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FINAL REPORT FOR THE
CHARGING-CIRCUIT STUDY
FOR
COPPER-VAPOR LASERS
COVERING THE PERIOD
29 JUNE 1981 THROUGH 30 NOVEMBER 1981

BR-13047

1 DECEMBER 1981

RAYTHEON COMPANY
MISSILE SYSTEMS DIVISION

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**Prepared Under
Purchase Order No. 4023201
For
Lawrence Livermore National Laboratory
P.O. Box 5508
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1. INTRODUCTION

This study is divided into three tasks whose combined purpose is to evaluate methods of charging high PRF pulsed power subsystems required in a proposed laser isotope separation (LIS) plant.

The work performed in this program follows directly from designs and experiments carried out in a recently-completed study and, in fact, utilizes much of the same apparatus described previously.*

The first task required the preparation and vugraph presentation of a review of eight potential charging methods. This review and the associated evaluation criteria are described in Section 2.

Tasks II and III entailed the experimental evaluation of the deQing methods of regulating the charging voltage of a pulse power conditioning module with respect to limitations imposed by continuous operation and the efficiency of recovery of energy diverted by the deQing circuitry. The results of these tasks are described in Sections 3 and 4.

*Final Report For The Pulse Power Conditioning Study for Copper-Vapor Lasers, Report No. BR-12773, Raytheon Company, Missile Systems Division, Bedford, MA (June 1981).

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2. CHARGING CIRCUIT CONCEPT REVIEW

The charging circuit options to be reviewed are divided into two groups depending on whether a regulated or unregulated dc power supply is used. These options are listed below:

- 1) Regulated dc power supply with:
 - a) Thyatron command charge
 - b) Saturable reactor
- 2) Unregulated dc power supply with:
 - c) Hard tube command charge
 - d) Thyatron command charge and deQing with energy returned
 - e) Thyatron command charge and deQing with energy lost
 - f) Saturable reactor and deQing with energy returned
 - g) Saturable reactor and deQing with energy lost
 - h) Resonant inverter

Each option was evaluated in a comparative and qualitative manner according to the following criteria:

- 1) Advantages
- 2) Limitations
- 3) Critical issues
- 4) Development cost
- 5) Development time
- 6) Capital cost
- 7) Operating cost
- 8) Reliability
- 9) Efficiency

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This review was presented at Livermore on 28 July 1981. Briefly, the Raytheon study indicated highest operating efficiencies would be found with the thyatron and resonant inverter charging circuits. Low efficiencies due to core losses were the most significant limitations found for the saturable reactor circuits. Improved magnetic materials may result in reduced losses and higher efficiencies. A summary of the review is given in Tables 2-1 through 2-8.

TABLE 2-1
REGULATED SUPPLY WITH THYRATRON COMMAND CHARGE

Advantages: Existing prototype, maximum flexibility, good fault isolation

Limitations: Requires individual supplies, regulator power loss, thyatron lifetime

Critical Issues: Capital cost, power consumption, thyatron lifetime

Development Cost/Time: Very Low, prototype available

Capital Cost: Very high, individual power supplies

Operating Cost: High, regulator losses, thyatron replacement

Reliability: Limited thyatron lifetime

Efficiency: < 70 percent as is, < 80 percent with ac preregulation

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TABLE 2-2
REGULATED SUPPLY WITH SATURABLE REACTOR

Advantages: Long-life switch, maximum flexibility, good fault isolation, less auxiliaries

Limitations: Reactor core losses, requires individual supplies, regulator power loss

Critical Issues: Reactor development, power consumption, capital cost, extension of saturable reactor concept to output switch

Development Cost/Time: Fairly lengthy and expensive due to reactor and circuit development, magnetic core material, thermal problem

Capital Cost: Very high, individual power supplies

Operating Cost: High, reactor and regulator losses

Reliability: Good, long reactor lifetime compared with thyatron

Efficiency: Poorest, 28 to 32 percent, reactor alone ~ 40 percent

TABLE 2-3
UNREGULATED SUPPLY WITH HARD TUBE COMMAND CHARGE

Advantages: Well-known technology, good fault isolation, compatible with pulse charging

