MODELING OF ELECTRIC SHIP POWER SYSTEMS

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Abstract: The central element of a ship power system model is typically a circuit model. This level of modeling has been valuable in evaluating architectures for future electric ships as it provides initial power flow and stability information as well as performance specifications, perhaps most notably overall efficiency. This circuit model is typically the middle layer in what is a three layer approach. At the more basic level, the physics of the components and processes is captured. In a power system, there are interactions among the electromagnetic, mechanical, and thermal behaviors. The third level is even more approximate than the circuit level. It includes such models as cost-of-ownership models, models of physical layout and integration of the power system with the balance of plant. These models are critical in the design process and depend on the circuit model to specify components and their interconnections. Incorporating breakdown physics demonstrates the linkage between the basic physics and the circuit models. Rotor dynamics provides examples of phenomena that cannot be captured in a circuit model. The design of insulation systems is an example of a field in which the circuit modeling may lead to less costly electrical systems for future electric ships.

1. INTRODUCTION

For the past decade, significant advances have been made in the modeling and simulation of the power system of electric ships. This growth is leading to an operational definition of what is meant by modeling of an electric ship power system. It is a premise of this paper that progress in the field will be aided by an examination of this evolving definition.

The central element of a ship power system model is typically a circuit model. These have been developed using a variety of programming languages and operate in real time [1,2] and other than real time [3,4,5]. This level of modeling has been very valuable in evaluating architectures for future electric ships as it provides initial power flow and stability information as well as numerous performance specifications, perhaps most notably overall efficiency. It should also be noted that this is the level of model that has proven useful for system control. A strength of this approach is that each component and the system can be described by sets of differential equations that are solved to predict overall system performance. These equations can provide the link between the system model and the physics of the system under test. A weakness is that the relevant temporal scales differ by orders of magnitude making further levels of approximation necessary for computational efficiency. In addition, the basic physics of many of the processes are too computationally intensive to make full modeling feasible. For example, it is traditional to rely on parameter extraction rather than an *ab initio* calculation to characterize the behavior of the semiconductors in a converter [6].

This circuit model is typically the middle layer in what is a three layer approach. At the more basic level, the basic physics of the components and processes are captured. In a power system, there are significant interactions among the electromagnetic, mechanical, and thermal aspects of the problem. This has lead to a design modeling approach which treats these as largely independent to assess the feasibility of various design approaches [7]. Then in more promising designs, the complexity of coupling is addressed. This approximate approach must be applied judiciously, but it can help achieve viable designs at less time and cost. It is also apparent that for many of the components, e.g., semiconductor switches [8], quantum mechanical effects can influence behavior and must be included.

The third level becomes even more approximate. It includes such models as cost of ownership models [9], models of physical layout, and integration of the power system with the balance of plant. These models are critical in the overall design process and depend on the circuit model to specify components and their interconnections.

2. RELATING PROCESS PHYSICS TO CIRCUIT REPRESENTATION

In power system modeling, the most common physics-based process is in the design of motors and generators. This approach is so powerful and well-established that there are numerous commercial software packages that combine material and geometric inputs and use Maxwell's equations to determine values of representative circuit components for conventional machine topologies. But the linkage of power system performance to the physics of key processes continues to evolve.

One emerging field is the modeling of system faults. Some of the underlying physics are the experimental observations that as the arc is propagating, the electric field between the streamer and the electrode toward which the streamer is propagating is that that would occur if the streamer were a conductor [10,11]. In addition, models predicted the growth of post breakdown arcs using parameters that permitted estimation of the arc's dynamic inductance and resistance [12]. While there were early attempts to use this data to predict the current and voltage waveforms that existed in a system while this breakdown was occurring, none were successful or general enough to warrant publication. This was due, at least in part, to subsequent work that demonstrated complex and variable morphology for the streamers [13].

