The Modeling and Simulation of a Shipboard Power System in ATP

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***Abstract* – An Alternative Transients Program (ATP) simulation model of a naval shipboard power system (SPS) was developed to provide a platform to study the behavior of an SPS during certain operating conditions, to aid in the development of automation methods such as restoration and failure assessment, and to test the performance of these automation methods. To determine the level of complexity needed for the component models, the salient features of the shipboard power system were considered. The components formed an ungrounded alternating current (AC) radial SPS with three-generator switchboards connected in a ring configuration. This system included three generators (of which one is reserved for an emergency), five load centers, nineteen motors, numerous cables, eleven transformers, and five types of protective devices. The modeling of this SPS presented unique modeling challenges, due to factors such as its ungrounded nature which is uncommon to most power systems. Issues during modeling and simulation such as numerical oscillations and trapped energy were encountered. Other issues encountered included simulation divergence problems and ATP dimensioning problems. Details of the issues and their solutions are presented in this paper.**

Keywords – Shipboard power systems (SPS), Reconfiguration, modeling decisions and Alternative Transients Program (ATP)

I. INTRODUCTION

A simulation model of an AC radial SPS was developed to provide a platform to study the behavior of SPS during certain operating conditions, to aid in the development of automation methods such as restoration and failure assessment and to test the performance of these automation methods. The test system shown in Fig. 1 was developed based on a navy combatant ship. This test system consisted of three generators (of which one is for emergency), five load centers, nineteen motors, numerous cables, eleven transformers and five types of protective devices. The generators were connected to generator switchboards that were connected in a ring. Then the topology was radial downstream of the generator switchboards. The system is ungrounded. The shipboard power system was designed as an ungrounded delta system to ensure system survivability during single line to ground faults. To ensure survivability and enhance reliability, the SPS was further designed with protective devices.

The SPS has certain characteristics that distinguishes it from most power systems. Alternative Transients Program (ATP) was selected as the modeling software to model the SPS characteristics as accurately as possible.

ATP, a royalty free program developed by Dommel and others at the Bonneville Power Administration [1], has been widely used for transient studies of AC systems. Components such as cables, induction motors, and transformers have detailed supporting subroutines for their modeling in ATP. However, it was discovered that standard use of these subroutines (such as the motors) led to erroneous modeling of the SPS. It was necessary to incorporate the distinctive features of our test system into ATP standard templates in innovative ways. Modeling the system became a learning process of determining data for the ATP templates and intelligently using the template to reflect desired behavior. This process was not without its failures and obstacles.

Principles used to model and simulate the test system will be presented. Specifically, in section 2 the system will be thoroughly discussed. In section 3 the modeling decisions, issues and solutions will be presented and the major findings during the simulation model development will be discussed. These findings will be reiterated in section 4 in the conclusion.

II. SYSTEM DESCRIPTION AND COMPONENT MODELING

The system modeled as shown in Fig. 1 represents a test system developed based on a US naval surface combatant ship. It was developed in ATP by an encapsulation of code approach using the include function. For some components a punch file was developed of each component model, other components were coded directly into the main data case. The punch files were included in the main data case by the INCLUDE function. This was done to facilitate the structured development of the big test system and to isolate the components for easier debugging and reading.

The types of component models incorporated into the big test system were: Generators, Buses, Cables, Transformers, Motors, and Protective Devices. The Protective Devices modeled were Circuit Breakers with inverse time delay relationship, low voltage protective relays called Low Voltage Protection (LVP) and Low Voltage Release (LVR), and power continuity devices called Automatic Bus Transfer Switches (ABT) and Manual Bus Transfer Switches (MBT). Generators were connected to switchboards called generator switchboards, which were composed of one or more switchgear units and breakers for various devices such as the generator, loads, and connected load center switchboards.

