

Electrical Power System Sizing within the Numerical Propulsion System Simulation

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Electrified aircraft propulsion seeks to address ambitious goals in the commercial airline industry, including significant decreases in fuel burn, emissions, noise, and takeoff field length. In order to move these electrified propulsion concepts forward, analysis tools are needed that can model propulsion systems containing both gas turbine and power system components. This work presents the definition of an electric port, a set of electrical power systems tools, and simulation examples for the Numerical Propulsion System Simulation (NPSS) software. NPSS is the industry standard modeling and simulation package for aircraft propulsion systems, and the ability to design, size, integrate, and analyze electric power systems will enable industry efforts towards the development of electrified aircraft propulsion.

I. Introduction

AIRCRAFT electrification is a prospective advanced propulsion concept to reduce aircraft noise, NOx emissions and aircraft fuel burn. In its most primitive definition, aircraft electrification refers to concepts that utilize electrical power in propulsion of the aircraft. This includes hybrid electric,¹ such as the Boeing-General Electric (GE) “Sugar Volt” and turboelectric concepts,² such as STARC-ABL, featuring two main engines and an electrically powered aft thruster for boundary layer ingestion. Both hybrid electric and turboelectric concepts utilize an electrical power system to deliver power from an electrical source, e.g. battery or generator, to a motor which drives a propulsor (or aids a turbine) that provides thrust for the vehicle. The electrical power system impacts the overall weight, thermal system requirements, and efficiency of the propulsion system and these tradeoffs need to be considered to meet the design objectives, especially in an optimized fashion. More specifically, this requires the power system to be included in the conceptual design phase of the propulsion system.³ One of the most widely used tools for conceptual design of propulsion systems is the Numerical Propulsion System Simulation (NPSS). This paper will discuss the design of an electrical port that enables the design, sizing, integration, and analysis of electrical power systems within the NPSS environment

II. Electric Port

While thermal-fluid modeling is the primary application area of NPSS, it is not natively capable of assessing electrical simulations.⁴ For this reason, the development of an electrical framework modeling capability in NPSS is required. The Electrical Port is the foundational programmatic object of this framework that represents the connectivity between any pair of electrical components. It conveys information such as voltage, current, phase, power and power factor between electrical components and acts as the vehicle for the conservation of Kirchhoff’s Current and Voltage laws⁵ throughout network balance techniques. This is analogous to the NPSS Fluid Port⁶ that conveys thermodynamic information between two fluid-driven elements as well as serving as an aid for fluid continuity balance in a thermal fluid network.

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Port objects typically reside inside a master object responsible for calculating appropriate transfer functions (voltage-current relationships) and transmit the output to the next element connected at the port. Figure 1 shows a schematic explaining the connection between generic elements E1 and E2 through their ports E1_O and E1_I respectively. The _O and _I represent the naming convention for the output and inputs of the electrical elements, assuming standard power flow convention. The elements E1 and E2 may represent any RLC net combination effect between their corresponding inlet and outlet ports. The connection between elements, via ports, is established by the user when building the network model. Once the connection is set, any change in either of the ports' electric states (voltage, current, phase, etc.) will instantly be reflected in the corresponding linked port pair, giving elements E1 and E2 timely and appropriate boundary condition information to perform their transfer function calculations.