Limitations: Moderate efficiency, auxiliary supplies and drivers, tube lifetimes

Critical Issues: Efficiency, circuit complexity

Development Cost/Time: Relatively low

Capital Cost: High, tubes and auxiliaries

Operating Cost: High, hard tube power loss, tube replacement

Reliability: Good, hard tube lifetimes expected to be longer than present thyatrons

Efficiency: ~ 70 percent as is, ~ 80 percent with ac preregulation

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TABLE 2-4

UNREGULATED SUPPLY WITH THYRATRON AND ENERGY-RETURN DEQING

Advantages: High efficiency, individual control

Limitations: Thyatron lifetime

Critical Issues: Demonstration of energy-return, SCR stack in feedback loop, thyatron lifetime

Development Cost/Time: Low-to-moderate, existing breadboard, prototype could start immediately

Capital Cost: Medium, thyatrons less than hard tubes

Operating Cost: Low to medium, depends on thyatron life

Reliability: Limited thyatron lifetime, low energy storage per module

Efficiency: Best, >95 percent

TABLE 2-5

UNREGULATED SUPPLY WITH THYRATRON AND LOSSY DEQING

Advantages: Simplicity, individual control

Limitations: Thyatron lifetime, lower efficiency

Critical Issues: SCR stack in feedback loop, thyatron lifetime

Development Cost/Time: Low, existing breadboard, prototype could start immediately

Capital Cost: Medium, thyatrons less than hard tubes, energy dissipation required

Operating Cost: Medium, energy loss and thyatron life

Reliability: Limited thyatron life, low energy storage per module

Efficiency: Good, ~85 percent

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TABLE 2-6

UNREGULATED SUPPLY WITH SATURABLE REACTOR AND ENERGY RETURN DEQING

Advantages: Fairly simple, long life switch

Limitations: Saturable reactor voltage sensitive, high core losses,
reset bias

Critical Issues: Reactor development with deQ and reset windings, power
consumption, interaction with unregulated supply,
extension of saturable reactor concept to output switch

Development Cost/Time: Very high and lengthy to develop multiwinding
reactor, magnetic core material, thermal problem

Capital Cost: Fairly low, simple system

Operating Cost: Moderate, core power loss may offset component lifetimes

Reliability: Very high, good component lifetimes, SCRs and reactors

Efficiency: Fair, ~ 40 percent

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TABLE 2-7
UNREGULATED SUPPLY WITH SATURABLE REACTOR AND
ENERGY LOST DEQING

Advantages: Simplest system, long life switch

Limitations: Saturable reactor voltage sensitive, high losses, reset bias

Critical Issues: Reactor development with deQ and reset windings, power consumption, interaction with unregulated supply, extension of saturable reactor concept to output switch

Development Cost/Time: Very high and lengthy to develop multiwinding reactor, magnetic core material, thermal problems

Capital Cost: Fairly low, simplest system

Operating Cost: Moderate to high, core power loss may offset component lifetimes

Reliability: Very high, good component lifetimes, SCRs and reactors

Efficiency: Poor, ~ 30 percent

TABLE 2-8
UNREGULATED SUPPLY WITH RESONANT INVERTER

Advantages: Flexible (ac or dc), good fault isolation, low voltage

Limitations: Incompatible with HVDC distribution

Critical Issues: Flyback extended to 20 kW, HVDC versus 480 Vac, transformer development

Development Cost/Time: Moderately high, need breadboard prior to prototype, transformer has less thermal dissipation than saturable reactor

Capital Cost: Low, replaces HV supply, no tubes, SCR switch

Operating Cost: Very low, long-life components, high efficiency

Reliability: Very high, long-life components

Efficiency: Very high, >90 percent

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From a system standpoint, the implications of modular power supplies, HVDC and ac power distribution systems have been considered. It was noted that individual units of 20 kW would provide maximum control flexibility and fault isolation at the expense of an order of magnitude increase in capital cost over multimodule 500 kW (or larger) power supplies. With respect to prime power distribution, a 480 Vac system has the benefit of many standard components and techniques and would be most compatible with the inverter/flyback method of voltage regulation (option 8). HVDC power distribution has obvious benefits in terms of capital cost and operating efficiency, but requires somewhat more sophisticated fault isolation techniques. Vacuum circuit breakers at each module appear to be within the state-of-the-art.

