SUMMARY OF BUCK REGULATOR CURRENT OUTPUT UPGRADE WORK DURING LOI COLLABORATION VISIT TO ISIS

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Modifications were performed on the buck regulator (BR) control electronics to increase the peak current output of the anode power supply by 30 percent, to approximately 32A peak at a maximum duty cycle of 50 percent. The engineering details of this upgrade modification were designed by Ian Roth at Diversified Technologies, Inc (DTI).

These modifications required passive component changes in the BR low-level control circuits, followed by validation tests of the BR control functions using a pulse generator and dc power supply to simulate current overload signals to confirm the function of the overcurrent interlock electronics prior to operating the BR in the normal fashion. After passing these tests, the BR was operated at high voltage into a resistive load to verify that the 30% output current increase was achieved.

Shown below are details of the actual modifications to the BR and validation tests performed:

- Buck regulator piggyback board:
  - Removed the buck regulator piggyback board and made the following modifications, as per instructions:
    - Changed R500 to 30kΩ.
    - Changed R507 to 13kΩ.
    - Changed R509 to 1.74kΩ.
    - Added a 2.4V zener diode in series with Z505.
    - Changed R532 to 2kΩ.
    - Set TP530 to 3.75V.
    - Replaced buck regulator piggyback board and performed tests to verify modifications as per instructions.

- Buck regulator control board:
  - Removed the buck regulator control board and made the following modifications, as per instructions:
    - Changed R82 to 75kΩ.
    - Set TP60 to 4V.
    - Verified that TP50 is -2V.
    - Verified that TP40 is 5V.
    - Replaced buck regulator control board and performed tests to verify modifications as per instructions.

- Opening switch control box:

   - Made the following modification, as per instructions, to the opening switch control box, in place:
     - Added 2kΩ resistor in series with the front-panel 10kΩ potentiometer labeled "Trip Level".

- Opening switch control box:
   - Made the following modifications, as per instructions, to the opening switch control board in place:
     - Removed R202.
     - Added a 0.1μF capacitor from TP20 to ground.
     - Performed tests to verify modifications, as per instructions.

- System tests:
   - Performed no-load test as per instructions.
   - Performed pulsed power tests into 400Ω, 550W load, as per instructions.

- System checks and measurements:
   - Visually checked the HV connectors on cable between the TR set and the BR.
   - Visually checked the oil levels in the TR set and BR tank.
   - Reversed-biased the TR set diode stack and measured 90ma at 74.6VDC.
   - Tested the HV cable between the TR set and buck regulator to 35kV (in air).
   - Operated the TR set with no load. Measured input phase currents at the soft start cabinet (front-to-back) of 53.5A, 37.9A, 38.6A.
   - Cycled power to the TR set a couple of times with no observable problems.
   - Operated the TR set with no load for ~20 minutes.
   - Operated the TR set and BR with no load to 16kV. Measure input phase current at the soft-start cabinet (front-to-back) of 50.5A, 36.6A, 37.5A.
   - Shut off TR set and BR. Turned it back on and brought it up to 16kV, no-load.
   - Performed crowbar test with 2.4kΩ dummy load to 5kV, ~2A.

In addition to performing the BR current upgrade modification, some tests and visual inspections were performed in order to understand the cause of several instances of blown 400-volt fuses at the input of the anode power supply transformer-rectifier (T-R) set. The high-voltage cable connecting the T-R set and BR was visually inspected for signs of arcing, and it was also hipot-tested, with no defects noted. Also, the T-R set rectifiers were tested for continuity with a dc power supply and found to be intact. After some discussion with Ian Roth, it is suspected that the blown fuse events were most likely caused by two different conditions:

1. The original 43.2Ω step-start resistors resulted in excessive T-R set inrush current at turn-on due to the much stiffer 400V mains supply in Hall 2.

(Note: The original 43.2Ω resistors were replaced with 0.75Ω resistors in December, 2007. Inrush current measurements made after the resistors were installed verified that the current is now within the safe rating of the fuses).

2. It may be possible that, under certain conditions, the BR output current overload sensing electronics could allow enough current into a short circuit to result in blown 400-volt T-R set primary fuses before the overcurrent interlock would open the output switch. One possible scenario for such an event would be if the BR is turned on into a short with the output voltage control set to zero, and then the output voltage control is slowly increased up from zero.

   (Note: This scenario occurred during the validation tests of the modifications, when the BR was accidently turned on into the test wire load with the test wire Ross relay still in the de-energized state and placing the test wire across the BR output. This resulted in the last blown fuse event, blowing two of the three fuses on the primary of the T-R set).

There were no further problems with blown fuses during this LOI testing period. T-R set input current was measured during LOI amplifier operation and was found to be consistent with values measured during previous LOI operation.

Another problem noted during preparations for testing the LOI amplifier was that the IGBT grid switcher was not functioning. It was determined that the IGBT device in the grid switcher had failed. The IGBT was replaced with a spare, and the grid switcher operation returned to normal. After some discussion, it was theorized that the IGBT was damaged when the bypass capacitor on the triode G1 bias power supply failed during the last session of LOI system operation.

