UCRL-JC-121817
PREPRINT

CONF-9505264--29

**Fault Tolerance of the NIF
Power Conditioning System**

RECEIVED

OCT 11 1995

OSTI

**D. W. Larson, LLNL
R. Anderson, American Control Engineering
J. Boyes, SNL**

**This paper was prepared for submittal to the
1st Annual International Conference on Lasers for
Application to Inertial Confinement Fusion
Monterey, CA
May 30 - June 2, 1995**

July 7, 1995

**Lawrence
Livermore
National
Laboratory**

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED **MASTER**

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Fault Tolerance of the NIF Power Conditioning System

D. Larson, LLNL, R. Anderson, American Control Engineering
J. Boyes, SNL

Summary

The tolerance of the circuit topology proposed for the National Ignition Facility (NIF) power conditioning system to specific fault conditions is investigated. A new pulsed power circuit is proposed for the NIF which is simpler and less expensive than previous ICF systems. The inherent fault modes of the new circuit are different from the conventional approach, and must be understood to ensure adequate NIF system reliability. A test-bed which simulates the NIF capacitor module design was constructed to study the circuit design. Measurements from test-bed experiments with induced faults are compared with results from a detailed circuit model. The model is validated by the measurements and used to predict the behavior of the actual NIF module during faults. The model can be used to optimize fault tolerance of the NIF module through an appropriate distribution of circuit inductance and resistance. The experimental and modeling results are presented, and fault performance is compared with the ratings of pulsed power components. Areas are identified which require additional investigation.

Introduction

The NIF laser requires a 320 MJ power conditioning system to drive the 7600 large Xenon flashlamps in the power amplifiers. The system consists of 200 modules which each store 1.6 MJ and drive approximately 40 flashlamps arranged in 20 parallel series-pairs. The power flow of one module is shown in Figure 1.

Conceptual power conditioning module layout

Figure 2 illustrates the compact design of the NIF module. The capacitors, switches, preionization hardware, charging supplies and control system share a common mounting structure and enclosure. Independence among modules is assured since a single primary power line feeds the module and all control connections are via fiber optics. A single large transmission line delivers the 500 kA, 360 μ s output pulse to the flashlamps. The pulse is distributed among the 20 flashlamp pairs by ballast inductors in a junction box near the laser amplifier. The nominal capacitor charge voltage is 23.5 kV.

40-00-0394-0765pb01

7/11/95

This circuit approach, shown schematically in Figure 3, represents a cost savings of roughly 20% compared with previous systems such as LLNL's Nova laser¹ which use individual pulse-forming-networks and output cables for each flashlamp circuit. The savings result from the reduced number of components and simpler assembly. Single-bushing capacitors, used in the NIF circuit are less expensive than dual-bushing capacitors required in previous systems. Charge and safety dump resistors previously required for each circuit are

eliminated. The simple, compact design minimizes assembly cost by reducing the cable installation and termination labor required.

70-50-0195-0234pb01

The parallel circuit topology presents different fault modes than previous designs which must be accounted for in order to minimize the impact of circuit faults on the system reliability. The fault conditions of primary concern are summarized in Table 1. Ten years of Nova operating experience support the predicted frequency of the fault modes.

We are primarily concerned with three fault modes

Fault	Fault mode	Failure concerns	Expected frequency	Nova failure rates
Flashlamp fault	Short-circuit	Neighboring flashlamps Amplifiers blast-shield Amplifier contamination Ballast inductors	Several per year	3 per year
Capacitor fault	Short-circuit	Neighboring capacitors Damping resistors Capacitor bus work	Several per year	4 per year
Bus or transmission line fault	Short-circuit	Bus structure or transmission line Capacitors Damping resistors	Several during facility lifetime	0

70-50-0595-1327pb01

Test Bed

A power conditioning test-bed was constructed to investigate fault tolerance and other NIF capacitor module design issues. The test-bed uses 36 capacitors that each store 52 kJ for a total of 1.9 MJ at 22 kV. The capacitors are surplus from the Beamlet² power conditioning system and exhibit the self-healing characteristics of a metallized dielectric system similar to those planned for the NIF. Although the Beamlet capacitors are rated for only 22 kV, they can operate, with reduced lifetime, at the 23.5 kV NIF operating point to simulate full power

operation. The test-bed, shown in the photograph of Figure 4 (top photo) is arranged to electrically simulate the NIF module. In addition to fault tolerance, the test-bed is used to test other pulsed power components and issues including transmission lines, charging supplies, mounting structures, flashlamp triggering, assembly methods and other fault modes.

