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Power Quality Management of NASA's Large, Nonlinear Research Loads

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Abstract The National Aeronautics and Space Administration (NASA) conducts research on aircraft and spacecraft concepts and materials at the Langley Research Center (LaRC) in Hampton, Virginia. In order to match real flight conditions, large, high energy research facilities are used with solid-state power supplies and variable frequency drives to power large motors and arc heaters. Incorporation of this technology introduces nonlinear loads to the electrical power distribution grid and the added consideration of power quality. Because of the resultant harmonic current injection to the line side of these loads, the requirements of IEEE 519 were specified by NASA for each installation in an effort to maintain an acceptable level of power quality across the entire Research Center. Selection of the point of common coupling and minimization of system resonances were design considerations that impacted the cost and performance of the installations. Several of these NASA installations are described here: a 101 MW synchronous machine with Load Commutated Inverter drive, a 9MW synchronous machine with cycloconverter drive, and a 20 MW arc-heater DC power supply. Results of design configurations, harmonic content, operational issues, site layout, and system performance are presented.

Key words

Power quality, harmonic filter, reactor, load commutated inverter, cycloconverter, arc heater, DC supply.

1. Introduction

NASA has a long history of aerodynamic research and development that has successfully advanced the global knowledge and application of air vehicles. To acquire the necessary physical laws and understanding of how vehicles perform in-flight, large wind tunnels are required to duplicate the conditions experienced by aircraft and spacecraft.

Installation of large nonlinear loads requires careful management of grid harmonic distortion and potential voltage rise/resonances. At NASA LaRC, addition of these large (>1MW) systems has to meet the requirements of IEEE 519 [1] at the Point of Common Coupling (PCC), within the localized grid system at the Center. In addition, there are power factor requirements (>0.95 at all loads) and voltage limits of +/- 10%. The Center power distribution initiates with two independent 115kV feeders supplying the main substation. From that point, general power to the Center is supplied via several 22kV distribution loops. In contrast to the general distribution approach, the high power required for specific large research equipment is distributed at 115kV via underground cables terminating close to the load equipment. For non-linear loads, localized transformation and harmonic filtering is installed at each research facility. These high-demand factor loads are not continuous, and therefore must be treated as intermittent, dynamic perturbations on the grid.

2. The National Transonic Facility (NTF)

The NTF is a world-class, unique research facility because it can match vehicle cruise flight Mach number and simulate the highest altitude Reynolds number of any wind tunnel in the world. The facility, shown in Figure 1, is used in part by the aircraft industry to simulate the full scale, in-flight performance characteristics of large transport aircraft at transonic speeds to improve fuel efficiency.

Figure 1. NASA's National Transonic Facility in Hampton, Va.

To reach these conditions, the tunnel injects cryogenic nitrogen gas at very low temperature (-250°F) and high density into the test gas stream. In order to move the dense gas at high Mach number with the tunnel circuit pressurized to several atmospheres, significant power is required. An overview of the complex subsystems required to achieve this high powered condition at the facility is provided in Figure 2.

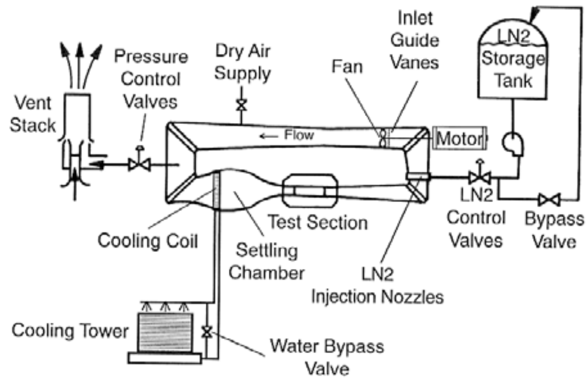

Figure 2. Overview diagram of the NTF.

The tunnel fan drive is powered by a 101 MW synchronous machine driven by a Load Commutated Inverter (LCI) as shown in Figure 3 [2]. The PCC for the system was chosen at the 115kV bus connection. Baseline electrical grid data indicated no resonances or high distortion levels prior to the connection of the system.

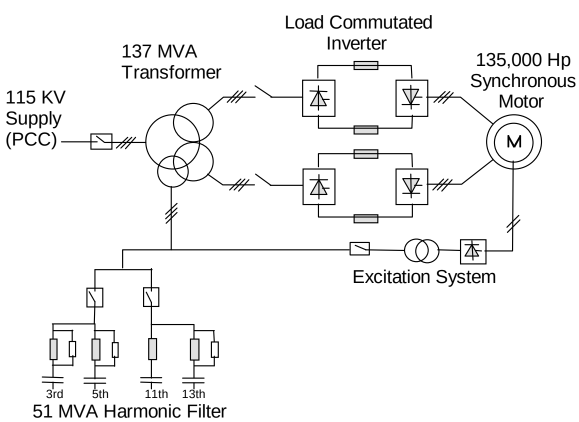

Figure 3. One line diagram of the NTF Drive System.