The electrical system was connected in a ring configuration of the generators which allows any generator to provide power to any load. This feature is of great importance in order to ensure supply of power to vital loads, if failure of an operating generating unit occurred. The other components of Fig. 1 were load center switchboards, power distribution panels, bus transfer units, transformers and interconnecting cable used for delivering power to the loads. Load center distribution which is a modification of radial distribution was used below the generator switchboard level. One or more load center switchboards were connected to each generator switchboards to supply power to loads [2]. Load Centers in the big test system are labeled LC31, LC12, LC11, LC41, and LC42. For loads with an ABT or an MBT, there were two paths leading to them. One path was the normal path shown in Fig 1 as a solid line and the other path was the alternate path shown as dashed line. The multiple paths to loads (which are designated as vital) were the necessary redundancy incorporated into the system to improve survivability and reliability [3]. The big test system was implemented in ATP with branch cards, Transients Analysis of Control Systems (TACS) cards, ATP template cards, and subroutines.

A. Generator

The Generator modeled in the big test system was a 2.5 MW, 60Hz, delta connected, 450V line to line rms synchronous generator with type 2 IEEE exciter and automatic voltage regulator, and speed governor. The template used in the ATP was the Type 59 synchronous machine template. The controllers (i.e. exciter and governor) were implemented in the TACS with the values of terminal voltage and speed, respectively, fed into TACS and the field voltage and mechanical power output from the TACS, fed into the Type 59 template. Modeling of the SM59 was as instructed in the Rule book [1]. But care had to be taken to enter the correct data for a Delta generator in the SM 59 template where usually the SM 59 generator template is a wye.

B. Busses

The model for the busses was a junction or a node without including the resistance and inductance of copper bars. This model was used for switchboard busses, load centers and power panels.

C. Cables

There were two categories of cables modeled in the big test system. These types were the low smoke three phase conductor unarmored (LS-TSGU) power cable and the single phase conductor unarmored (LS-SSGU) power cable. They were both rated at 1kV. Within the two categories, a total of seven gauges were used. The sizes used for the three phase cable were 250MCM, 500MCM, 2AWG, 4AWG and 6AWG. The sizes used for the single phase cables were 250MCM and 350MCM. Cable parameters are found in [4]. The three phase cables were modeled in ATP using class B of ATP's cable constants routine. The ATP cable constants routine requires cable geometry, cable characteristics and length to generate a punch file containing the PI model of the cable being modeled. Similarly, the single phase cables were modeled as Class A of the cable constants routine. The resulting models for the single phase cables were also PI models. The ungrounded nature was achieved for the cable models by specifying three phase, three wire configuration for three phase cables and two phase, two wire configuration for the single phase cables in the cable constants routine resulting in a PI model with high impedance paths to ground. This meant that the shunt capacitors were very small.

D. Transformers

One type of transformer was modeled for the SPS. It was a three – phase 450V /120V delta – delta transformer which operated at 60Hz [5]. There were two sizes of transformers modeled; these were 3*15 KVA and 3*25 KVA. The transformer was modeled using the BCTRAN subroutine and the three phases were modeled separately as three single phase units.

BCTRAN uses open circuit and short circuit test data, short and open circuit losses, transformation ratio, number of windings, and transformer power to compute the matrix pair [R] and [L][5]. A punch file containing the connectivity information and the matrix pair were included in the main circuit [5]. The delta connection for the transformers was achieved by connecting the single phase windings between phases in the connectivity input in the subroutine.

E. Motors

The induction motors were modeled as UM Type 3 (squirrel cage induction motors) in ATP. A punch file containing the design of the induction motor was generated for each motor in the big test system by the INDMOT supporting program. The data required by the INDMOT supporting program included full load KVA rating, rotor type, starting current, starting torque, machine efficiency and power factor. The automatic initialization was used for the motors in the big test system. However, for some of the applications that will use these simulation results, the loads need to be able to be started after simulation starts. Hence, we are working on developing motor models that would use decoupled initialization. The output power ratings of the induction motors range from 4.2 kW to 192.6 kW, and there were nineteen motors incorporated into the big test system [5].

