Simulation and Visualization of a Shipboard DC Zonal Distribution System

Wenzhong Gao, Eugene Solodovnik, and Roger A. Dougal

***Abstract*—This paper describes the simulation and visualization of a shipboard DC zonal electric power distribution system. The study system consists of six regulated buck converters supplying power to normal and critical loads. The Virtual Test Bed (VTB) software developed at the University of South Carolina is employed to conduct the simulations. The VTB supports multi-lingual and interactive simulations as well as advanced visualization techniques. Multi-lingual capabilities of the VTB are demonstrated by using Matlab to implement the decision-making supervisory controller that controls the output voltage levels of power converter modules and the states of tie switches between different buses. The visualization consists of a 3-D ship with animations indicating the magnitudes of voltages or currents at various buses, power converter modules, and loads. The visualization objects are linked to the real time simulation processes. Two-way communication between the visualization and simulation yields highly interactive simulation. For example, the converter modules can be turned "on" or "off" from within the visualization environment during simulation run-time. This action changes the circuit topology during the simulator run-time, which results in interactive simulation that closely models the behavior of a realistic physical system.**

***Index Terms*—dc power system, power distribution, power system simulation.**

I. INTRODUCTION

DC ZONAL electric distribution systems (DC ZEDS) are under investigation for possible implementation on future Navy ships [1]. Compared to radial distribution, zonal distribution architectures provide maximum protection (fault tolerance), reduced cabling, and cost savings, especially for larger-class ships. DC ZEDS use layers of DC-to-DC or DC-to-AC converter modules, which improve system efficiency and reliability. Additional advantages of DC ZEDS are given in [1].

A typical DC zonal system consists of power generators, transformers, AC-to-DC converters (rectifiers), DC-to-DC power converters, and DC-to-AC power converters. DC-to-AC converters are needed to feed multiple AC loads such as induction motors that are commonly used in propulsion and precision weapon systems, as well as in auxiliary ship systems. Interest in using fuel cells as power sources [3] makes the system heavily reliant on power electronics and advanced control strategies to allow seamless integration of various power sources into the system. The design of such a system needs a high-level simulation tool for analysis and prototyping. The tool should be able to address such issues as system stability, harmonics, and power quality.

This paper presents the simulation of a DC ZEDS within the Virtual Test Bed, which is an interactive simulation environment that allows analysis of mixed discipline systems and provides advanced visualization capabilities. The advanced visualization capability is especially beneficial for educational purposes. The VTB architecture is described in [2].

In section 2, the main features of the VTB simulation environment are presented. The typical structure of DC ZEDS is considered in section 3. The coupled simulation of the VTB with Matlab/Simulink objects is described in section 4. The simulation and visualization results are presented in section 5.

II. VIRTUAL TEST BED SIMULATION ENVIRONMENT

Virtual Test Bed is a topology-oriented simulation environment that employs Resistive Companion Form (RCF) method [3] as primary simulator for conservative systems (such as circuits). The VTB environment supports virtual prototyping of interdisciplinary dynamic systems including for example power electronics, analog electronics, digital electronics, power systems, controls, electro-mechanics, electrochemical and mechanical systems [3]. The VTB environment supports the following features:

1. Multi-formalism: different languages can be used to build models of the different components that compose a system. This allows an individual to build models using the preferred language within his or her discipline area (in this case mechanical, electrical, chemical) such as MATLAB, ACSL, SPICE, etc. VTB also supports symbolic modeling languages in which users can easily define their own models thereby greatly reducing the effort in developing complex device models.

2. Co-Simulation: users can change the language and also use other solvers together with the VTB primary solver. This means that any part of the system can be solved with more appropriate integration step and method without affecting the solution of the rest of the system.