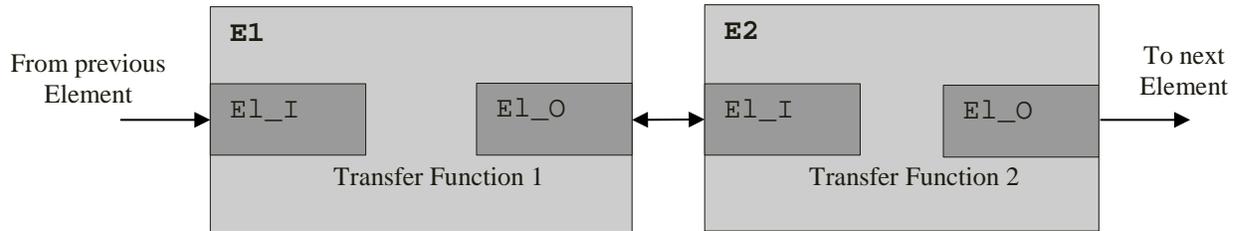


Figure 1. Electric Port connectivity schematic

Generic capability has been developed into the Electric Port to handle either Alternate or Direct Current (AC/DC) power transfer. The internal calculations are all in the complex plane (complex numbers as phasors or space vectors) with the special case being DC power transfer where all the imaginary components of the complex numbers are zeroed out. Given the heavy complex math involved in electric circuits for sinusoidal analysis, a Complex Number variable definition was developed in NPSS to simplify the programmatic math footprint. The Complex Number object holds information about the real, imaginary, absolute magnitude, and phase angle of the complex plane for voltage, current and power inside the Electric Port. It is intended for the Electric Port, as well as the Complex Number routines, to be integrated into the next NPSS revision and available for NPSS users.

Electrical power system data is transferred between components by sending the root mean square (RMS) current and voltage (line-to-line) data to the electrical port in one of three ways. The RMS data can be written to the electrical port in polar format (magnitude and phase) with the angles in either radians or degrees, or in complex conjugate form, as shown in Table 1. In the electrical port, the voltage is assumed to be line-to-line voltage unless noted as line to neutral with the subscripts *ln*. As mentioned earlier, the electric port computes power for DC, single phase AC, and three phase AC, although additional electrical current concepts could be added. The power system variables calculated in the port, along with standard units are shown in Table 2.

Table 1. Electric Port function calls

Input Method	Function Call
Polar format in Radians	<i>setIVRMSphaseRad (Imagnitude, Iphase, Vmagnitude, Vphase);</i>
Polar format in Degrees	<i>setIVRMSphaseRad (Imagnitude, Iphase, Vmagnitude, Vphase);</i>
Complex Conjugate	<i>setIVRMS(Ireal, Imaginary, Vreal, Vimaginary);</i>

Table 2. Electrical variable data based on electrical current type

ELECTRICAL VARIABLE	SYMBOL	UNITS	DC	AC, 1-PHASE	AC, 3-PHASE
POWER	<i>S</i>	Kilo Volt-Amps	X	X	X
VOLTAGE (LINE TO LINE)	<i>V</i>	Volts	X	X	X
VOLTAGE (LINE TO NEUTRAL)	<i>VLN</i>	Volts	X	X	X
CURRENT	<i>I</i>	Amps	X	X	X
POWER FACTOR	<i>PF</i>	-		X	X
FREQUENCY	<i>Frequency</i>	Hz		X	X

III. Electric Node

Practical electrical networks have more than two elements connected to each other. By itself, the Electrical Port cannot address such connectivity as it only links a pair of elements per port. For such scenarios, an Electric Node definition was developed to handle more than two port-to-port connections. Figure 2 shows a specific example where

three elements are connected to a single node. The Electric Node generates three Electric Ports that reside within; each one paired to an external Element's Electric Port. The Node has two main goals: 1) set the input voltage (V_{node}) to all the ports contained within and 2) calculate the net current from the arithmetic addition of all the ports contained within. These two processes are typically handled by a solver executive that will drive the balance of net current into the port to be zero by iterating on its node voltage. This is to preserve Kirchoff's Current Law⁵ for each node in a network system. Recalling the Electrical Port behavior, when the node sets either of its internal port's voltage, the corresponding linked external port will immediately reflect the same voltage change that will serve as boundary condition to the external elements.

