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Dynamic Response Comparison of Dual-Wound and Single-Wound Machines in Multi-Bus Power System Architectures

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***Abstract*— Power systems with highly flexible architectures (i.e. permitting many configurations) may allow for more economic operation as well as improved reliability and resiliency. The greater number of configurations enable optimization for attaining the former benefit and redundancy for achieving the latter. Flexibility is of great importance in electric ship power systems wherein the system must ensure delivery of power to vital loads. The United States (US) Navy is currently investigating new architectures that enable a greater number of interconnection permutations. Among the new features considered are generators that may supply two buses; this may be done using conventional (single winding set) generators and two rectifiers or a dual wound machine with two rectifiers. In systems supplied by dual-wound machines, buses may not be tied directly but are linked dynamically through the shared generator dynamics. In systems with conventional generation supplying two rectifiers, the two buses are tied through a common AC bus supplying both rectifiers. This paper presents a comparison of these two approaches of supplying two buses from one generator; the evaluation considers issues associated with dynamic coupling through these two candidate architectures, including the coupled response due to faults and systems with pulsed loads. Results are based on analysis, simulation results, and hardware experiment.**

Keywords—dual-wound generator, Navy all-electric Warship

I. Introduction

The US Navy is considering several advanced architectures that improve the economy and resilience of ship electrical systems. In particular, systems are designed to ensure a power path from generation to load even in the event of equipment damage. As noted in [1], "[t]he most popular topology used in Navy electrical systems is a ring configuration of the generators … [wherein] any generator can provide power to any load." Recently, new architectures are being investigated to enable greater improvement in flexibility, including configurations wherein two buses are supplied from a single machine. This approach could allow for redundant systems where one generator can be used to supply power for both port and starboard buses [2]. This may be accomplished using a conventional generator with two rectifiers (i.e. with a common AC bus supplying both) or with the use of dual-wound generators, with separate windings supplying each rectifier. Herein, the term "dual-wound" is used to refer to a machine with two sets of windings, with each winding set supplying a different load or bus. In contrast, the term "single-wound" refers to a machine with one set of windings supplying one bus or load.

A benefit of this approach is that it enables dispatch scenarios with fewer generators. A concern lies in the potential dynamic coupling of electrical disturbances through the common generator and/or common AC bus.

Previous work has focused on the characterization of this coupling through a dual-wound machine. In [3], simulation studies were done to characterize this coupling between buses in the frequency domain, with the primary focus being on voltage and current disturbances on one bus in response to load power changes on the adjoining bus. In [4], the authors showed that the construction of the motor could affect the nature of this coupling. Therein, a chirp signal with a frequency range of 0.1 Hz to 10 kHz, and an amplitude of 1 MW, was applied to the load power on the starboard bus, and the response was observed on the port side bus. In this paper, the two candidate architectures are more directly compared. Specifically, the coupling is characterized for the conventional generator case and compared to that of the dual-wound generator case. This comparison is done using analytical, simulation, and experimental methods.

II. System Description

For the purposes of this paper, two candidate architectures have been identified. These are shown in Figure 1 and Figure 2; therein, the architecture in Figure 1 uses a dual-wound machine to supply two separate DC buses by grouping the windings into two winding sets; the system in Figure 2 uses a single-wound machine to feed two separate DC buses through two active rectifiers.

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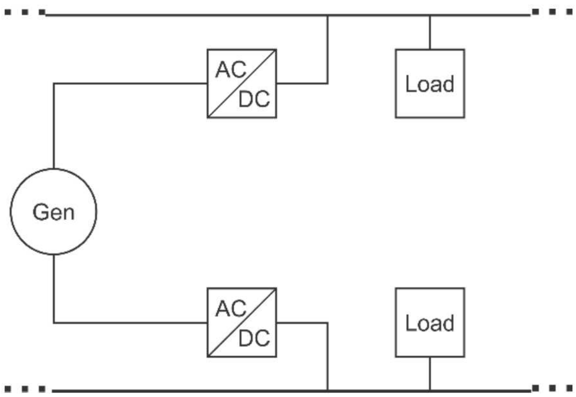

Figure 1: System architecture with two DC buses supplied by a dual-wound generator.