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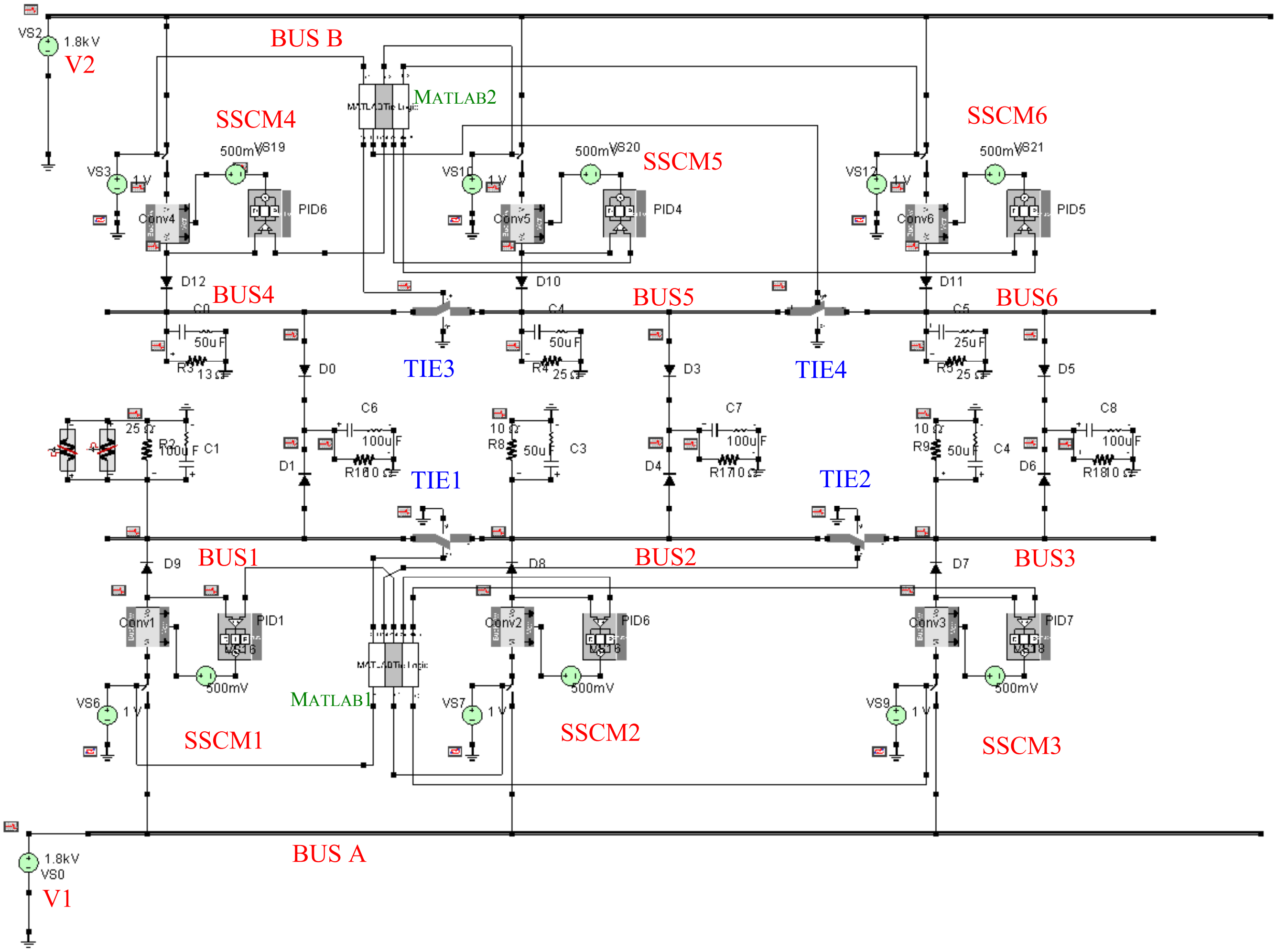

Fig. 1. The simulated DC ZEDS.

3. Interactive environment: users can change the system topology or parameters while a simulation executes. This allows the user to rapidly investigate interactions between components or to explore the influence of design parameters or other variations on system performance.

4. High-level visualization: visualization models of the system can be created and linked to live simulation data. Visualization helps the user to rapidly comprehend the system performance. Visual outputs include data-driven animation of the motion of solid objects, imposition on top of the solid objects of novel representations of abstract simulation data, or simply oscilloscope-type graphs. This feature seems to be particularly interesting for the case analyzed here, where management of the electrical variables produces concrete and visible electrical effects. Furthermore, a high level visualization better supports the interchange of information among the designers cooperating on the project.