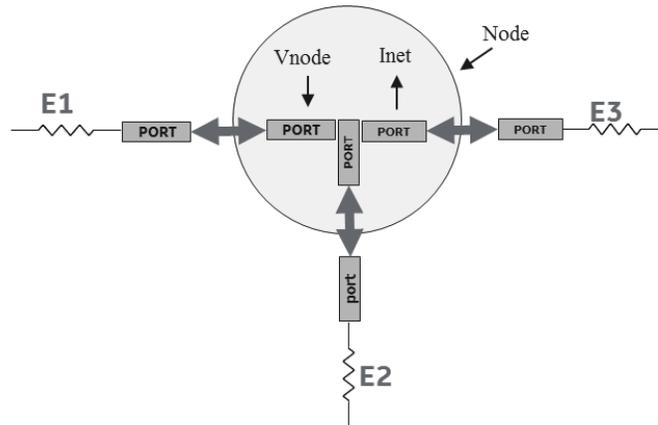


Figure 2. Electric Node connectivity schematic

IV. Electrical Toolbox

To make use of the electric port (and node), an electric toolbox was created consisting of various power system and circuit elements. The elements contain standard sizing equations (on-design), performance maps, static and dynamic performance equations (off-design), along with configurable input/output types. The toolbox is open source,⁷ and can be found via the NASA Software Catalog.⁸ A full list of the current toolbox elements and the respective port modes are listed in Table 3.

Table 3. Toolbox elements and associated features.

ELEMENT	MAP	DC	AC, 1-PHASE	AC, 3-PHASE
CABLE		X	X	X
MOTOR	X			X
GENERATOR	X			X
RECTIFIER	X	X		X
INVERTER	X	X		X
BREAKER		X	X	X
LOAD		X	X	X
RESISTOR		X	X	
CAPACITOR		X	X	
INDUCTOR		X	X	

Element interface connections via the various ports, in addition relevant data, is demonstrated via a flow diagram in Figure 3. In this example, a DC bus (voltage source) connects with an inverter through an electric port in DC mode. The inverter, which contains its own performance map (e.g. power vs. efficiency), outputs thermal loss through a thermal port and its electrical data through an electrical port in three-phase AC mode. This electrical connection continues to a motor element which also has a thermal output and mechanical connection to a fan through a shaft port. The system can be designed, simulated, and evaluated by the use of a Newton-Raphson solver. General use of the NPSS solver is detailed in References 7 and 8 and is beyond the scope of this paper. However, setup of the solver variables will be described in the following section.

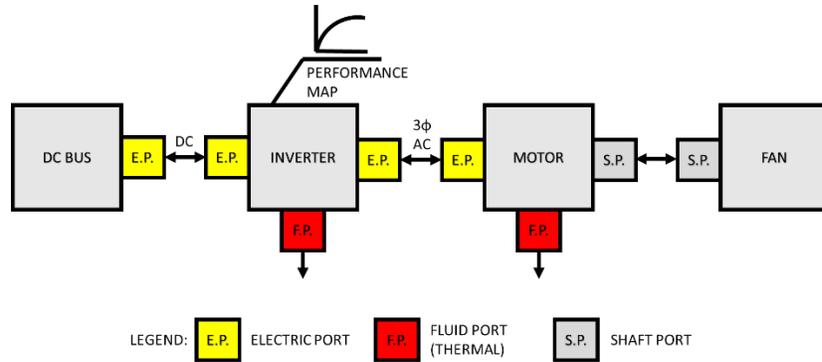


Figure 3. Toolbox Element Connectivity

V. Applications of the NPSS Electric Port

One of the goals associated with the development of the NPSS electrical port was to be generic enough such that it could be used for different levels of analysis. For example, one user may want to use the port to connect basic electrical circuit elements while other users may want to only develop models of higher level electrical distribution elements. Therefore, to verify the NPSS electrical port, three sample applications were chosen that cover the anticipated different uses of the port; a simple RLC circuit, a three-phase electrical power system application, and an aircraft example. These examples can be found from the NASA GitHub page.