F. Circuit Breakers

Circuit breakers were modeled with their principal function being the inverse time delay characteristic. The time versus current characteristic curve of air circuit breakers (ACB) were used to represent all of the test system's circuit breakers. The circuit breaker pole was modeled as a TACS controlled Type 13 switch with its inverse time delay characteristic curve implemented in TACS [6]. The circuit breaker contained three poles for a three phase circuit. The principal feature of the circuit breaker model was the integration unit which integrated the rms of the terminal currents once an over-current was sensed. The output of this integrator was compared with preset boundary values from the current-time curve to produce a logic that opens/trips the main Type 13 switches. The boundary values corresponded to instantaneous, short time delay and long time delay regions. The model did not have a reclosure feature.

G. Low Voltage Relays

There were two types of low voltage relays modeled for the test system. They are the low voltage release (LVR) and the low voltage protection (LVP). The LVR and LVP protect the load from experiencing a sustained low voltage condition. The minimum allowed voltage was set at 400V line to line rms. The LVR can automatically reengage the load after the low voltage situation is cleared but the LVP requires an operator to reengage the isolated load [5].The LVR and LVP were modeled as TACS controlled switches. Their functions were coded in the TACS with voltage information input into TACS and the binary switch control output to control the switches.

H. Bus Transfer Switches

There are two types of bus transfer switches. They are manual bus transfer (MBT) and automatic bus transfer (ABT). The MBT and ABT are power continuity protective devices. The MBT accepts two sets of three phase voltages as input. The functionality of the MBT is that an operator selects a path of supply from these independent supply paths since MBTs are entirely manual.

The ABT is also a power continuity protection device. It differs from the MBT in that its operation is automatic with an option for manual operation. The ABT is designed as a normal power seeking device, that means when power in normal path is lost the ABT will automatically connect the load to the alternate path. When normal power is restored, the ABT will automatically connect the load back to the normal path.

The ABT and the MBT were modeled as TACS controlled switches with logic developed to generate a TACS signal that controls the TACS controlled Type 13 switches.

I. Switches

ATP has time controlled switches that open after Topen and at zero current and close at Tclose input in the template. These were extensively used in the modeling of the big test system for connecting single phase loads downstream of transformers and solving trapped energy problems. Measuring switches were also used extensively. They were used to obtain currents flowing to loads and circuit breakers.

III. COMPONENT, SYSTEM INTEGRATION AND SIMULATION ISSUES

When each component was developed, it was tested individually in small test systems. During this time, a number of issues were discovered. The issues were, motor ground and torque value issues. Issues encountered during system integration included allocation and dimensioning problems, ATP error in the GIFU slaves, numerical oscillation and signal quality issues, trapped energy and signal value accuracy issues, and motor divergence issues

A. Motor Ground and Torque value issues

The INDMOT supporting program is a commonly used supporting program to generate the UM3 format of the Universal Machine Module. However, the program assigns nodes of the stator coils in the UM coil table group automatically between the input terminal node names and ground which in ATP is also the blank node. This meant that when the motor data was generated the stator was wye connected and its neutral node was grounded. In the case of an ungrounded delta system, this connectivity could not be used. To make the model delta connected, each stator coil had to be connected between phases. In addition, the stator coil parameters obtained from the INDMOT had to be multiplied by three to convert them to delta values. There was also a problem in the rotor connections. Typically, the output of the INDMOT connects the squirrel cage terminals to ground (the blank node) through a small connecting resistor which makes the motor grounded. Removing this grounding completely by floating the terminals resulted in an error in ATP. The solution was found by increasing the grounding resistor to a very large value of 10^9 ohms.

The torque value did not converge to correct steady state values when the motor was input with an initial slip of one which is the normal case at startup. INDMOT generated an initial slip value but, the initial slip obtained from INDMOT had to be changed to yield the correct torque. Initial slip values were tried through trial and error until it gave the correct torque with automatic initialization used.