5. Distributed computation and Hardware-in-the-loop (HIL) simulation: Large or complicated systems require that the computational load be distributed across a network in order to achieve speeds suitable for interactive explorations. This also supports HIL simulations, which are not a subject of this paper.

III. THE DC ZONAL SYSTEM

The schematic diagram of the simulated DC zonal system is illustrated in Fig. 1. It consists of two DC voltage sources, six buck converters along with corresponding local controllers (also called Ship Service Converter Module, SSCM), and various loads. The SSCMs are regulated by Proportional-and-Integral (PI) controllers so that the output voltages stay at specified constant levels. Each critical load is connected to two SSCMs via two diodes. This configuration guarantees an uninterruptible power supply to the high-priority loads under conditions of failure of several SSCMs. In this intermediate study the loads are simplified to a parallel-Resistor/Capacitor networks. Further effort will apply physically realistic loads on each bus, for example, DC motors, inverter-driven induction motors, pulsed loads, etc. Actually, on BUS 1, there are two pulsed constant power loads. These loads operate at different frequencies and have different power levels. They are used to demonstrate the dynamic critical load sharing between BUS 1 and BUS 4.

The tie switches are controlled by a Matlab/Simulink logic supervisory controller. Under normal operating conditions each tie switch is kept “off” so that each of six buses is supplied by its own dedicated power converter module. However, during any particular SSCM failure, the corresponding ties are turned “on” to reroute power to loads from other SSCMs. For example, if SSCM 1 is off (to simulate component failure), then the tie switch between BUS 1 and BUS 2 is turned “on” so that BUS 1 is supplied by SSCM 2; the tie switch will be turned “off” to relieve SSCM 2 if SSCM 1 comes back to service (see Fig. 3—5).

The properties of load pickup by neigboring converters are relatively straightforward to analyze when all buses are at the same voltage. But in practice each bus will have a different voltage for a variety of reasons, including both tolerance variations and intentional deviations in voltage setpoint to control the sharing of power to critical loads. Under these conditions it is difficult to analytically predict the system behavior when the buses become interconnected. Indeed, each of the local controllers should try to regulate voltage levels independently of each other that can cause either instability in the system or some other negative effects. The goal of simulations presented in this paper is to investigate DC ZEDS behavior under condition of rerouting power with voltage-regulated buses at slightly different voltage levels. In particular, the voltage set-point of each PI controller for each converter is given by the Matlab/Simulink logic supervisory controller. In the simulated case, the voltage levels of the SSCMs are listed in Table1.

Table 1 Voltage levels of SSCMs

SSCM No.	Voltage Setpoint
SSCM1	900 Volts
SSCM2	900 Volts
SSCM3	873 or 900 Volts
SSCM4	890 or 900 Volts
SSCM5	900 Volts
SSCM6	900 Volts

IV. VTB SIMULATION COUPLED WITH MATLAB/SIMULINK

Matlab/Simulink has the capabilities to model and simulate advanced control systems. But it is not always convenient or suitable for simulating a power system with multiple devices and complex dynamics. The VTB architecture supports natural coupling between circuit-based simulation and Matlab simulation [4]. In DC ZEDS that is considered in this work, the ties between buses are controlled according to a pre-specified decision-making logic. The Matlab/Simulink supervisory logic controller is based on the combinatorial logic block that can be implemented as a truth table. The Simulink diagram is illustrated in Fig. 2. The logic controller also sets the reference voltages for the local PI controllers depending on the state of the system. Inputs 1—3 of the controller (see Fig. 2) sense status of each of the converter modules. Outputs 1 and 2 control the states of the tie switches. Finally, outputs 3—5 control the reference voltages for the local PI controllers. The Simulink file is compiled into the dynamic linked library (dll) format compatible with the VTB software using the tool specifically developed for that purpose. The coupling between VTB and MATLAB dll object is equivalent to signal coupling. Specifically, the input impedance of the compiled Matlab model is infinity, while its output impedance is zero (i.e., input and output terminals of the model are treated equivalent to ideal voltage sensor and ideal voltage source). With the capability of supporting MATLAB, VTB can be used for mixed-signal simulation, where analog and digital logic subsystems in an integrated power system can be simulated. This feature is especially useful when the simulated power system requires advanced power management.

