Protection circuitry for high-power diode laser arrays

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A comprehensive protection scheme is presented for use with high-power ($\sim$500 W dc input) diode laser arrays. The circuitry requires no separate power, using instead the voltage from the laser's power supply. Overcurrent and overvoltage silicon controlled rectifier crowbars are the primary protection circuits. In addition, tripping of either crowbar will turn off the main power to the laser's power supply. This feature makes use of a main power controller that incorporates two interlock loops, for protection against overtemperature, low coolant flow, undervoltage, and other undesirable conditions. [S0034-6748(98)01806-1]

I. INTRODUCTION

Several applications have driven the development in recent years of stacked arrays of near-infrared diode lasers. These devices cost in excess of $10,000, so it is crucial to reliably protect them from extremes in voltage and current and to interlock their operation with conditions of coolant flow and temperature. Indeed, relatively simple and common failures in many power supplies, from shorted regulator transistors to dirty potentiometers, can result in excess output power that may destroy the diode laser array. We have developed and present here a simple, reliable, and inexpensive power-supply controller with protection circuitry for this type of laser.

The circuitry described here was designed for the diode laser array used in our application, optical pumping of rubidium vapor[1] for nuclear spin polarization of ^{3}He or ^{129}Xe for magnetic resonance imaging of lungs.[2,3] The diode array is a model CZ-150 from Opto Power,[4] comprised of 200 individual 1 W diodes with an emitting surface of $\approx$1 cm^2. The maximum output is 150 W at 795 nm with an input of 26 A at about 17 V. The array is watercooled by a closed-loop chiller.[5] While we currently use a linear, series-regulated power supply, we have also used a high-frequency switching supply. The power supply should have both voltage and current regulation modes, with automatic crossover. While the component values are specified for our installation, the design may readily be changed to suit lower or higher power laser arrays.

The protection circuitry consists of two parts. First, the primary protection is overcurrent and overvoltage silicon controlled rectifier (SCR) crowbars[6] which short the power supply output when tripped. Because of the very low dynamic impedance dV/dI of the diode array,[7] overvoltage protection alone is not adequate — a damaging amount of current can flow without significant voltage increase. Thus, the overcurrent crowbar is a crucial element.

The second part of the circuitry is a main power controller, through which several interlocks are implemented. Thus, an open circuit from any of a number of interlock switches (we use an overtemperature switch on the laser mount and a low-flow switch on the coolant return leg to the chiller) will interrupt the main power into the laser power supply. The power remains off, whether the fault condition persists or not. We have also implemented an emergency shutdown switch in this interlock loop, as part of the necessary laser safety considerations. The reader is reminded that 150 W of invisible radiation must be regarded as an extreme hazard.

The crowbar SCRs are mounted on a large heatsink, so that (if tripped) they can endure the full current output of the power supply. However, as an added protection feature, a simple circuit detects the undervoltage condition of the power supply when either SCR is conducting. The undervoltage relay is part of one of the interlock loops, so the main power to the laser power supply is removed.

II. PRIMARY PROTECTION CIRCUITRY

The high current section of the primary protection circuitry is shown in Fig. 1. The input from the power supply is from the left and the laser diode load connects to the right. Two high-current diodes (1N3291A) offer redundant protection against reverse-polarity output from the supply. An overvoltage SCR crowbar[6] is driven by two zeners; when the supply voltage reaches $\sim$19.2 V (two 9.1 V zeners plus about 1.0 V gate-to-cathode), this SCR conducts and drives the supply voltage down to about 1 V. The overcurrent SCR crowbar is driven by the TIP-112 Darlington emitter-follower transistor,[8] which is in turn driven by the comparator[8,9] circuit (see below). The two 0.1 Ω resistors in parallel develop a voltage proportional to the laser current, for use by the overcurrent comparator and the current meter. The input fuse limits the continuous current the crowbars are ever required to handle.