Recent modeling results, however, reopened the possibility of improved physics-based models of fault behavior. The breakthrough resulted from a careful re-analysis and modification of a software tool that had been used to predict some aspects of streamer growth [14]. The computational challenge is that the growth is stochastic, stepped, and each step modifies the electric field distribution. In general, solving Laplace's equation is numerically intensive. The complexity here is to re-solve it for each step and to constrain the stochastic growth as it would be constrained by the growth physics in the real world. The significant contribution made by Fowler and his colleagues [14] was that the required physics to match the experiment is very simple. Subsequent refinements in the physics and the computational approach have led to numerical results that match a wide range of observations with a single simple set of consistent assumptions [15-17].

For reasonable results, this simulation requires parallel processing. The current program runs effectively on a set of 32 processors and requires about 1/25 the time that would be required if a single processor were used. Typical computational results are shown in Figure 1.

Figure 2 shows that the calculated results agree well with the experimental observations. The upper portion in Figure 2 is an experimental observation of a streamer that propagated from an upper point electrode to a lower nearly planar electrode. A striking feature of the experiment is the fact that, due to field perturbations in the stochastic nature of the process, the experimental observation shows a slight growth back toward the point electrode shortly prior to completing the circuit. This behavior is occasionally, but not frequently, observed in experiments. The lower portion of the figure shows it is also seen, again occasionally, in the simulation of growth.