A. Simple RLC Circuit

One possible use of the electrical port within NPSS is for steady-state circuit analysis. A circuit model can be created and NPSS would solve for the steady-state currents and voltages, which could be either alternating current (AC) or direct current (DC). To demonstrate this capability, a circuit containing the basic electrical circuit elements, including an AC source, capacitor (C), inductor (L), and resistor (R) was created and is shown in Figure 4. In NPSS, a model file was created to connect these components with 2 nodes inserted. Node 1 connects the output of C1 to the inputs of L and R and node 2 connects the output of L to the input of C2. The solver variables set up in this system are the node current dependents, and the node voltage independents for both nodes. In order for the toolbox and electric port to interpret the electric port variables properly, for this single-phase AC system, each port must be specified as a single-phase AC port. This is done in this example with a global “setOption” command in NPSS which sets all of the ports in the system to the proper type. The results from NPSS compared to the results from SPICE are shown in Table 4. This data indicates that NPSS with the electrical port is capable of performing circuit analysis.

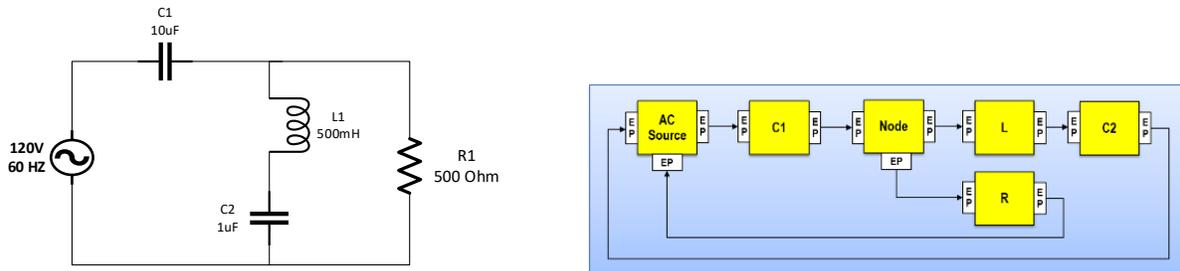


Figure 4. RLC Circuit Diagram (left) and NPSS Representation (right)

Table 4. RLC Circuit Analysis

COMPONENT	NPSS ELECTRIC PORT	SPICE
C1 VOLTAGE DROP	31.8777 – j42.2068 V	31.8777 – j42.2068 V
C1 CURRENT	0.1591 + j0.1201 A	0.1591 + j0.12017 A
L1 VOLTAGE DROP	-6.7411 – j3.2287 V	-6.7411-j3.2287 V
L1 CURRENT	-0.0171 + j0.0357 A	-0.0171+j0.0357 A
C2 VOLTAGE DROP	94.8634 + j45.4355 V	94.8635+j45.4355 V
C2 CURRENT	-0.0171 + j0.0357 A	-0.0171+j0.0357 A
R1 VOLTAGE DROP	88.1223 + j42.2068 V	88.1223+j42.2068 A
R1 CURRENT	0.1762 + j0.0844 A	0.1762 + j0.0844 A

B. Three-Phase Power System Example

The simple circuit example in the previous subsection demonstrates capabilities that are useful for some applications, but it is unnecessary to use a full circuit model for a balanced three-phase system. A simplified example demonstrating operation of the electrical port for a three-phase system is shown on the left side of Figure 5. In this system, a 208 Volt (line-to-line) three-phase source transmits power across a line impedance of $0.5\angle 88^\circ$ Ohms to a Y-connected load of $5\angle 45^\circ$ Ohms. The source, load, and cable are connected in NPSS as shown in the diagram on the right side of Figure 5. What distinguishes the components in this example from the ones in the previous example, are that the electric ports are set up as three-phase electric ports. In three-phase mode, the voltages and currents in the ports are interpreted as three-phase line-to-line voltages and phase currents, as opposed to single-phase quantities. With the port electric power type set up appropriately, the generic voltage source, cable (line), and load components will compute the correct outputs, consistent with the desired power type. Like the previous example, the only dependents in this system are node current dependents and node voltage independents. The only node with unknowns, and thus the node with solver variables in this system, is the node between the transmission line and load. Note that the neutral connection between source and load is represented by the arrow that loops back, underneath the components, in the right-hand side diagram in Figure 5. The comparison of the results from NPSS and SPICE is shown in Table 5, which verifies the operation of the three-phase mode of the NPSS electrical port and demonstrates applicability to power system analysis.