The cases of the SCR crowbars and the 1N3291A diodes are mounted to a substantial finned heatsink (22 cm$\times$10 cm $\times$4.5 cm), so that the device can absorb an overvoltage, overcurrent, or reverse-polarity condition without time limit. The cases of the 0.1 Ω current sensing resistors (Dale RH-50) and the Darlington driver are also mounted to the heatsink. The rule is to make the protection circuit much more robust than ever will be needed. The physical parts layout is suggested by the schematic, Fig. 1. The main current path is through the heat sink (plus side) and through a 18 cm$\times$5

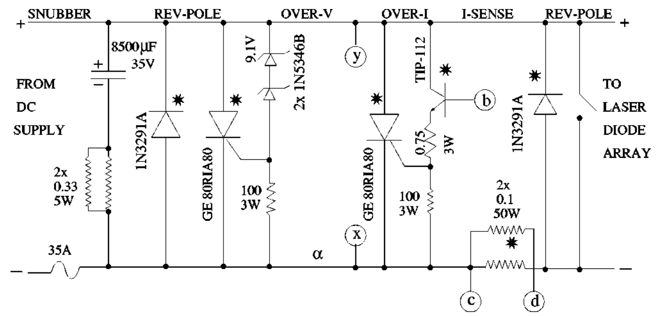

FIG. 1. High-current portion of the primary protection circuit, with overvoltage and overcurrent SCR crowbars and reverse-polarity protection. The points x, y, b, c, and d connect to circuitry in Fig. 2.

cm×0.5 mm copper strap (minus side). A knife switch immediately at the output terminals shorts the laser when not in use. Because one of the 1N3291A diodes is on the load side of the current sensing resistors, there is protection from an inductive spike[10] that would occur if the 0.1 Ω resistors were to open.

When used with a switching supply, the SCR crowbars would properly trigger in response to overvoltage or overcurrent conditions but would not remain in the conducting state. This resulted in an undesirable oscillatory behavior. The source of the problem was output inductance of the supply, leading to ringing and commutation (turnoff) of the SCR by a small reverse-polarity inductive kick.[10] The RC snubber network at the left-hand side of Fig. 1 removed the problem. This also indicated, however, the need to have a backup device to turn off the power supply whenever either SCR is triggered (see below).

The comparator circuit in Fig. 2 is used to compare the laser current (as measured by the voltage across the current sensing resistors) with the desired trip point. The trip point is dialed in on a ten-turn potentiometer, with a full ten turns corresponding to 2 V, which is 40 A through the laser load. The LM111 comparator is an older device but can function with the inputs down to within 0.3 V of the negative rail, corresponding to a trip point of 7 A. The 180 kΩ resistor adds hysteresis (snap action) to the comparator.[8,9]

Power (5 V) for the comparator, meter, and undervoltage interlock (Fig. 2) comes from a single 3-pin regulator, driven off the laser power supply voltage (nominally 18 V). The 1N4007 diodes (two for redundancy) in series with the power connection allow the control circuitry to continue to run for several ms after the triggering of either SCR. The

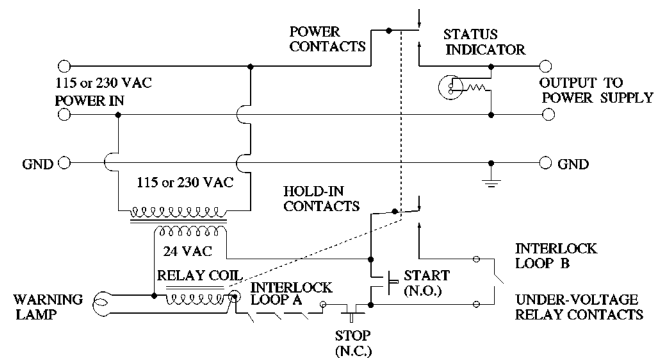

FIG. 3. Power controller, with two interlock loops using 24 VAC for control. Loop A is for the overtemperature and low-coolant-flow switches as well as the emergency stop switch. Loop B, for the undervoltage interlock, is temporarily defeated during startup by depressing the START switch.

digital panel meter is a convenience for testing. Connections are provided for reading the current with an external voltmeter.

The undervoltage interlock (Fig. 2) consists of the relay (5 VDC coil) and the power field-effect transistor (FET), a source follower. The gate of the FET is slowly charged to the power supply's voltage (or 9 V from the 1N4739A zener, whichever is least). When the gate reaches ∼6 V, the source will be ∼4 V and the relay will pull in. But if either SCR conducts and shorts the power supply, the 0.47μF gate capacitor rapidly discharges through the 1N914B diode. With this slow-charge/rapid-discharge network, the relay driven by the FET drops out and stays out for at least 2 s, *whether the SCR remains conducting or not*. This is more than adequate time for the power controller (below) to shut down. Thus, should either SCR be triggered, it will dissipate power for less than a second (though the design could tolerate the crowbarred condition indefinitely). The diode in parallel with the relay coil is a free-wheel diode to absorb inductive kick from the coil.[10] The 1N4739A zener protects the FET gate by limiting the maximum voltage applied to it.