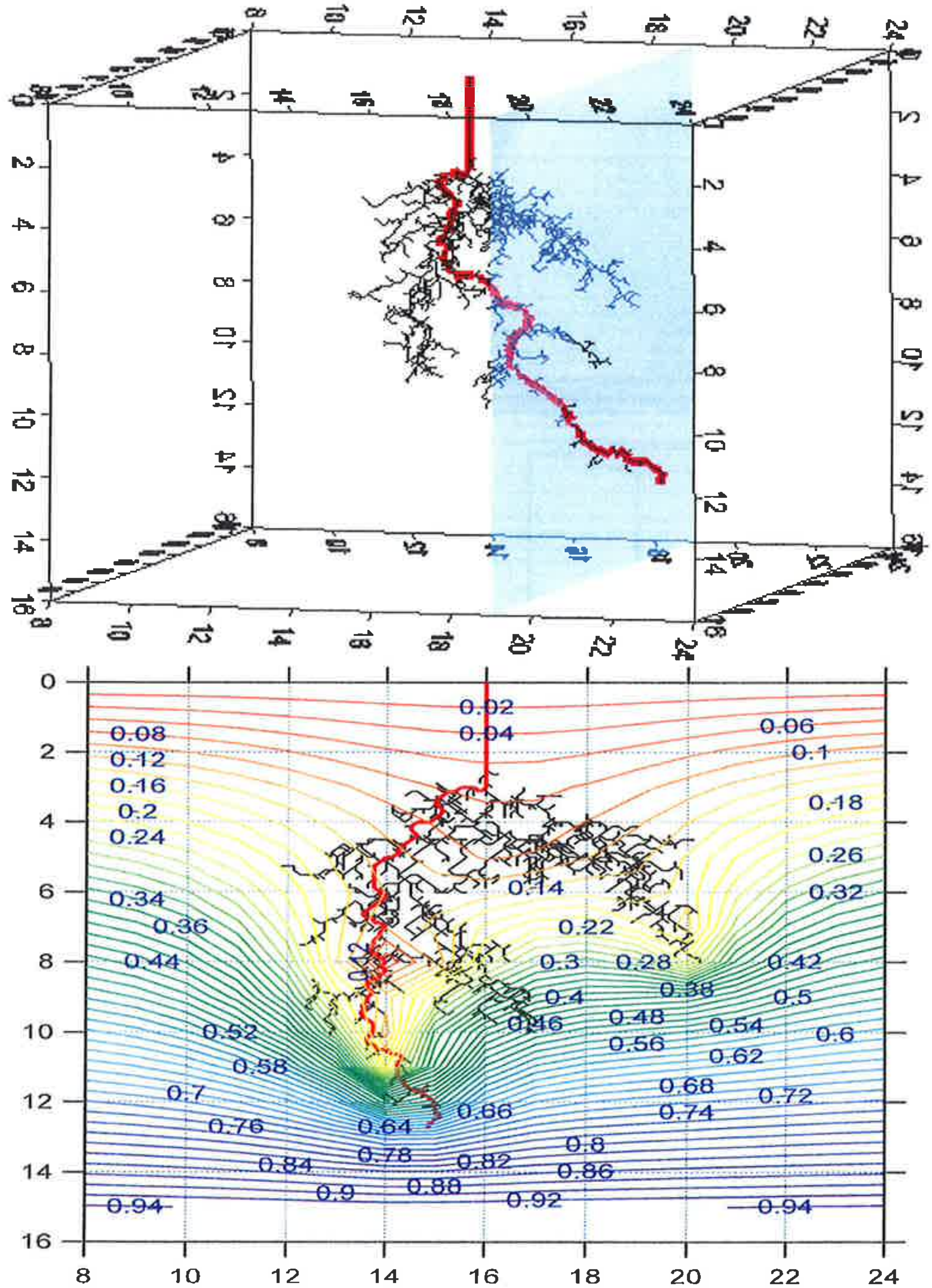

Figure 1. Computational results for a simulation run. The upper plot shows the three dimensional nature of the computation and the lower is a map of equipotentials in the plane highlighted in the upper plot.

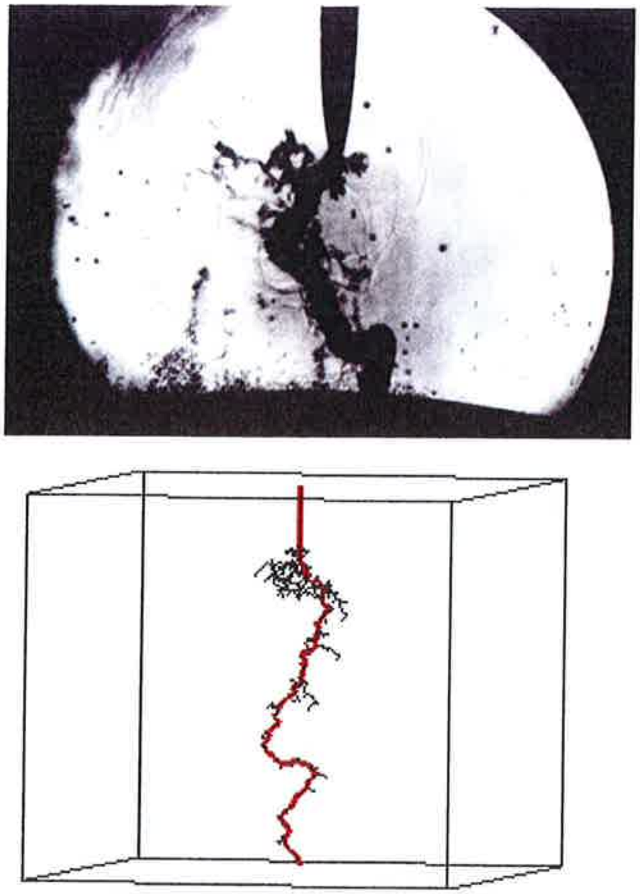

Figure 2. The experiments and the simulation both exhibit an occasional change in the growth direction by which the streamer grows approximately orthogonal to the initial geometric field direction. In both the experiment and the simulation, this is assumed to be a result of the stochastic nature of growth and the distortion of the geometric field by the streamer itself.