B. Allocation and Dimensioning Problems

Based on the transient phenomenon that is being investigated, modeling and simulation may focus on either the component level or the system level. If modeling and simulation is conducted at the component level, only a subsystem containing the components of interest is modeled in detail. The rest of the system is simplified as an equivalent circuit. However for certain applications such as fault studies in SPS, a detailed model of the SPS is needed since electrical faults during battle damage may spread to various unpredictable places within the SPS. This reason resulted in a large system (called the big system) to be modeled. The size of the big test system required a large allocation of all vardim and startup parameters. Drs. Liu and Meyer of BPA (ATP chairmen of America and Canada User group) graciously provided us with ATP custom upgrades when needed. Salient issues encountered in dimensioning were

a. TACS dimension overflow in overall (list 19 in vardim). A list size of 400000 storage cells is currently being used.
b. Switch number (list 6 in vardim) overflow which was unique to our case since we used a large number of TACS controlled switches. A total of 1000 switches are currently being used.
c. Branch and node name lists in vardim overflow and other lists overflow, which were due to the large size of the big test system.

The solutions for these dimensioning and allocation issues were ATP upgrades and unique allocation saving techniques like absolute TACS dimensioning and economizing of available allocation (e.g. less measuring switches).

C. ATP error in GIFU Slaves

During the times when allocation limits were either approached or overflowed, there was observed a rather unique ATP system error. It indicated that ATP allocation quota for GIFU switches overflowed. At the time GIFU switches were little known by the programmers. Typically TACS controlled Type 13 switches are used to model MOSFETs and IGBTs. However, power electronic switches were not used in this work. Type 13 switches were used in the big test system for modeling relays which use the GIFU allocation. The solution of this issue came by general switch allocation increase with another correction in which Drs. Liu and Meyer did a custom upgrade of our TPBIG.

D. Numerical Oscillation and Signal Quality Issues

During the testing of individual component models in testbeds, numerical oscillations were not noticed since the testbed switching was limited to the device being tested and the inductance of load and lines were small. However, when these components were integrated in the big test system, it became apparent that the system had numerical oscillation or signal quality issues. An example of the level of signal quality present without corrective measures can be seen in Fig. 2. Figure 2 is the voltage profile at switchboard 1 which shows a transient due to circuit-breaker switching in response to a fault down stream of a load center.

The method to mitigate this oscillation was found in EMTP theory book [7] which was empirically discovered by authors of the theory book, that a parallel resistor of value given in (1) can alleviate the numerical oscillation observed due to inductive switching in the big test system. L is the inductance of the branch to which Rp is parallel and Δt is the time step of simulation. It is also known that some electromagnetic transients programs do not require a parallel resistor to damp numerical oscillations since a technique known as "critical damping adjustment (CDA)" has been implemented on them.

An example of the same switchboard voltage during a simulation study for the system with Rp resistors in parallel with all the system cables and motors is given in Fig. 3. The figure shows the improvement in signal quality.

$$R_P = \frac{5.4 * 2 * L}{\Delta t} \qquad (1)$$

E. Trapped Energy and Signal Value Accuracy Issues

It was also discovered that when a switch opened a line, very often when the downstream node to the switch was measured, the value of the voltage was non zero and very high as shown in Fig. 4. This posed a problem for low voltage protective devices which needed the downstream signals (i.e. the downstream voltage) to be below a threshold value for proper operation. A link was further observed between the trapped energy problem and the circuit not being interrupted at zero current magnitudes. When the circuit interrupted at zero or near zero current, the voltage levels seen on isolated downstream circuits were at pre-interruption levels as opposed to extremely high values when the circuit was interrupted without zero current considerations.

Solutions offered for this problem have included reviewing Rp resistor values to converge these voltages to zero faster and implementing zero current switching in the TACS controlled Type 13 switches. In the interim to implementing these and other solutions, the downstream nodes isolated by the switching have been grounded to ensure the zero voltage for downstream protective devices proper functioning. This did not pose a problem to the ungrounded system because when the system worked properly only an isolated cable branch is typically grounded.

F. Motor divergence issues

Another problem encountered during the modeling of the big test system was a motor divergence problem. It was observed that when motors were disconnected and connected by circuit switching due to fault or reconfiguration, that, the motors could not be reconnected with the main circuit because EPSOM tolerance limits were violated. This meant that the motors could only be disconnected once during simulation and not reconnected (automatic initialization was used for the motors).