70-50-0595-1329pb01

Detailed measurements have been made using the test-bed in three configurations: capacitor fault with a resistive damping element, capacitor fault with a resistive and inductive damping element, and bus fault. The experiments have been performed at low voltage (1-3 kV) because of limitations of the existing damping element design. A resistive and inductive element is planned for the NIF module, however only the prototype was available for these measurements. Figure 5 illustrates the locations of detailed capacitor current measurements in the 6x6 capacitor array, and of the capacitor and bus faults.

70-50-0595-1332pb01

Modeling and Results

A detailed SPICE model is used to explore a larger parameter space than is possible with the test-bed. Current and voltage measurements from the test-bed are used to refine and validate the SPICE model. The model is then modified to account for the differences between the test-bed and the NIF module design. The model can then be used to predict the NIF module performance, and to optimize the circuit values to enhance the fault tolerance of the design. The waveforms of Figure 6 (modified to distinguish waveforms in black-and-white) demonstrate good agreement between the test-bed and model results for the bus fault and capacitor fault with inductive damping element cases. The model accurately replicates features on the waveforms caused by the distributed inductance of the capacitor bus plates.

70-50-0595-1333pb01

The total circuit inductance and resistance are defined by the amplifier pulse width and system transfer efficiency requirements. However, some flexibility in distributing the total inductance and resistance budgets may be exercised in order to maximize system fault tolerance. Parametric analyses using the SPICE model are performed for this purpose. The results, shown in Figures 7, 8 and 9 illustrate worst-case fault current as a function of the ratio of circuit inductance and resistance in the ballast inductors and capacitor damping elements.

70-50-0595-1336pb01

70-50-0595-1336pb03

70-50-0595-1336pb02

These plots show that it is clearly desirable to place as much of the budgeted inductance and resistance as possible at the "two ends" of the system, e.g. at the capacitors and flashlamps, therefore minimizing the impedance of the transmission line and switch. Careful inspection of the plots also shows that resistance is more effective at limiting fault current at the capacitors than at the flashlamps for reasonable values of ballast inductance. The plots are used to select values of inductance and resistance for the damping and ballast elements as shown in the budgets of Table 2.

Component	Inductance (μH)	Resistance ($\text{m}\Omega$)
Capacitor damping resistor	$10/20_{\text{ea}} = 0.5$	$40/20_{\text{ea}} = 2$
Transmission line	0.5	1.5
Ballast inductors	$30/20_{\text{ea}} = 1.5$	$20/20_{\text{ea}} = 1$
Misc. bus and switches	0.2	0.7
Total	2.7	5.2

70-50-0595-1334pb01

The selected circuit values are used by the model to calculate the worst-case current in the critical components during fault modes of interest. The results, tabulated in Table 3 show that the values are within the ratings of available components in most cases. Two cases are identified which require additional development. The 300 kA current flowing in the damping resistor during a short-circuit of the corresponding capacitor will likely cause permanent damage, and this element will be replaced after such an event. Additional tests will validate adequate performance of this component during full-energy faults. The second issue identified is the fault current flowing in the bus or transmission line during a short-circuit bus fault. The 1.6 MA peak current may result in forces which exceed the material strength for reasonable methods of force-bracing. Additional analysis and force-bracing design work will resolve this issue. Since the expected frequency of this type of fault is very low, a reasonable solution might be to allow the bus to fail (non-catastrophically) and replace the damaged hardware after the fault.

Fault mode	Fault current in:				Expected frequency
	Damping resistor (kA)	Ballast inductor (kA)	Bus/T-line (kA)	Capacitor (kA/% reversal)	
Flashlamp	27	100	530	27/0%	Several per year
Capacitor	300	—	—	16/18%	Several per year
Bus	83	—	1600	83/60%	Several during facility lifetime

Within component capabilities

Exceeds component capabilities

70-50-0595-1335pb01

Conclusions

The fault-tolerance of the low-cost NIF pulsed power circuit approach has been investigated with a combination of experiments and modeling. A test-bed was used to validate a SPICE circuit model. The model was used to perform parametric analyses which enable an optimum distribution of the budgeted inductance and resistance. The resulting predicted fault current values were then used to determine the required ratings of system components and identify areas requiring further development.

Acknowledgments

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.