The installation was completed almost twenty years ago and is notably still the world's largest LCI connected to a horizontal shaft synchronous motor [3]. As part of the overall system solution, a harmonic filter was designed to meet the NASA requirements for line power factor and mitigate harmonic distortion. The filter was designed to connect to a tertiary winding of the step down inverter rated transformer. The filter has a fundamental reactive power of 51 MVAR split into four series-resonant circuits tuned to the 3rd, 5th, 11th and 13th harmonic frequencies. The custom designed transformer included the tertiary winding purposefully to take advantage of the transformer's capability to dampen the harmonic signature of the LCI. In all NTF operating conditions (speed and load), the 0.95 lagging power factor requirement and voltage and current harmonic distortion limits were met, as shown below in Table I and Figure 4.

Table I – NTF Drive Injected Voltage Distortion at the PCC

Shaft Power [HP]	Speed [RPM]	THD [%]	LIMIT IEEE 519 [%]
25000	180	1.4	2.5
50000	240	1.7	2.5
86000	300	1.3	2.5
135000	360	1.1	2.5
135000	480	1.1	2.5
135000	600	1.1	2.5

During the commissioning of the drive system, a parallel resonance at 420 Hz was discovered. The filter was detuned slightly using a multi-tapped iron core reactor to minimize the effects of this resonance. The final harmonic distortion was still higher than anticipated, but within specified limits [4].

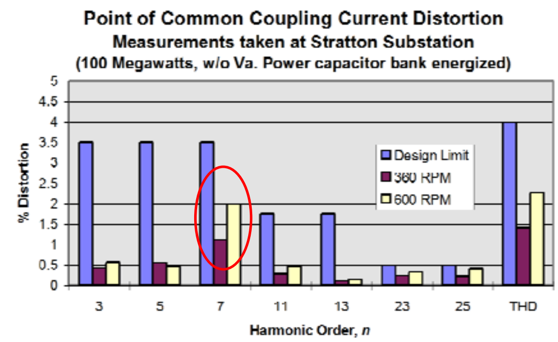

Figure 4. Harmonic current distortion of the NTF drive.

Over the years, there have been several problems with the iron core reactors used in the harmonic filter. Initially there were internal manufacturing issues that resulted in a complete change out of the units. The stress of transient overvoltages due to frequent starting and stopping cycles have also destroyed the units, as shown in Figure 5. Spare reactors are now on hand in case of future problems.

Figure 5. Failed iron core reactor.

The failure of these units prompted the system manufacturer to conduct additional analysis to define operational constraints with selected elements of the harmonic filter offline. This provided guidance to allow the NTF to conduct research within the allowable speed and load ranges in the event of a failure mode [5]. An example of these operating windows is shown in Figure 6.

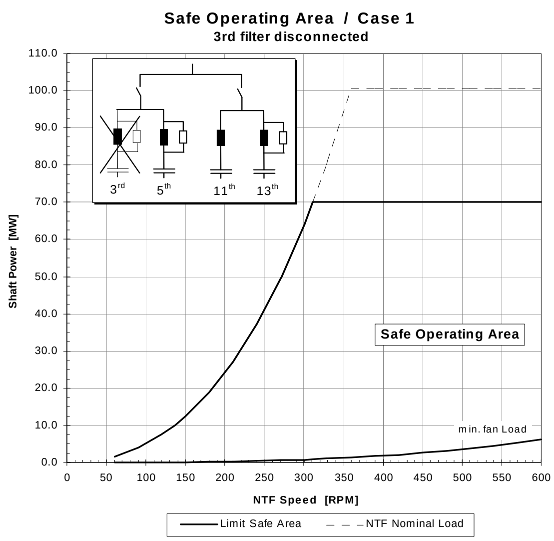

Figure 6. Operating envelope of the NTF Drive without the 3rd harmonic filter.

3. The 14x22' Subsonic Wind Tunnel (SWT)

The 14 by 22' Subsonic Wind Tunnel is an atmospheric, closed circuit tunnel that provides the test environment for both powered and unpowered models of various fixed and rotary wing configurations. The facility is used to assess aerodynamic and acoustic performance of aircraft over a wide range of take-off, landing, cruise, and high angle-of-attack conditions. The fan drive system incorporates a nacelle mounted, 9MW synchronous machine (shown in Figure 7) powered by a variable frequency 3 phase to 3 phase, 12-step cycloconverter.