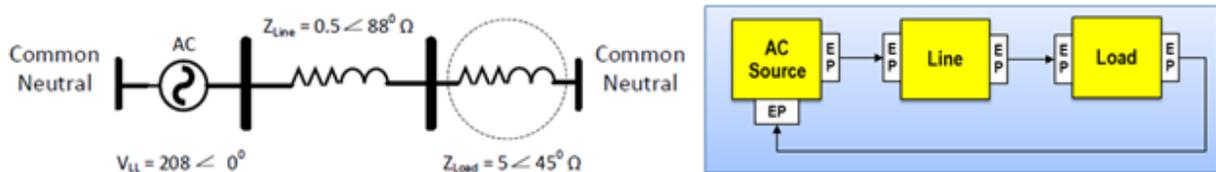


Figure 5. One-line Diagram (left) and NPSS Model (right) of a balanced three-phase system operating at 60 Hz.

Table 5. Three-phase System Analysis

COMPONENT	NPSS ELECTRIC PORT	SPICE
LINE PHASE VOLTAGE DROP	11.0154 + j1.8165 V	11.0095+ j1.8186 V
LINE PHASE CURRENT	4.4015 – j21.8985 A	4.4036 – j21.8786 A
LOAD PHASE VOLTAGE	92.9846 - j61.8609 V	92.9217 – j61.7945 V
SOURCE POWER	5.3179 + j6.0394 kVA	5.3111 + j6.0284 kVA
LOAD POWER	5.2918 + j5.2918 kVA	5.2835 + j5.2826 kVA
LOAD POWER FACTOR	0.7071	0.7071

C. Turboelectric Aircraft Powertrain Example

One primary use of the NPSS power system toolbox and electrical port is to construct models of turboelectric and hybrid electric systems. A simple turboelectric model was created to demonstrate the modeling of these systems. A diagram of this system is shown in Figure 6. The system includes a turbine (T), generator (G), rectifier (R), inverter (I), motor (M), and propulsor (P). Note that the turbine and propulsor (likely a fan) are connected to the generator and

motor through their associated shaft components (Propulsor Shaft and Turbine Shaft in Figure). Also, the motor and inverter (and also generator and rectifier) are connected via 3-phase AC cables (Cable1 and Cable3) and the inverter and rectifier are connected via a DC cable component (Cable2). Not shown are the flow-start, nozzle, and flow-end components used to set the airflow conditions through the turbine and fan. Note that this model does not include ambient or inlet blocks, and so it cannot simulate varying altitude or other flight conditions. This example is intended to show how to integrate a gas turbine and electrical power system components together.

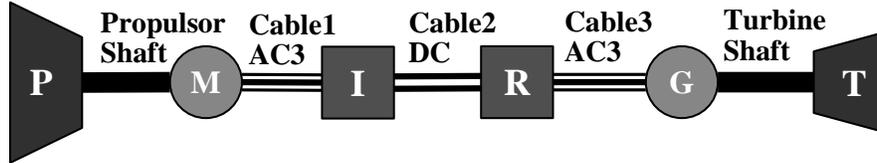


Figure 6. Diagram of the turboelectric system.

After creating the NPSS components for this example, the solver must be set up before running. The solver independent and dependent variable setup for this example is shown in Table 6.