After the modifications and associated tests were completed on the BR, high-power operation of the LOI amplifier was started. During the initial operation at 50% duty factor, the average output current of the BR (read from the moving-coil output current meter on the BR opening switch control chassis front panel) indicated that the peak output current was approximately 46A peak, which is above the expected overcurrent interlock trip point of 32A. At this point, operation of the BR was halted to determine the cause of the discrepancy.

Subsequent operation of the BR at lower output current revealed that the output current monitor in the BR tank was indicating an apparent calibration of 25A/V (the output current monitor signal indicated approximately 800mV peak with 10A average output current at 50% duty cycle). The average current output value was confirmed within approximately 5% by using a remote CCTV camera to view the shunt-meter plate current monitor on the rear of LOI amplifier. The LOI amplifier and BR moving-coil current meters agreed to within approximately 5%.

After analysis of the overcurrent trip comparator circuitry and discussion with Ian Roth, it was determined that the BR output current monitor (a transformer with a 2500:1 current ratio) was terminated on it's secondary winding with a 100Ω resistor rather than the expected 500Ω, resulting in the observed 25A/V output current calibration factor. This error resulted in the overcurrent trip point being set artificially high with the upgrade modification design. Ian Roth recalled that this resistor change was made when the BR was at KEK several years ago in an effort to overcome inrush current spikes, but unfortunately was not documented on the system schematics.

To overcome this problem, Ian had initially suggested replacing the 100Ω termination resistor with a 500Ω resistor. However, the risks involved with removing the opening switch control board to implement this change were considered too great. It was decided that resistor values in the overcurrent comparator trip-point voltage divider would be modified to correspond to the 25A/V calibration and provide a maximum output current trip point of 50A peak ("10.0" reading on the trip point potentiometer dial). Ian Roth felt that a 50A absolute limit in peak output current would not pose a problem with the BR. This modification was made, and subsequent operation of the BR with the LOI amplifier indicated that the overcurrent interlock trip point now appeared to be functioning normally, and scaled to a 50A absolute limit.

During further operation of the LOI amplifier system, the BR tripped several times on overcurrent faults when the average output current value was well below the trip point. Further investigation indicated that there were very narrow spikes on the BR output current that were exceeding the overcurrent trip point, and that these spikes were occurring time-coincident with the LOI tetrode driver being gated on and off. Slowing the rise time of the tetrode grid bias gating pulse reduced the amplitude of the current spikes, preventing further trips. During the final run of the LOI amplifier system, the BR output parameters were 15kV@15A average current, corresponding to 30A peak current at 50% duty factor.

ADDENDUM

On the spike noises tripping the Buck Regulator over-current

Date: Thu, 24 Jan 2008 09:05:28 -0500
From: "Roth, Ian" <roth@divtecs.com>
Subject: RE: LOI BR progress
To: Doug Horan <horan@aps.anl.gov>
Cc: mrmiddendorf@anl.gov

Hello Doug,

I'm glad that things worked out well.

It would not be a good idea to filter the over-current signal to prevent over-current trips, since the system needs to respond quickly in event of a short circuit.

Instead, the output inductor could be replaced with one that has more inductance (about 100 uH instead of 60), and the over-current threshold should be increased. This will eliminate trips while keeping the peak fault current the same.

While changing the inductor is fairly simple, it will require lifting the tank. Let me know if you're interested in pursuing this option.

Ian

-----Original Message-----
From: Doug Horan [mailto:horan@aps.anl.gov]
Sent: Sunday, January 20, 2008 4:27 PM
To: Roth, Ian
Cc: mrmiddendorf@anl.gov
Subject: LOI BR progress

Ian,

The current upgrade to the LOI BR was a success, and the BR delivered ~ 32A peak @ 15kV with no problems. Thank you for all your help with this project.

As we discussed on the phone, the full-scale setting for over-current was set to 50A max by adding a 40k resistor in series with the 10k pot. The output of the LEM was totally consistent with a 100-ohm secondary termination; everything made sense.

One new thing that appeared with the BR while we were running the LOI amplifier was an occasional trip of the over-current interlock would trip when the average current was way under the trip point (based on simple analog meters). I looked closely at the LEM output with a scope and saw very narrow spikes (~ 120us width) of current on the BR output (triode rf amplifier output stage) which occurred exactly when the tetrode driver was gated on and off. These spikes were almost twice the peak current value, which, of course, would trip the interlock. To make a long story short, these spikes in BR output current were real, caused by voltage spikes on the triode grid bias that are generated when the tetrode driver is gated on and off. We addressed this problem enough to get through this round of tests by slowing the rise and fall times of the tetrode gating pulse, but we will not be able to eliminate it entirely; this behavior is inherent to the design of the LOI rf amplifier.

Yoshiro asked if I could add a capacitor in the overcurrent interlock comparator to slow the response of the current interlock enough to ignore these spikes. I told him that I would forward the question to you to see if this would be possible without delaying the response of the overcurrent interlock and causing problems. What do you think of Yoshiro's suggestion?

Regards,

Doug