Solutions are still being sought for this issue but it was discovered that if the isolated motor could remain energized by a supplementary source during the time that the motor is separated from the main circuit then the motor EPSOM limits (which is the rotor speed convergence factor) were not violated. To temporarily solve this problem, Uninterruptible Power Supplies (UPS) were included with the motor models. The battery sources of these UPS were used as the supplementary sources during the time the motors were isolated from the main circuit.

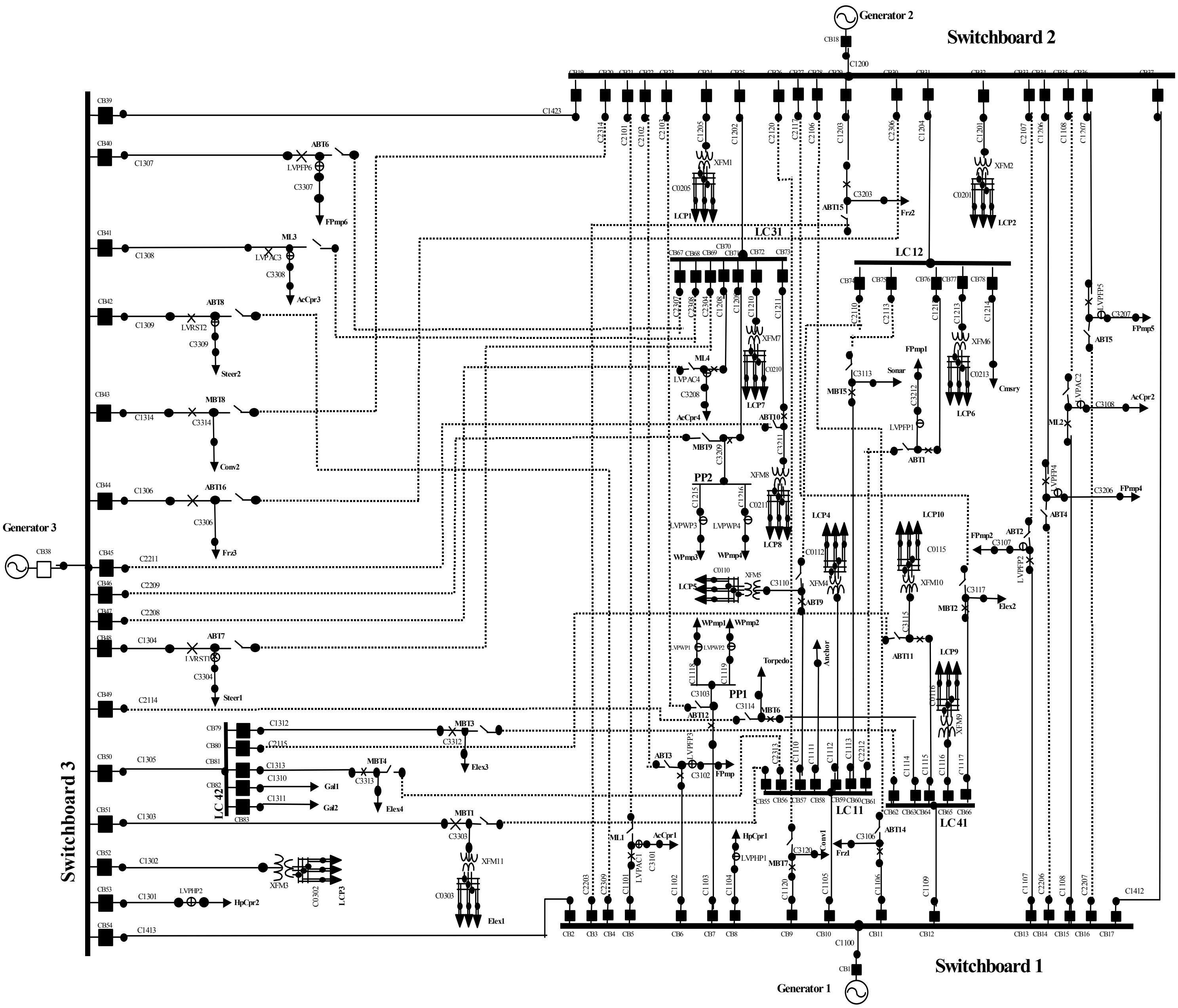

Fig. 1 Layout of big test system

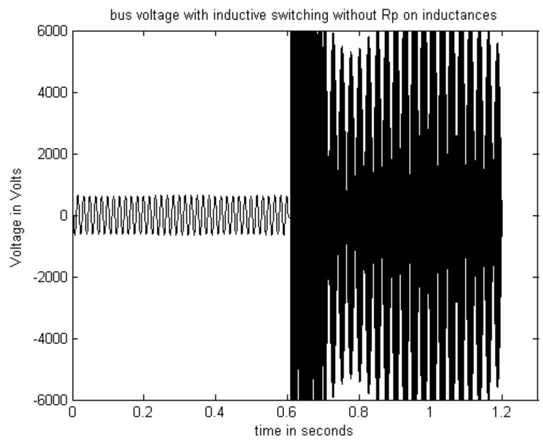

Fig. 2 Numerical oscillation example

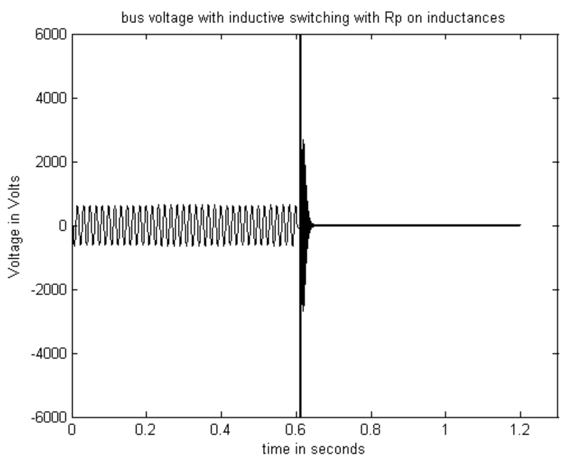

Fig. 3 Numerical oscillation solution example

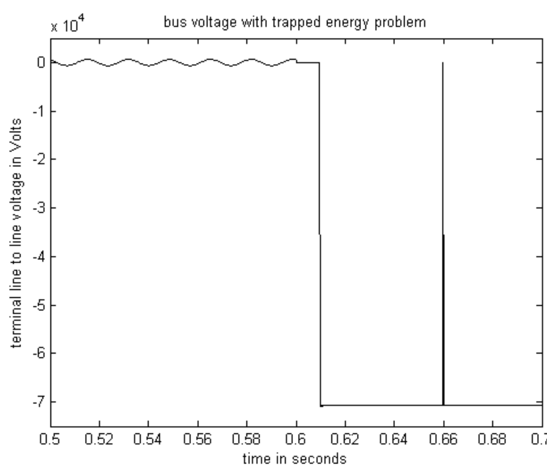

Fig. 4 Trapped energy problem example

Another solution which is being investigated further is the change of the motor from that of constant torque to the variable torque so that when input power to the motor is zero, the load torque can be constrained to be zero which produces a motor at rest (ω =0). Currently INDMOT supporting program which is being used to generate the motor punch file only generates constant torque or two torque levels. The use of the decoupled initialization mode is also being investigated as a solution to this problem.

IV. Conclusions

A scaled down version of a US naval surface combatant ship was modeled in ATP to provide a platform to study the behavior of the SPS during certain operating conditions, to aid in the development of automation methods such as restoration and failure assessment and to test the performance of these automation methods. Many issues were encountered during the modeling and simulation of this test system in ATP, they range from dimensioning problems, signal quality issues, trapped energy, numerical oscillation, and motor divergence. Solutions were obtained for these problems with varying success and work is ongoing to improve on solutions and system behavior.

This paper has sought to share the experiences of the modeling and simulation of a naval SPS in ATP and to present its successes and its ongoing challenges.

Acknowledgments

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