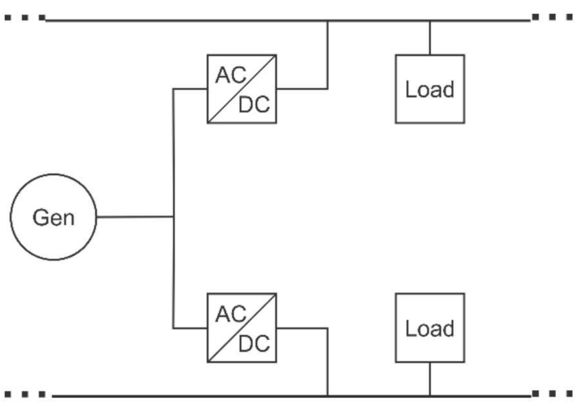

Figure 2: System architecture with two DC buses supplied by a single-wound generator.

In both cases, a change in the loading on one bus will affect the behavior of the other bus. Minimization of this coupling between the two buses is desired so that a fault on one bus will not cause the other bus to violate compliance. Therefore, determining the relative coupling in the two system layouts is the goal of this work.

III. Simulation Results

To analyze both systems, Simulink models for a system with a single-wound generator connected to two active rectifiers through a single AC bus and a dual-wound generator connected to two active rectifiers were constructed. For the purposes of our comparison, the dual wound machine considered herein includes two 3-phase windings configured 60^o apart, and the single-wound machine includes one 3-phase winding. Specifically, the two cases shown in Figure 1 and Figure 2 were realized using the circuits shown below in Figure 3 and Figure 4.

In order to aid in the analysis, a toolbox has been developed at Sandia National Laboratories to streamline the process of constructing models with AC and DC components in MATLAB/Simulink. The tool is called *Software for Automatic Generation of System Models* (SwAGSM). SwAGSM automatically generates models for generic power systems consisting of both ac and DC components. Parameters are entered into an Excel spreadsheet and a Simulink model is automatically generated from this information. This happens in lieu of constructing a model using Simulink's drag-and-drop interface. This tool was first detailed in one of its earlier versions in [9] and was applied to develop models in [10] and [11]. Sample inputs for a simple 5 bus model with 1 3-phase ac bus and 4 DC buses are shown in the figures below. Figure 5 shows the Excel sheet where system-wide model parameters are set and as well as the sheet where the branch parameters are defined. There are also various other sheets which are specific to the type of devices present in the system.