Figure 7. The 14x22' SWT motor nacelle and nine blade fan (40' diameter).

The cycloconverter design was chosen because of stringent shaft torsional dynamic constraints due to the slender nacelle support struts. The one line diagram of the drive system is shown in Figure 8. The two custom-designed transformers incorporated a robust method for handling the DC circulating currents and harmonic cancelling capabilities.

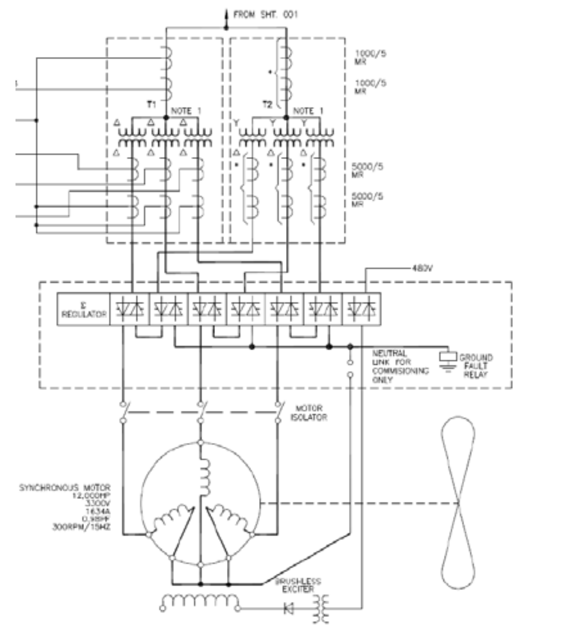

Figure 8. One line diagram of the 9MW machine with cycloconverter drive at the 14x22 SWT.

An extensive electrical system model (ref. Figure 9) was developed and analyzed at various load points. Connection case studies were conducted to determine the appropriate level of harmonic mitigation and required line power factor correction MVAR.

The final filter configuration consisted of a 7.8MVAR, three segment filter at 2nd, 3rd, and 9th harmonics. The 540 Hz unit included a damping resistor to improve transient response.

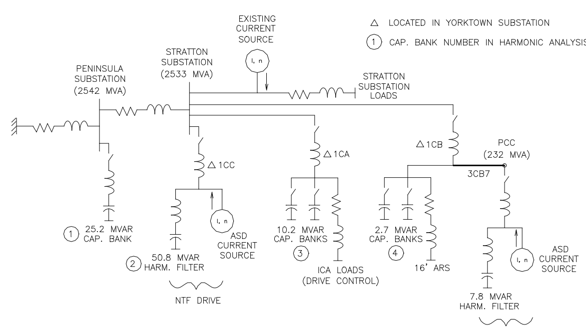

Figure 9. 14x22 SWT Harmonic Anaylsis Model

During final testing, full load on the motor could not be achieved due to the lack of sufficient tunnel blockage to develop the design pressure drop across the wind tunnel fan. The motor was loaded to approximately 8 MW at full speed (300 rpm), and the following harmonic data was taken as shown in Figure 10.

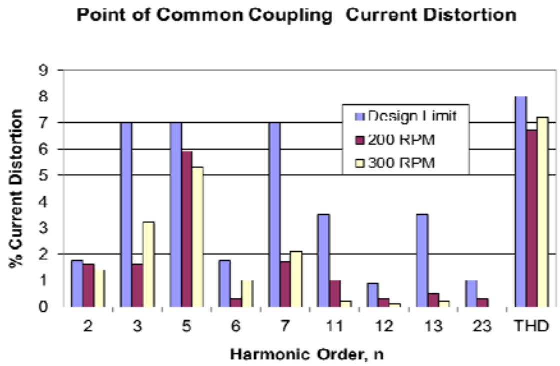

Figure 10. Harmonic Distortion of the fan drive at 8MW.

4. The 20 MW DC, Arc-Heated SCRAMJET Test Facility (AHSTF)

The Arc-Heated Scramjet Test Facility is used to research complete subscale, scramjet component integration models in flows with stagnation enthalpies duplicating flight at Mach 4.7 to 8. The flow at the exit of the of the arc heater into the nozzle simulates the flow entering a scramjet engine in flight. The stagnation enthalpy necessary to simulate flight Mach number for the engine tests is achieved by passing air through a rotating electric arc. [6] The SCRAMJET arc heater is shown in Figure 11.

