable with available hardware and software.

Within control system applications, some of the time constants are determined by nature; physics dictate the dynamics. Other time constants are the choice of the control system designer. Time scale separation seeks to simplify the control systems by minimizing the interactions of different dynamic elements. If the time scale of dynamics cannot be separated, they should be addressed together by the control system.

A narrative example of time scale separation would be the operation of an office coffee mess. In this coffee mess, members pay annual dues, coffee and supplies are replenished, monthly, and coffee is consumed daily. The daily users, when pouring and preparing their coffee, are not concerned with the monthly replenishment of supplies, nor the annual dues. Once a month, the coffee mess supply officer estimates demand for the following month, adds in a reserve amount then subtracts off the remaining amount of coffee in the mess to determine how much coffee to procure that month. The coffee mess supply officer purchases the coffee using funds provided by the coffee mess treasurer. The coffee mess supply officer is not concerned with each individual's daily consumption of coffee; knowledge of the overall monthly consumption is sufficient. The coffee mess supply officer is also not concerned with how funds are procured; as long as there are always sufficient funds to cover the monthly bill. Once a year, the coffee mess treasurer estimates the amount of funds that will be needed in the following year, adds a reserve amount, then subtracts the current amount of funds in the coffee mess treasury and divides the result by the number of members in the mess to determine the annual dues amount. The coffee mess treasurer is not concerned with the daily consumption of coffee, nor is the coffee mess treasurer concerned with the monthly purchase of supplies. In this way, the coffee mess members, coffee mess supply officer, and coffee mess treasurer are each operating independently with time scale separation between their decision-making processes.

4. Electrical power system logical architecture

IEEE Std 1676 provides a recommended control architecture for high power, power electronic applications. While shipboard electric plant control systems are not limited to only power electronic equipment, the basic control layers defined in IEEE Std 1676 are useful. The explanations for each level are modified to reflect the broader application to shipboard electric plant control systems. IEEE Std. 1662 provides additional guidance on control systems for power electronics in electrical power systems.

The IEEE Std 1676 System Control Layer and Application Control Layer together correspond to the DPC 202-1 Control Layer. The lower IEEE Std 1676 layers correspond to the DPC 202-1 Field Device Layer.

4.1. System Control

Functions at the total ship level and if applicable, zonal power system level, that determine the control objectives of application control at the power system component level. System control has a characteristic time on the order of 10 ms or greater. Includes remotely or automatically starting or shutting down generator sets and converters, configuring bus-tie breakers, commanding load shedding, commanding generator sets to parallel to the power system, etc.

Human machine interfaces for the system control layer are usually in a centralized engineering control station, on the navigating bridge, near, but outside of the machinery spaces., and/or inside the machinery spaces.

For zonal ships, IEEE Std. 1826 identifies three sublevels to system control

a. Multi-Zone Control: Concerned with accomplishing the system's mission, zone coordination, and the total ship human-machine interface.
b. Zonal Control: Concerned with accomplishing the zone's mission, energy management at the zone boundaries, inter-zonal coordination, and zone level human-machine interface.
c. In-Zone Control: Concerned with management of zonal sources, zonal loads, and internal power conversion.

4.2. Application Control

Functions at the power system component level to implement the control objectives provided by the system control. In this context, a component level corresponds to a generator set, power converter, energy storage system, switchboard, etc. Implementation is done via set points of converter control. Application control has a characteristic time on the order of 1 ms to 1 s. Includes implementing operating modes for the components and determining the optimal configuration and setpoints for converters and hardware.

Human machine interfaces for the application control layer are usually in the machinery spaces, close to or a part of the equipment that is controlled.

As defined in IEEE Std 1662, the application control (equipment level controller) includes the following functions:

- Provide autonomous control of itself and equipment served. — Provide health/status to, and receive control commands from, higher level equipment or supervisory control workstation.

- Provide autonomous fault detection, isolation, and reconfiguration coordinated with a supervisory controller.
- Provide ability to export conditions and diagnostics via network links.
- Provide power flow management in accordance with allocations provided by higher level equipment or the supervisory control workstation.
- Provide a multi-line display capability as well as a minimum of hardwired controls and indicators for local operation and maintenance of the equipment's functions. This functionality will be provided via HMI and will provide a means for the operator to handle each type of alert and to review alert status for itself and equipment served.
- Provide built-in test capability.
- Respond to changing load conditions.

IEEE Std 1676 provides additional guidance for application control

4.3. Converter Control

Functions to control individual converters within a power system component. These functions are generally hardware independent. Converter control has a characteristic time of between 10 µs and 1 ms. Converter control performs functions needed to translate the objectives of the application control to specific set-points and control schemes for implementation by the switching control. Converter control usually does not have a dedicated human machine interface.

4.4. Switching Control

Functions to control the converter switching logic to implement the control scheme defined in the converter control layer. Switching control has a characteristic time of 1 to 10 µs. Converter control usually does not have a dedicated human machine interface

4.5. Hardware Control

Provides the direct interface with hardware to include snubbers, gate drives, sensors, A/D and D/A conversion, etc. May directly interface with the application layer if a converter is not directly interfaced with the hardware. Converter control usually does not have a dedicated human machine interface

5. System Control functions

The electrical power system concept of operations (EPS-CONOPS) describes how the electrical power system is intended to be operated. The electrical power system control system is the primary method of implementing the EPS-CONOPS. IEEE Std 45.3 identifies the following electrical power system control functions (System control layer):

- Remote monitoring and control of electrical power system equipment
- Resource planning and system configuration to support the EPS-CONOPS
- Mission priority load shedding
- Coordination of fault detection, fault isolation, and reconfiguration
- Optimization of QoS and QoS load shedding
- Interfacing with the overall machinery control system
- Performance analysis, parameter trending, and logging

Additionally, the electrical power system supervisory control design should facilitate the following processes:

- Maintenance support (such as special modes, electrical isolation, and tag-outs)
- Training

6. References

DPC 202-1 (T9070-BR-DPC-010/202-1), Design Practices and Criteria for the Architecture of Shipboard Machinery Control Systems

IEEE Std 45.2, IEEE Recommended Practice for Electrical Installations on Shipboard – Controls and Automation.

IEEE Std 1662, IEEE Recommended Practice for the Design and Application of Power Electronics in Electrical Power Systems.

IEEE Std 1676, IEEE Guide for Control Architecture for High Power Electronics (1 MW and Greater) Used in Electric Power Transmission and Distribution Systems

IEEE Std 1826, IEEE Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW.

Doerry, Norbert, "Designing Electrical Power Systems for Survivability and Quality of Service", presented at ASNE DAY 2007, Arlington, VA, June 25-26, 2007. Also published in ASNE Naval Engineers Journal, 2007, Vol. 119 No 2, pp 25-34.