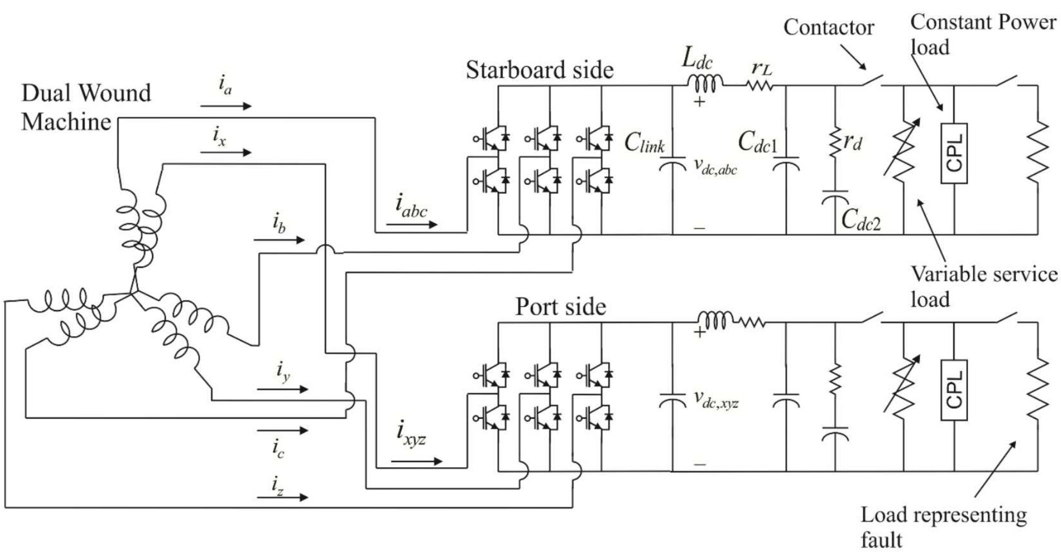

Figure 3: Circuit diagram of a dual-wound generator fed system with two DC buses.

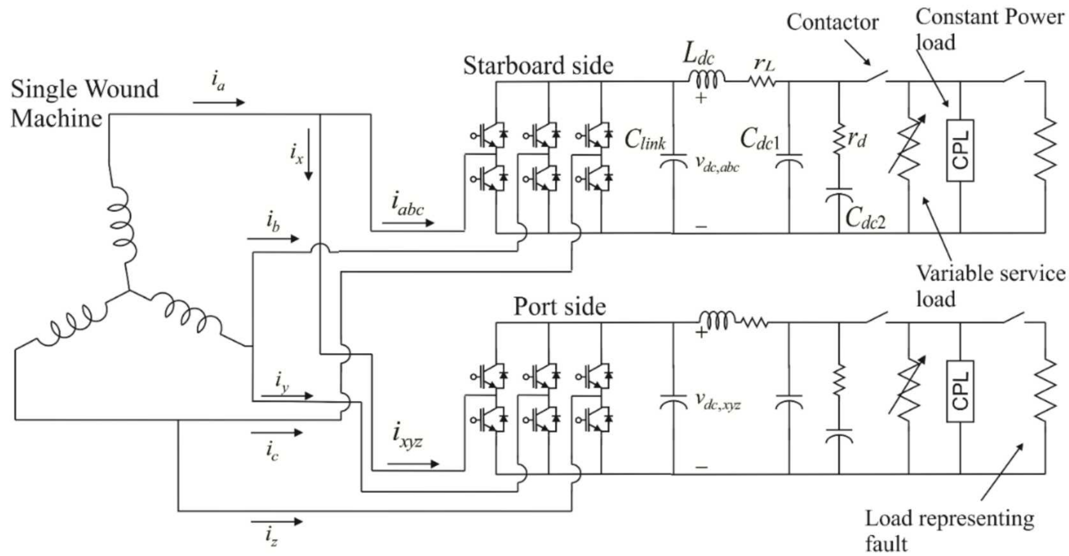

Figure 4: Circuit diagram of a single-wound generator fed system with two DC buses.

	A	B	C
1			Unit
2	Start Time	0	minutes
3	End Time	10	minutes
4	Step Size	0.1	milliseconds
5	Number of Data Points	1000000000	
6	Decimation	10	
7	Solver Method	ode3 (Bogacki-Shampine)	
8	Solver Mode	Normal	
9	Model Type	dynamic (Simulink)	
10	Optmizer Update Period	5	seconds
11	Optimizer Iterations	100	
12	Optimizer Error Tolerance	0.001	
13	tau	0.75	
14	Nominal AC Line-to-Line Bus voltage	7.348469228	kV
15	System Base Power	100	MW
16	ac grid base frequency (Hz)	60	Hz
17	power loss objective factor	0.001	
18	objective factor	0	
19	log data	yes	
20	power electronics mode	average	
21	switching frequency	1	kHz

Model Parameters | Bus Data | Line Connections | Diesel Generator Par

(a)

	A	B	C	D	
1	from	to	R	L	type
2	1	2	0.01	0.001	rectifier
3	2	3	0.01	0.001	dc
4	3	4	0.01	0.001	dc
5	4	2	0.01	0.001	dc
6	5	3	0.01	0.001	boost

... | Bus Data | Line Connections | Diesel Ger

(b)

Figure 5. SwAGSM Excel Sheet for (a) System-Wide Parameters and (b) Branch Parameters.