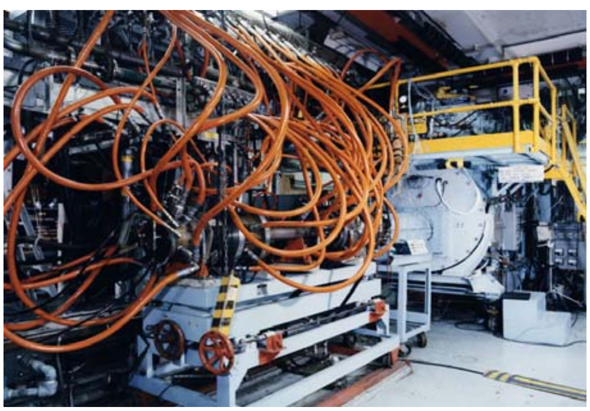

Figure 11. NASA's Arc-Heated SCRAMJET Test Facility

The arc is powered by a 20 MW inverter which includes ballast reactors to dampen output current instabilities due to the arc. The inverter system includes a custom built rectifier duty transformer, harmonic filter/power factor correction bank, deionized water cooling skid, power inverter, and control integration system. In addition, the DC supply was configurable for either series (Mode 1) or parallel (Mode 2) outputs from the 12-pulse rectifier bridges. The system one line electrical diagram is provided in Figure 12.

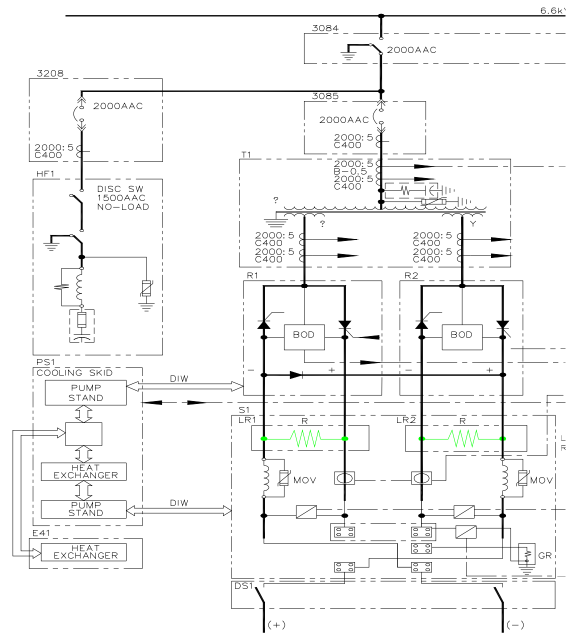

Figure 12. One line diagram of the arc heater 20MW DC power supply.

The resulting harmonic analysis was very challenging because the incoming power could be fed from two supply cables with different system impedances. In addition, two power factor correction banks of 10.2 MVAR each could be in operation at any given time. Several different filter options were studied, with the final configuration consisting of a 10th harmonic filter with power factor correction. Figure 13 shows the selected harmonic filter configuration used in the analysis. A 35 ohm parallel resonance was calculated at 211Hz, but was deemed acceptable as it fell between the 3rd and 4th integer harmonics. However, operation of the power supply and the two upstream capacitor banks was determined to be mutually exclusive.

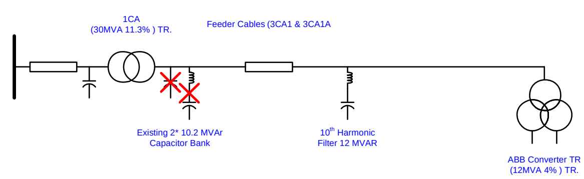

Figure 13. System model of the final configuration of the 20MW DC Power Supply Harmonic Filter.

As a result of the selected system configuration, the series/parallel (Mode 1/Mode 2) operating curves of the DC output had different line-side characteristics, as shown in Figure 14. In addition, operating constraints had to be exercised because of resonances induced by the upstream capacitor banks and supply feeder cable routing.

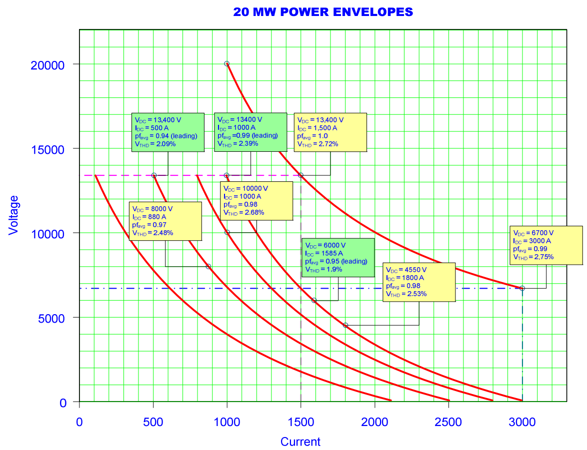

Figure 14. Operating curves for the series and parallel configuration of the 20 MW DC Power Supply.