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3. EVALUATION OF DEQING CHOKE IN BREADBOARD CIRCUIT

The concept of a command-charged module with energy return deQing was presented earlier* and summarized in Figure 3-1. This concept is compatible with the large, common dc supply approach. The common supply itself is assumed to consist of stacked 1 kV power supply modules to provide coarse adjustment of a large number of load modules. Stepping could be accomplished at the ac source. Final regulation over a 2 kV range is provided by the deQing circuit at each module.

Fault isolation is provided from other modules by means of steering diodes and from the common HVDC supply by vacuum contactors which are available in the required voltage and current ranges. It is important to note that this concept calls for a minimum amount of energy storage in the filter capacitance of the HVDC supply. The main energy storage for each load module is within the module itself where it is isolated from all other modules by a steering diode. Fault sensing would be provided in the system design so that the appropriate vacuum breakers could be actuated on command from the circuit fault detector rather than waiting for current build-up in the breakers.

Although the discharge circuit per se is not part of this study it certainly can impact the design and operation of the charging circuit. For example, the use of a small charging inductor across the gas load, as shown in Figure 3-1, instead of a resistor, is expected to increase the system efficiency.

3.1 Description of Apparatus

The breadboard circuit described earlier* is modified as shown in the schematics of Figures 3-2 and 3-3. The power supply which provides a bias for the deQing SCRs as well as a repository for returned power is shown schematically in Figure 3-4 and in the photograph in Figure 3-5.

Other components and assemblies which have been developed during this program are the 3-to-1 ratio deQing choke shown in Figure 3-6 and the deQing SCR switch shown in Figure 3-7.

*See footnote in introduction.

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COMMON HIGH VOLTAGE dc POWER SUPPLY
(MULTI-MEGAWATT)

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Figure 3-1 - Command Charge Module with Energy Return deQing Schematic

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Figure 3-3 - deQing Circuit Schematic

3-4

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POWER SUPPLY CHASSIS

NOTES:

1. ALL POWER SUPPLY CIRCUITS (FOUR) TO BE IDENTICALLY ASSEMBLED FOR 5000 VOLTS ISOLATION BETWEEN OUTPUTS & BETWEEN EACH OUTPUT CHASSIS & GROUND
2. ALL POWER SUPPLY CIRCUITS OPERABLE IN SERIES OR PARALLEL COMBINATIONS
3. T1 OUTPUT TAPS MANUALLY CONNECTIBLE TO PROVIDE 670Vdc, 835Vdc OR 1000Vdc FROM EACH POWER SUPPLY CKT

4. POWER SUPPLY CKTS TO BE INTERNALLY CONNECTED SUCH THAT OPTIONAL OUTPUT VOLTAGE & CURRENT METERS ARE ALWAYS PROPERLY CONNECTED
5. LOW INDUCTANCE LEAD LENGTHS & CONDUCTOR (COPPER BRAID OR BUSS) TO BE USED BETWEEN OUTPUT TERMINALS, RESISTIVE LOADS & OUTPUT CAPACITORS

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Figure 3-4 - Laboratory deQing Power Supply Schematic

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Figure 3-5 - Laboratory deQing Power Supply

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Figure 3-6 - deQing Charging Choke

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Figure 3-7 - deQing SCR Switch Assembly

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3.2 Experimental Results

Testing was carried out at 5 kHz and charging voltage of 8 to 9 kV up to the limit of the power supply. The deQing supply was maintained at 1000 V. Measurements were made of all pertinent current and voltage waveforms during operation runs of a few minutes duration.