Based upon the settings and values in the spreadsheet, different models can be directly defined without the need to manipulate models in Simulink or even open Simulink directly. When the main MATLAB script is run, a model is automatically constructed which, at the top level, looks like that shown in Figure 6. Inside the sm_grid subsystem are the plant model and the optimal power flow computation. The sc_scopes subsystem contains scopes for various states. A dual-wound generator model was added to the tool for this analysis based on the model developed in [3].

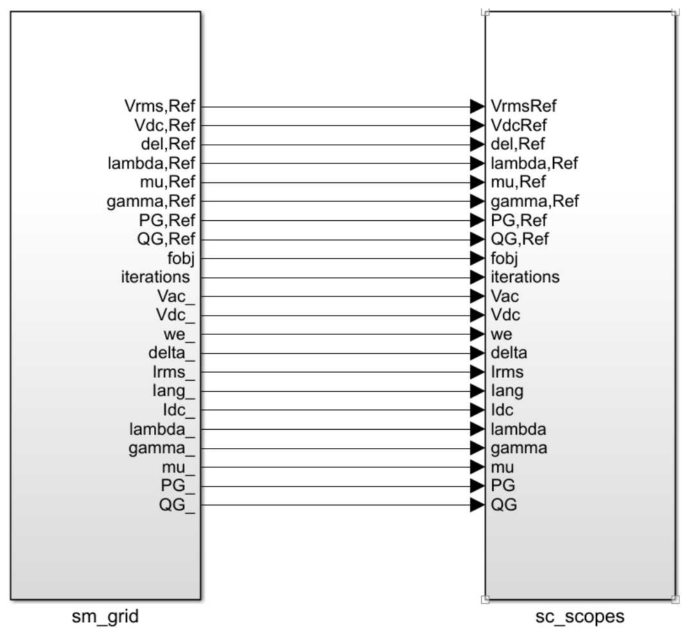

Figure 6. Top Level of SwAGSM Generated Model.

Of particular interest is how a load change on one DC bus will affect the electrical response of the other DC bus. This can be determined by examining the transfer functions between a load change on one bus and a voltage change on the other. Figure 7 shows the bus loading that was applied to both simulations. The port bus is held at a constant 5 MW while the starboard bus has a 4 MW chirp with frequencies from 0.01 Hz to 10 kHz added on to a 5 MW constant load.

After simulating the systems in the time domain, the MATLAB fft() function was then used to extract the frequency domain behavior of the system and find the transfer function between load power on the starboard bus and voltage perturbance on the starboard and port side buses.

As shown in Figure 8, the single-wound generator system has more coupling than the dual-wound generator system across most frequencies. This can also be seen in Figure 9, which shows the difference in the coupling magnitude between the two cases. The magnitude of this difference has a maximum of ~25 dB at 0.5 Hz which corresponds to approximately 18 times the coupling between buses which a single-wound machine connected to two rectifiers compared to the dual-wound machine system. At most frequencies, one observes a difference of approximately 10 dB, although there is a minimum error at 1 Hz where the single-wound system has less coupling.