During the system commissioning, voltage and current distortion levels were recorded to validate the specification requirements. Tuning of the current controller was difficult because of instabilites introduced by the fluctuating inmpedance of the rotating arc. These instabilities resulted in a fourth-order line side harmonic resonance, limiting the system gain and reducing the duration of high power runs. This could be ameliorated by adding another harmonic filter branch circuit.

4. Benefits of Power Quality Management

NASA has benefitted from this approach by the following results:

A. Reduced Harmonic Content

By using the IEEE 519 guidelines and adhering to the harmonic content limitations, the NASA Langley Research Center has effectively kept the power quality at a nationally recognized high-quality level. Therefore, no sensitive equipment that could be damaged or impacted by power quality issues has been affected. In addition, there have been no cases of failed electrical distribution or load equipment traceable to grid power quality.

B. Better Power Factor

By optimizing the harmonic filter capacitive element for power factor correction and designing the harmonic filter requirements based on that value, the integration of the harmonic filter and power factor compensation is possible. Tuning of the filter is critical in this design, and is critical to system stability. The power factor correction has been successful, substantially reducing high demand penalties from the power provider as well as reducing losses from system reactive current flow.

C. Minimal Voltage Variations

Voltage tolerances remain within the ANSI standard values at all times and at all levels, from the incoming 115 kV down to the 480 volts and 120 volt distribution levels. Surges, sags, and oscillations resulting in load variations have not been experienced, nor have system shutdowns resulted from over/under voltage conditions.

D. Reliability and Stability

Reliability of the power system has been excellent. Each additional non-linear load addition and the combined operation of these loads has not resulted in any system disturbances or resonant-induced transients that caused any issues with other connected power users.

5. Conclusion

Harmonic mitigation is critical to maintain power quality and prevent potentially catastrophic grid instabilities when large, highly nonlinear loads are brought on line. NASA has chosen to proactively manage and control the conditions with which large non-linear loads are added to the Center grid infrastructure. By successful management of these system parameters, good power quality characteristics are maintained for all users. This approach has successfully demonstrated large, intermittent nonlinear loads can be reliably operated simultaneously with sensitive electronic equipment by managing the injected harmonic content at a localized level. In order to properly design the harmonic mitigation equipment, it is important to follow certain steps to achieve the desired power quality without unintended consequence.

A. Management Definition and Plan

A clear plan of harmonic management should be in place prior to development of system requirements for large, non-linear loads are added to the grid. Numeric values for power factor, limits on individual frequency and total voltage and current harmonic magnitudes, and duty cycles need to be defined and enforced.

B. Selection of PCC

The selection of the electrical point of common coupling and resulting possible voltage rise and impedance resonances can impact the overall stability of the system. The PCC used for system analysis must be considered in relationship to other power users as well as including additional loads, cables and transformers that can provide damping contributions.

C. Baseline Measurements

It is important to record baseline system data (power factor, voltage, fundamental and harmonic current, etc.) in all operating modes of the power system before designing a new harmonic filter to understand the existing level of harmonic distortion. Otherwise, it is possible to overdesign a filter network. Component characteristic impedances and other loads can have lead to system operating constraints, parallel resonances, and potential system voltage rise.

D. Simulation Studies

Once the baseline system information is acquired at the PCC, a simulation model of the system should be accomplished using robust software tools. The simulation model is important to quantify the harmonic impact of the planned non-linear load(s) on the grid as well as designing mitigation systems and tuning any electrical parameters. Accurate system simulation studies are crucial to accurately determine the impact of harmonics on the grid. By correct simulation, different filter configurations can be compared using sensitivity analysis to determine the best overall performance and cost effectiveness.

E. Component Selection and System Integration

Components should be high quality with appropriate safety feature included. Reactors should be air core and multi-tap for in-situ optimization tuning, capactiors should include individual fuse protection, blown fuse detection, and phase current balance sensing circuits. Ventilation and cooling methods may be required in hostile environments for enclosed equipment.

F. Load Testing

Operation of the integrated system at load conditions is essential to determine the new baseline characteristics throughout the operating envelope of the equipment. Operation of other significant loads should be included to assure that all scenarios of grid performance is covered during start-up. Initial monitoring should include additional temperature, current, and voltage sensing to assure that all components are performing as specified. Recordings of system data should be make exactly like the previous baseline measurements so accurate comparisons can be made.

Acknowledgements

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