Overall efficiency, based on average power measurements, was found to be consistently in the 95 percent range. This compares well with the charging efficiency calculated from single pulse data in the previous program.* Average input power as read from the dc power supply panel meters was correlated with current and voltage waveform measurements and duty cycle.

Some examples of the current waveforms through the charging circuit and the deQing circuit at 5 kHz are shown in Figure 3-8. The waveforms of the resonant charge voltage rising on the PFN with and without deQing are shown in Figure 3-9. As in the

Figure 3-8 - Current Waveforms at 5 kHz

*See footnote in the introduction.

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a) WITHOUT deQING

b) WITH deQING

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Figure 3-9 - Resonant Charge Voltage on PFN at 5 kHz

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previous program,* high voltage measurements were taken by means of a comparator plug-in and a Tektronix P6015 probe so that signals in the 10 to 20 kV range could be presented on a 100 to 500 V per division scale with a calibrated reference line.

An attempt was made to run the breadboard for one hour at 5 kHz with 9 kV power supply voltage, the maximum available, and full deQing. This test was curtailed after 15 minutes due to internal voltage breakdown of the charging choke. Although this test was of substantially shorter duration than planned, no evidence of thermal instability of any of the circuit components was noted. The choke breakdown was due to incomplete solid dielectric insulation between choke segments. The construction of the choke coil had been modified from an earlier design which had failed during preliminary testing. This second design performed substantially better than the first, but still required more attention to construction techniques and process.

*See footnote in the introduction.

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4. DEMONSTRATION OF ENERGY RECOVERY

Energy recovery was demonstrated and measured by comparing the prime power required to maintain a 1000 Vdc output at the terminals of the deQing power supply (Figures 3-4 and 3-5) with and without deQing. When allowance was made for the change in input power from the dc supply, about 90 percent of the power diverted by the deQing circuit was returned to the deQing supply. Alternately, the sum of the power delivered to the PFN plus the power returned to the deQing supply amounted to 93 percent of the input power from the main dc power supply.

An example of these calculations taken from runs of five to fifteen minutes duration is shown in Table 4-1. In this table the total input power at 215 Vac to the deQing power supply is calculated from the single phase current shown. The power delivered to the PFN capacitance of 12 nanofarads plus the power returned to the deQing supply is considered output power for the purpose of efficiency calculations. An auxiliary deQing supply would not be required in a complete system since this bias voltage would be tapped from the main power supply and the recovered energy would be returned directly to the main supply. Thus the reduction in 215 Vac power required by the deQing supply when the deQing circuit is operating, relative to the prime power required without deQing, is listed as output power gained in the P_{deQ} column of Table 4-1.

TABLE 4-1
ENERGY RETURN DEQING SUMMARY

PRF	Input			deQ		Output Power			Efficiency
	Hz	kVdc	Adc	W	Aac	W	kV (PFN)	W (PFN)	P_{deQ} (W)
5025		7.5	0.87	6525	3.6	1340	14.3	6181	-
		7.6	0.73	5548	1.6	596	12.1	4412	744
4729		8.6	0.94	8131	3.5	1303	16.6	7818	-
		9.0	0.80	7240	0.5	186	14.2	5721	1117

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5. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The thyatron-command-charge with deQing has been demonstrated to be a highly efficient means of charging with regulated voltage at the individual module level. This system is compatible with the HVDC power distribution and can provide fault isolation by means of vacuum circuit breakers and steering diodes.

Comparison with other charging methods indicates a substantial advantage in terms of efficiency for the thyatron-command-charge over hard tubes and saturable reactor techniques.

Additional work is required to improve the reliability of the charging choke by a comprehensive analysis of the manufacturing process and to perform the design and integration of feedback circuitry so that this power-conditioning system could be demonstrated with a laser or laser-like load. Moreover, the details of step-regulation of voltage during individual laser warm-up or replacement and the formulation of an overall fault-isolation philosophy need to be addressed.

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