Table 6. Solver independent and dependent variables for the turboelectric example.
ON-DESIGN (Sizing)

Independents	Dependents
Cable1.ind_Ireal	MotorAngle
Cable1.ind_Iimag	Cable1.dep_Vreal_err
Cable2.ind_Ireal	Cable1.dep_Vimag_err
Cable3.ind_Ireal	Cable2.dep_Vreal_err
Cable3.ind_Iimag	Cable3.dep_Vreal_err
Turb.S_map.ind_PRbase	Cable3.dep_Vimag_err
EM1.ind_Vimag	Turbine_Shaft.integrate_Nmech
EM1.ind_Vreal	Propulsor_Shaft.integrate_Nmech
Rect1.ind_Vimag	Rect1.dep_Power
Rect1.ind_Vreal	Rect1.dep_phase
Inv1.ind_Vimag	Inv1.dep_Power
Inv1.ind_Vreal	Inv1.dep_phase
prop_pwr	target_pwr
OFF-DESIGN (Transient)	
Independents	Dependents
Turb.S_map.ind_PRbase	MotorAngle
Gen1.ind_trqTemp	Turb.S_map.dep_errWp
EM1.ind_Vimag	Noz.dep_Area
EM1.ind_trqTemp	Gen1.dep_trq_map
EM1.ind_Vreal	EM1.dep_trq_map
Turbine_Shaft.ind_Nmech	Turbine_Shaft.integrate_Nmech
Rect1.ind_Vimag	Propulsor_Shaft.integrate_Nmech
Rect1.ind_Vreal	Rect1.dep_Power
Inv1.ind_Vimag	Rect1.dep_phase
Inv1.ind_Vreal	Inv1.dep_Power
ind_AtmW	Inv1.dep_phase

As can be seen in Table 6, the inverter (Inv1), rectifier (Rect1), and motor (EM1) all have voltage independents, and the rectifier and inverter have power and phase dependents both on and off design. The inverter and rectifier's respective pairs of variables mean that the solver must select rectifier and inverter voltages (input and output respectively) that make the power and phase dependent errors of zero ($P_{in}*\eta = P_{out}$ for both inverter and rectifier power, and $V_{in(phase)} = I_{in(phase)}$ for rectifier phase and $V_{out(phase)} = 0$ for inverter phase).

The electric motor and generator each have a solver independent and dependent pair (ind_trq_temp, dep_trq_map) that are needed to run their respective maps properly off-design. The motor also has real and imaginary voltage independents. By default, these independents do not have dependent variables to pair with, and so some dependent variables must be defined in addition to the default ones described here in order to have a fully defined system. In most cases, as in the turboelectric example described later, there will be a dependent that forces the motor to operate at a given power factor. The other dependent may force the motor output shaft power or speed to equal a given value.

Also, the cables have independent and dependent pairs (current and voltage error across the cable(s)) needed for sizing during on-design operation. The solver uses these to select a current through the cable, to be used in the cable's sizing logic as an ampacity constraint. The sizing logic then selects a cable design that, given the calculated current, will produce a certain voltage drop. The voltage dependent ensures that the voltage drop for the given cable design and solved current, matches the difference between the voltages that the cables sees at its ports. Off design, the sizing logic is no longer needed, so the cable will compute current based on the voltages seen at its ports and the cable impedance.

Standard NPSS shaft speed integrators are also included both on-design and off-design. The turbine pressure ratio (PR) independent is a standard turbine independent from NPSS that is always added and gives the solver the ability to vary the power produced by the turbine while changing how the turbine affects the airflow through it. Note that the propulsor inlet flow independent *ind_AtmW*, turbine flow error dependent *Turb.S_map.dep_errWp*, and propulsor nozzle area dependent *Noz.dep_Area* are all variables that NPSS turbomachinery components normally add off-design. All of the solver variables mentioned in this paragraph are automatically set up and are standard for their respective components.

Non-standard solver variables include the following. The *target_pwr* and *prop_pwr* dependent and independent used in on-design are intended to set the on-design power of the system at the turbine, as opposed to setting the power of the system at the load (propulsor) end as is done in off-design. *MotorAngle* is used to force the motor to run at a given power factor and is used both on- and off-design. Also note that, during on design, the associated shaft speed independents are not used since the shaft speeds are treated in this simulation as design variables. During off design, the turbine shaft independent is set up in the solver, but the propulsor shaft independent is not. This is because this model is intended to represent a propulsor running at a constant speed with varying load (the load power on the propulsor is accounted for via the power value set in the propulsor component). Other simulation scenarios (varying speed at constant power or constant torque) can be achieved by adding additional solver variables.