3. PHENOMENA THAT DO NOT HAVE CIRCUIT EQUIVALENTS

In the development of circuit models for future electric ships, the modelers must continue to be aware that some of the key parameters do not and will not have circuit equivalents. Some of these parameters are critical to safe operation. One such broad set of parameters is the field of rotor dynamics. Once a motor or generator has been designed, built, and tested, it can usually be assumed that the rotor dynamics are stable and only the circuit elements are important. But there are some interesting instabilities that can occur. One of these is given the name the Morton Effect [18,19].

The phenomenon known as the Morton Effect is a thermohydrodynamic mechanism present in the bearings of nearly all turbomachinery. The effect occurs when the temperature distribution within the shaft becomes dependant on the shaft vibration amplitude. Ordinarily, the Morton Effect does not affect the performance or operation of the machine. In some cases, however, the vibration becomes so severe that operation at design conditions is not possible. This results when the temperature response leads to additional vibration which leads to increasing temperature, and so on. This is a phenomenon that is difficult to correct after a machine is built, so it is an ideal candidate for modeling.

Unfortunately, the modeling is challenging. A sophisticated blend of thermal, mechanical, and hydrodynamic analytical methods is required to predict the onset of the Morton Effect. Such analytical tools are not generally available and there is extremely limited data available to validate the modeling approach. While analytic approaches are being developed [19], additional research is needed.

4. ELECTRIC INSULATION FOR ELECTRIC SHIPS – A MODELING OPPORTUNITY

Electrical insulation is an important component of the power system. Unfortunately, it is also a component for which there is insufficient data to provide good design information. Obviously a good design is important because too little insulation adds risk to the system. Too much insulation increases the purchase price. But it also has other effects. The thicker the insulation on cables, for example, the more difficult and costly they are to install and replace. In addition, superfluous insulation also needlessly increases the cost of transporting the unnecessary insulation weight throughout the life of the ship.

Inherently, the design of an insulation system requires two sets of knowledge [20]. The first is the knowledge of the properties of the insulation material itself. This is typically the emphasis of most basic research in the field of electrical insulation. The second, which is a new opportunity for modeling, is the characterization of the electrical environment in which the insulation system must operate. The specific aspect of that environment is the electromagnetic environment.

The preponderance of insulation systems fail under impulse stress [20]. An obvious exception to this observation is capacitors. Because they effectively transfer transient voltages, they tend to fail via degradation at operating stresses.

The role of transients in insulation failure has led to the development of standard tests for insulation systems. For land-based power systems, standards have been developed to address three types of insulation systems. The first is called the lightning impulse. The shape of this impulse was selected to represent the range of pulse shapes that would be induced in a power system when lightning struck near high voltage transmission lines. The overhead lines would conduct this disturbance throughout the neighboring power system.

The second class is switching surges, so called as they generally arise due to switching operations in the power system. These generally have slower rise times and longer durations than lightning impulses

The final class is that of the pulses introduced into a power system due to motor drives using pulse width modulation. These pulses have a faster rise time than lightning impulses. Because of the high frequency content, they tend to affect insulation systems nearest the source, as power systems generally tend to attenuate high frequency. It is anticipated that these standards will initially serve as the standards for the more general introduction of power electronics, with their faster switching times, into the power grid.

Obviously, the shape and influence of the various pulse sources are due to the inductance and the capacitance of the power system and the nature of the source of the disturbance. It is in these two areas that ship power systems differ from land-based power systems. The characteristic resistance, inductance, and capacitance of a ship power system are significantly different from those of a widely distributed overhead transmission system. Therefore, it is not prudent to assume that the pulse shapes that led to insulation failure in a land-based system would be the same in a ship power system.

The situation is similar for the sources. A future electric ship will have a very high density of power electronics attached to the system. The proximity of the various devices enhances the possibility of interaction, while the additional filtering provides some isolation. Switching will be done at various parts of the circuit, likely using a variety of switching technologies. Lightning will not be conducted to the ship from kilometers away, but will have to strike the ship itself to have an influence. The shielding provided by the ship may be affected by the amount of composite material used.