III. MAIN POWER CONTROLLER

The simple power-control circuit is presented in Fig. 3. A 24 VAC circuit controls a power relay, with traditional push-to-start and interrupt-to-stop design. One set of relay contacts provides the relay ''hold-in'' path and the other contacts control the power to the laser power supply. There are two distinct interlock loops. One loop (A) has the over-

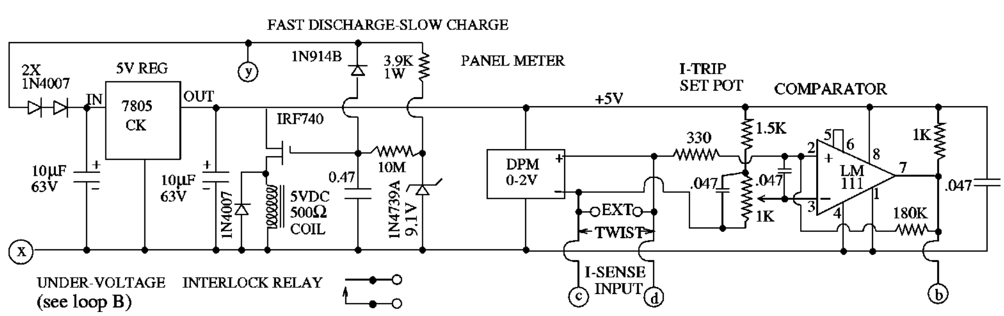

FIG. 2. Low-level control section of the primary protection circuit. From left to right appear the local 5 V supply, the undervoltage interlock relay circuitry, a digital panel meter (DPM), and the overcurrent comparator. The points x, y, b, c, and d connect to points in Fig. 1.

temperature switch, low-coolant flow switch, and emergency shutdown switch (located at the entrance to the room) all in series. Opening any one of these removes the power until (1) the fault condition is removed *and* (2) the circuit is restarted by pushing the START button. This design prevents faults from healing (e.g., overtemperature) and the entire cycle repeating endlessly.

A second interlock loop (B) is just for the contacts of the undervoltage relay. An open contact in this loop, even temporary, will cause the power relay to drop out and remain out, until manually re-STARTed. The reason for the separate loop B is that one must temporarily defeat the undervoltage interlock to start the laser power supply. Thus, in practice, the START button is depressed while the power supply voltage is increased to ~10 V (with the current set knob at ~0.1 A). After 6 s or so the undervoltage relay pulls in; the START button can be released and the system will remain energized. Then the current setting can be increased to the desired level, with the voltage setting at about 20 V (just slightly above the operating voltage).

In general, any interlock switches for conditions that can attain the correct status without the laser energized are in loop A; conditions that only attain correct status with the laser running are wired into loop B. The advantage of the two-loop scheme (over putting all interlock switches into loop B) is that loop A faults cannot be overridden by the manual START switch.

IV. DISCUSSION

The system should be tested thoroughly with a dummy load. We employ various lengths of Nichrome resistance wire for this. During test, we replace the input fuse in Fig. 1 with a shortcircuit. We ascertain that both the overvoltage and overcurrent crowbars trip at the correct conditions, that the crowbars remain conducting after a trip (with the undervoltage interlock removed), and then finally that the undervoltage interlock works within a fraction of a second after either SCR trips.

The controller and protection circuit have been in operation for 10 months and about 600 h of laser operation. Each interlock is periodically tested to ensure that it trips for the appropriate fault condition. We have had no problems with false trips or other inappropriate shutdowns. We have experienced one episode in which the protection circuit may have played a beneficial role: one of the output FETs on a switching power supply failed suddenly and catastrophically, shutting down the laser and even tripping the ac-line circuit breakers. This failure was completely independent of the controller and protection circuitry. After installing a different power supply (the one we now continue to use), the laser performed as before the failure.

The reliability of the controller hinges on the proper functioning of both the main and undervoltage relays. These relays are tested every time the laser is normally shutdown by allowing them to switch off the power supply as the dc output voltage falls below 5 V (the current setting is always turned all the way down first, then the voltage setting).

One improvement for the protection circuit would be to add a small resistance at point α in Fig. 1, so that an overcurrent condition would trigger the overvoltage SCR, despite the low dynamic resistance of the laser diode load. While substantial power dissipation would be involved, considerable simplification would result — the overcurrent SCR and its control circuitry could be removed. We have not tried this modification.

ACKNOWLEDGMENT

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