The design efficiencies for all power electronic devices (rectifier and inverter) and electric machines (motor and generator) were set to be 95%. Further, efficiency maps are included in the power electronic devices and electric machines to model how component efficiency varies with operating point. In the power electronics, the maps are defined as lookup tables that take in component output power and return the efficiency. The maps used for the electric machines take in machine torque and speed and output the efficiency. Note that the maps used in this work were produced manually, to reflect maps published in the literature for SOA devices. The efficiencies produced by these maps are near maximum throughout most of the operating range, and thus, when running the model, the efficiencies are not observed to vary much.

This model is included in a run file, where it is first run in the on-design mode to size all of the components. It is then repeatedly run off-design, reducing power by 10% each time, until the model reaches an idle power setting (in this case, defined as less than 1/3rd of maximum power). An NPSS page viewer file was created to output all of the relevant system variables (voltages, currents, phase angles, electrical powers, shaft powers, etc.) at each point run in the simulation. After running the model, the output from the viewer script was checked to make sure that results were consistent with the component performance calculations and the port connections. Of particular interest are the powers throughout the system as the load power at the fan is decreased. This power data is shown in Table 7.

Table 7. Power (kiloWatts) in different components in the turboelectric example system.

CASE #	TURBINE SHAFT POWER, kW	GENERATOR OUTPUT POWER, kW	RECTIFIER OUTPUT POWER, kW	INVERTER OUTPUT POWER, kW	FAN/MOTOR SHAFT POWER, kW
1	3750.28	3598.62	3415.98	3235.86	3105.00
2	3321.22	3189.19	3049.77	2909.71	2794.5
3	2951.28	2834.08	2726.88	2617.88	2515.05
4	2638.32	2532.95	2445.44	2356.26	2263.54
5	2370.16	2273.6	2198.69	2122.96	2037.19
6	2131.36	2043.43	1978.54	1912.79	1833.47
7	1917.25	1836.84	1780.62	1723.86	1650.12
8	1726.86	1653.04	1603.22	1553.38	1485.11
9	1559.99	1491.92	1447.28	1402.61	1336.6
10	1409.17	1346.56	1306.25	1266.23	1202.94
11	1273.57	1216.16	1179.24	1142.77	1082.65
12	1155.97	1102.68	1068.34	1034.64	974.38

This data shows that, as load power is varied, each component is consistently operating with an efficiency near 95%. The power that must be extracted from the turbine is always significantly higher than the power produced at the fan shaft by the motor, as the turbine must supply power to the fan as well as all of the losses within the components. The data show that power can successfully be passed between typical NPSS turbomachinery components through a power system model constructed with the power systems library. This demonstrates how the library can enable NPSS to study more-electric propulsion systems. Further, by successfully running the model on-design and then off design through a wide range of output powers, the library is shown to be capable of supporting the kinds of systems studies that make NPSS so useful (e.g., running through flight profiles, conducting sensitivity studies, etc.).

VI. Summary and Future Work

This paper presents the development of an electrical framework modeling capability in the Numerical Propulsion System Simulation (NPSS). NPSS is one of the most widely used tools for the design and analysis of propulsion systems. Adding the ability to design, size, and evaluate the performance of the electrical power system at the same time as the propulsion system allows for a more robust and optimized design. This capability has been demonstrated and will be incorporated in NPSS in a future release. In addition, an open-source electrical power system library containing the examples presented in this paper along with standard electrical components is available. Future work related to the electrical power system sizing capability includes integrating this capability within electrified aircraft designs, continuing to build-up the electrical power system library for more components and higher fidelity, and partnering with aeronautics companies.

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