All of these differences suggest that the insulation systems used in land-based power systems will not likely be appropriate for future electric ships. In addition, the standard methods for testing the adequacy of insulation will likely yield results that are inappropriate for ship systems. The current standards were developed to mitigate decades of failures in land-based systems. If accurate models of the transient behavior of future ship power systems are developed, they could reduce the cost of developing and testing components for electric ship applications.

Since this has never been done, the models are being developed and a model dc microgrid is being established on which to validate the model. The microgrid is shown in Figure 3.

The concept is to develop a model of a ship power system and this microgrid using the same level of detail and approximation. The microgrid contains many of the key elements of the full circuit, but operates at a lower power level. The microgrid will be instrumented to record transients on the grid. These measurements will be used to validate the model and provide guidance for the modeling of more complex ship power systems.

The model can then be used to characterize the electrical environment in power systems that have yet to be built. These model environments can provide the basis for insulation tests for components that are expected to operate in this new electrical environment.

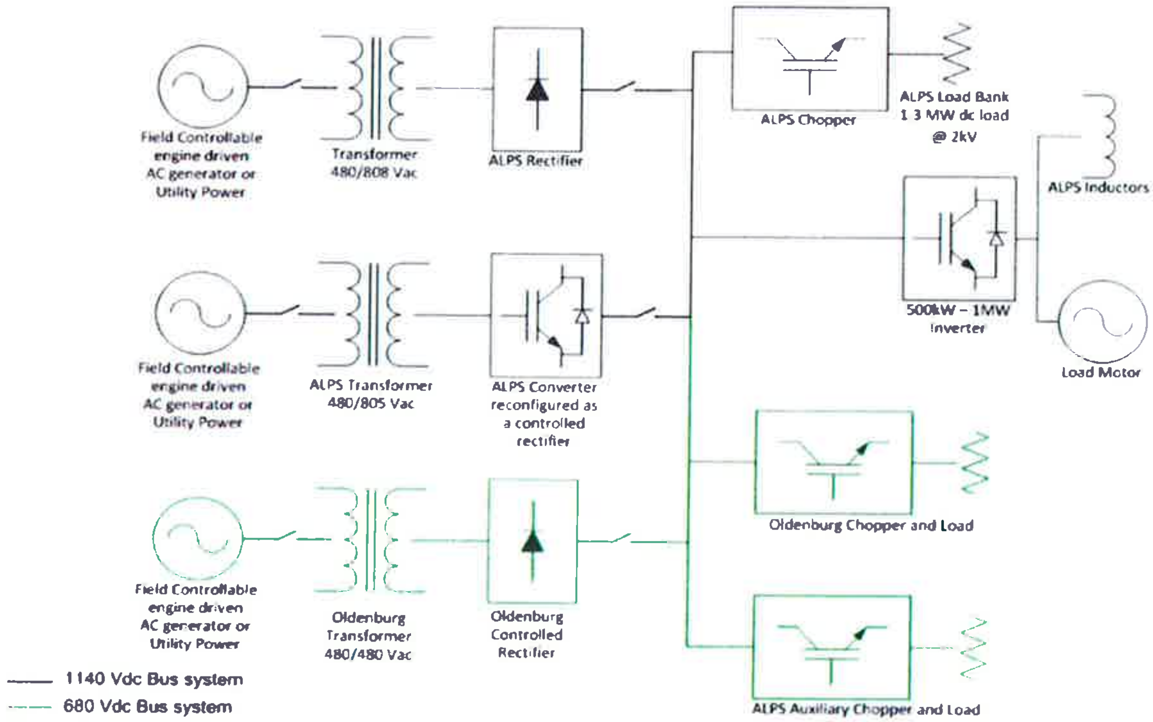

Figure 3. Schematic diagram of dc microgrid. The entire grid can be operated at 680 V dc. If the lower half is removed, the operating voltage can be increased to 1100 V dc.

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