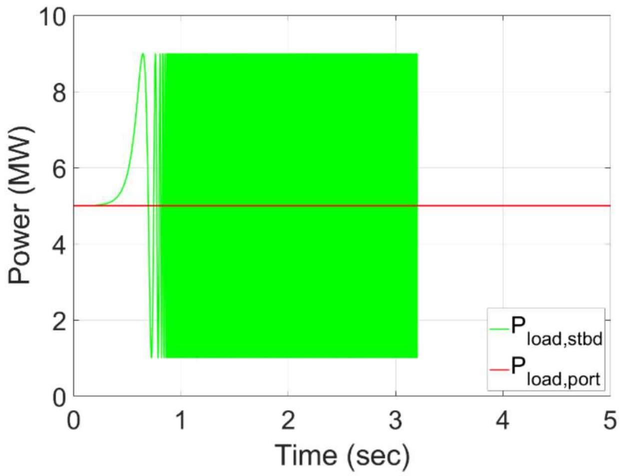

Figure 7: Chirp function used in to compare coupling in dual-wound and single-wound generator

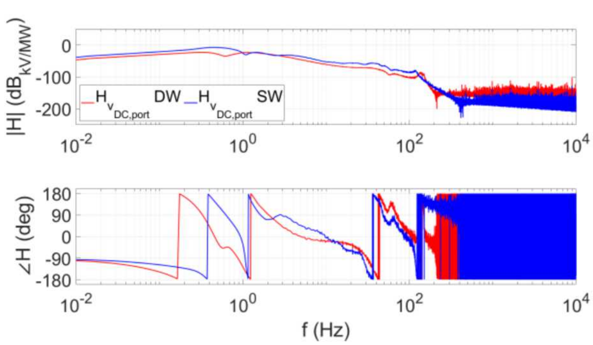

Figure 8: Comparison of the port bus responses to a starboard load chirp in the single- and dual-wound generator cases

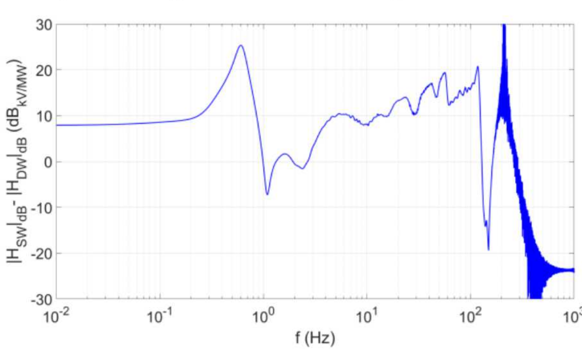

Figure 9: Difference in coupling between the single-wound and dual wound systems

IV. MICROGRID TESTBED DESCRIPTION

The Secure Scalable MicroGrid Test Bed (SSMTB) was designed to conduct experiments on networked microgrids that share information flow and power flow [6]-[8]. The testbed includes three microgrid systems, a central bus cabinet for interconnecting the components, and computers used for control, data acquisition, and situational awareness. In total, the system components include: a reconfigurable bus cabinet, five permanent magnet generators, nine energy storage emulators capable of sourcing or sinking 5kW of power, seven 600V commercial power supplies, mechanical source emulators based on commercial motor drives, a DC/AC converter, a three-phase resistive load, three high-power digital resistors rated to 6.7 kW at 400V bus voltage, and a master control console that scripts the experiments with designated source and load profiles. Some key components are shown in Figure 10. A master control computer is used in the coordination of components and monitoring of quantities for each scripted experiment. Additional information may be found in [6]-[8]. In order to analyze the behavior of a dual-wound generator, a six-phase version of the generators already present in the system was obtained from the vendor. Additionally, to match the proposed naval system a gas turbine code was added to the mechanical source emulators [3], [4].