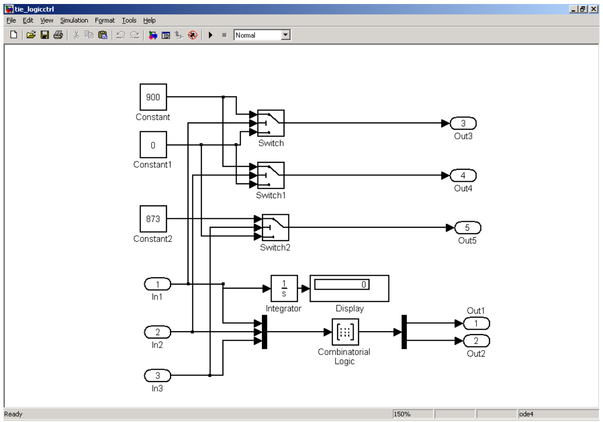

Fig. 2. Matlab/simulink logic controller.

V. SIMULATION RESULTS AND VISUALIZATION

First, simulation was conducted for the system under normal condition with equal voltage levels at all buses. The visualization of nominal system operation is illustrated in Fig. 3. All SSCMs are functioning, all ties are “off”, and all the loads are powered up.

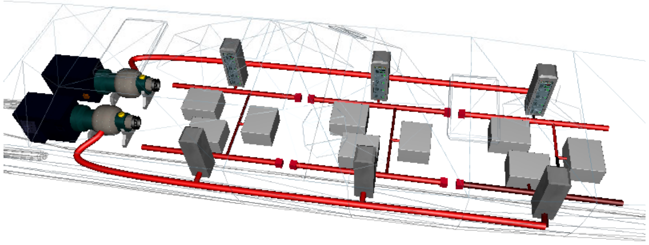

Fig. 3. The visualization of the DC ZEDS—nominal operation.

Suppose now that during system failure SSCM1 and SSCM4 through SSCM6 (see Fig.1) are turned “off”. The simulation results for this scenario are presented in Fig. 4. The TIE1 is turned “on” by the logic controller MATLAB1 (see Fig. 2), so that power for the loads connected to the BUS1 is not interrupted. However, some loads connected to buses 4 through 6 lost power. Note, that all critical loads are still powered up despite such extensive failures in the system.

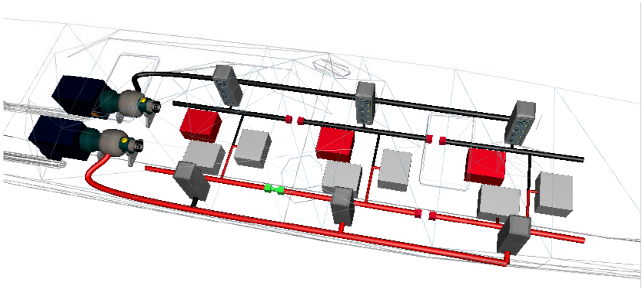

Fig. 4. The visualization of the DC ZEDS—operation under failures.

It is necessary to emphasize that all visualization objects are color-coded. For example, red color indicates the levels of voltages or currents at each bus, i.e. the higher level of voltage or current in the bus, the more saturated the color. If there is no current flow in the bus, this bus will turn black. If the current is oscillating due to some abnormal processes in the system or during the transients, the color saturation will also pulsate. The gray blocks indicate that the loads are being supplied with power, while red color indicates that the load lost the power. This approach to visualization of DC ZEDS allows an operator to grasp immediately if the system operates normally or if there are problems in the system such as faults or failures. Apparently, observing dozens of meters and scopes results in delays in assessing the system performance.

The second simulation was conducted for the system under the assumption that some buses are not at the same voltage levels. Specifically, the regulated voltage level at SSCM3 is 3% less than the voltage levels at modules SSCM1 and SSCM2. Thus, under condition of SSCM2 failure, the logic controller MATLAB1 will turn ties 1 and 2 “on” connecting buses 1 and 3 with slightly different voltage levels through bus 2 together. The tie resistances in “on” state are assumed to be equal to $1m\Omega$. The diodes D7—D12 (see Fig. 1) in the output path of each converter ensures that current does not flow back into any converter.

The 3D visualization is given in Fig. 5. It is obvious to see that indeed, the ties 1 and 2 are closed when SSCM2 fails.

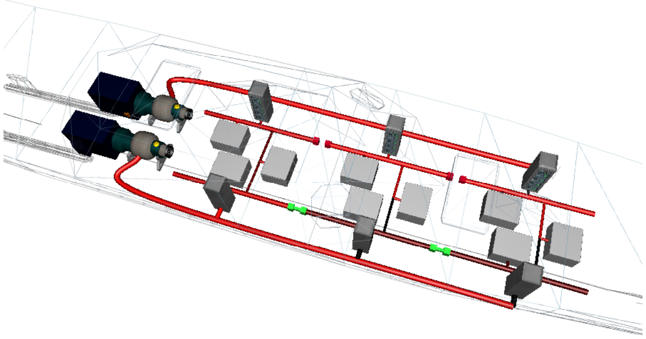

Fig. 5. The visualization of the DC ZEDS—operation under SSCM2 failure.

The duty ratios of switching converters for SSCM1 and SSCM3 are shown in Fig. 6.

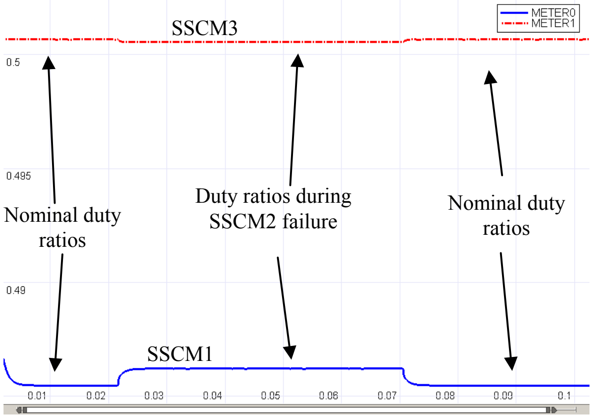

Fig. 6. The duty ratios of switching converters SSCM1 and SSCM3.

It is possible to see that local controllers of SSCM1 and SSCM3 try to regulate voltages at their buses by adjusting the duty ratios of the corresponding converters. After some transient, the system reaches a steady state point. The transients of voltages at buses 1, 2, and 3 are shown in Fig. 7. As it is possible to see, the local controllers of SSCM1 and SSCM3 were able to adjust bus voltages to their corresponding levels.

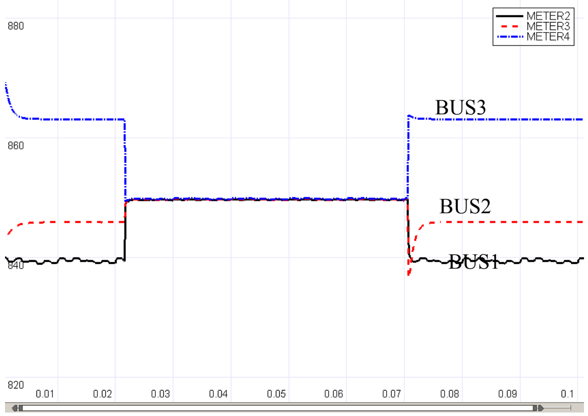

Fig. 7. The voltages at buses 1, 2 and 3.