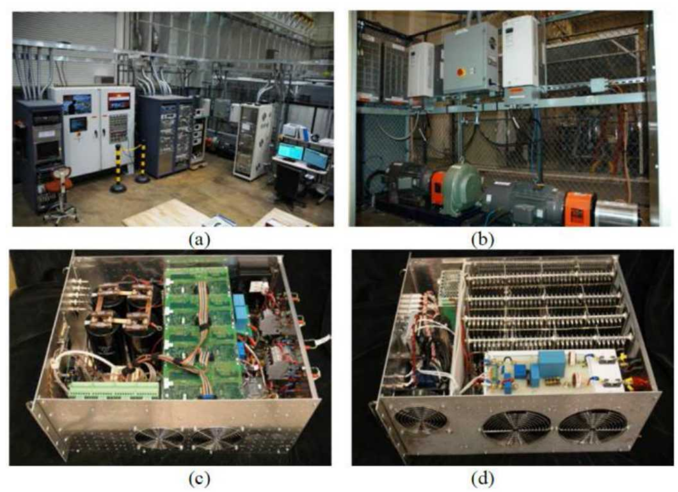

Figure 10: Photos of (a) the microgrid testbed including (b) mechanical source emulators, (c) energy storage emulator, and (d) high power digital resistor

V. HARDWARE RESULTS

A scaled representation of the power system was emulated in hardware using the Secure Scalable Microgrid Testbed (SSMTB) [5], similar to the approach taken in [3]. The hardware set up currently includes passive rectifiers and permanent magnet synchronous machines connected to a gas-turbine emulator [3].

A log-sine chirp was applied to the resistive load on the starboard side of the system. The resulting voltage variations on the port and starboard sides of the system were then measured. The load power and voltages were transformed into the frequency domain using the MATLAB fft() function, which were then used to find the transfer functions shown in Figure 11. As can be seen in the figure, the system using a dual-wound generator source has less coupling between the buses than the system using a single-wound generator source. This is further seen in Figure 12, which shows that the system with a single-wound generator always has more coupling, especially at frequencies above and below 0.4 Hz. While these hardware results are based on a system using a passive rectifier, the comparison does show that the single-wound machine based architecture does have more coupling between buses. Since this additional coupling is mostly due to the shared impedance at the point of connection on the AC side, this additional coupling between buses would also be present in a system using active rectifiers.

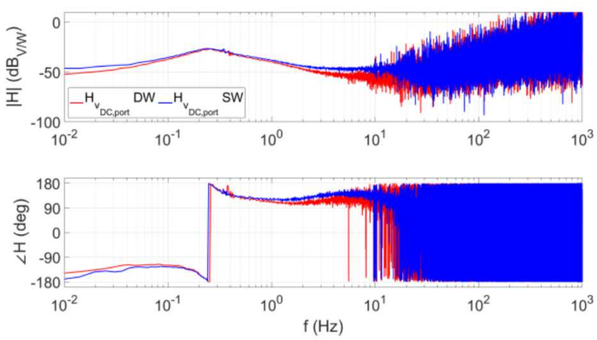

Figure 11: SSMTB hardware results

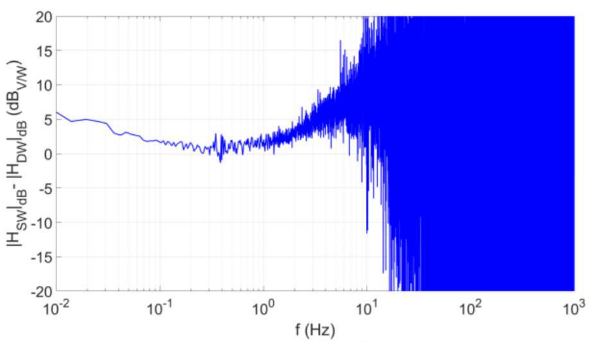

Figure 12: Difference in coupling on SSMTB hardware

VI. Conclusions

In this paper, an analysis of two architectures that supply two DC buses from a single generator was performed. The first architecture uses a three-phase generator to supply the DC buses through two rectifiers connected together while the other supplied the buses with a six-phase generator where each three-phase set of windings was connected to a rectifier. The performance of each architecture was analyzed based on how much change on one bus effected the electrical behavior of the other bus. It was shown in simulation and scaled hardware testing that the dual-wound solution has less coupling at most frequencies than the single wound solution. This will provide more isolation between the two buses.

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