The current in BUS A is plotted in Fig. 8. It can be seen that despite the failure of SSCM2, currents through BUS A

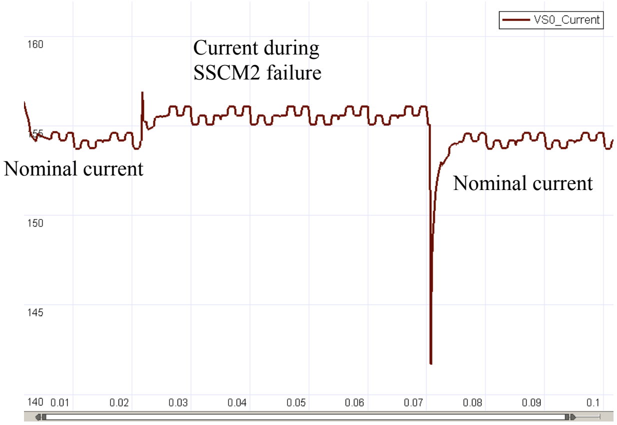

Fig. 8. The current in BUS A.

and consequently through SSCM1 and SSCM3 (see Fig. 9) are within allowable levels.

Note that following the failure of converter 2, converters 1 and 3 share the load currents.

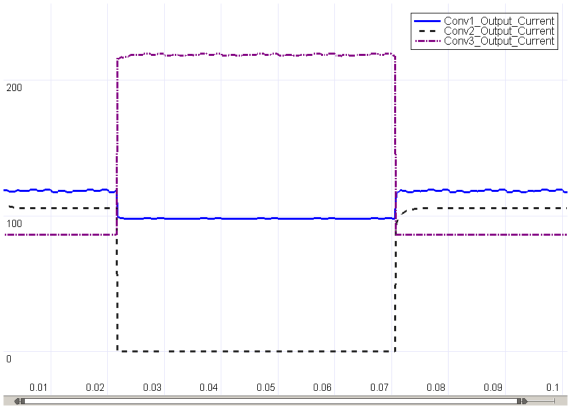

Fig. 9. The converter currents.

The converter voltages are shown in Fig. 10. As can be seen, the SSCM1 and SSCM3 voltages are different and maintained at the specified levels by the local controllers regardless of the presence of pulsating loads and failure of the SSCM2. Note that the bus voltages (see Fig. 7) are slightly lower than the converter output voltages due to voltage drops across the output protection diodes.

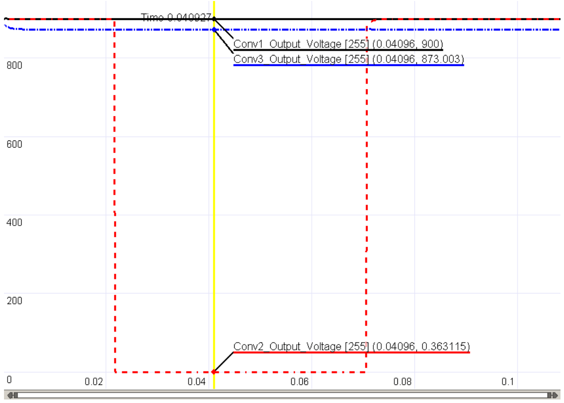

Fig. 10. The converter voltages.

The simulations of DC ZEDS allow us to conclude the following. The supervisory logic controllers considered here provide acceptable performance for uninterruptible provision of the power to all loads under condition of several SSCMs failure. The converter and bus voltages are also maintained at specified levels. Even under extensive failures in the system of four of total six SSCMs, critical loads are still being powered by the supervisory logic controllers.

VI. SUMMARY AND FUTURE WORK

The VTB is a useful tool for modeling, simulation, and rapid prototyping of systems such as the DC zonal system. With its support of Matlab/Simulink, the effects of different controllers can be studied. The advanced visualization capability is especially advantageous for comprehending the simulation data.

The following problems are still under investigation: supervisory control for load-shedding based on the importance of each load and overall system stability.

VII. ACKNOWLEDGMENT

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IX. BIOGRAPHIES

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Roger A. Dougal earned the Ph.D. degree in electrical engineering at Texas Tech University in 1983 and immediately joined the faculty at the University of South Carolina. Dr. Dougal has received the *Samuel Litman Distinguished Professor of Engineering* award, and has been honored as a *Carolina Research Professor*. He is a Senior Member of the IEEE. Prof. Dougal is the director of the Virtual Test Bed project, which is developing an advanced simulation and virtual prototyping environment for multidisciplinary dynamic systems.