

Controlled Current Mode:

Compensation Network Tuning Guide

This guide is intended for assisting with the process of tuning the Controlled Current Compensation Networks in order to give the most stable operation for your specific inductive load.

Please read all warnings before beginning as not following the required guidelines could result in damage to the equipment and/or personal harm.

What is a Compensation Network?

AE Techron amplifiers are designed by default to operate in Controlled Voltage mode, wherein the voltage output of the amplifier is tightly regulated while the current output is determined by the total impedance of the external load and test setup. However, all of our amplifiers may also be operated in Controlled Current mode, by changing the dipswitch settings on the rear panel of the amplifier. In Controlled Current mode, the input signal controls the current output of the amplifier, rather than the voltage output, while simultaneously delivering whatever voltage is required to achieve the desired current output.

Operation in Controlled Current mode enables highly accurate user control by directly coupling an inductive load, such as the gradient coil of an MRI system, to the negative feedback control circuit of the amplifier through a user-configurable circuit called the "Compensation Network". This network consists of a resistor and capacitor placed in parallel with the main feedback gain control in order to cancel out the inductance of the load so that the feedback network is able to operate with a linear frequency response.

There are two available compensation networks, "CC1" and "CC2" which can be selected one at a time by dipswitch configuration on the rear panel. CC1 contains pre-populated values that are tuned for typical user loads, while CC2 is unpopulated to allow for the end user to finely tune amplifier behavior for their exact needs and setup. The component values of the resistor and capacitor in the CC1 network support a relatively wide range of load inductances, while the ideal component values for CC2 must be tuned through a process of observation and correction. This guide serves as a starting point for safely and accurately tuning the CC2 compensation network by providing both process instructions and a guide for initial component values.

Before You Start

Warning!

- **Never operate any AE Techron amplifier in Controlled Current mode without an attached, inductive load!**
 - Operation into an open load may cause severe voltage damage to some amplifiers as the amplifier attempts to deliver current that cannot flow.
 - Operation into a purely or primarily resistive load can also cause severe voltage and power oscillations due to the amplifier correcting its output faster than needed for stable operation. This overcorrection can quickly become self-reinforcing and lead to runaway oscillations.
 - Either situation can cause damage to the amplifier if allowed to continue (a few seconds normally is OK as long as you stop it) The load attached could be damaged depending its construction.
 - The High frequency output will cause internal components to heat extremely quickly, undergoing thermal runaway and component failure faster than the amplifier's protection circuits can react to protect itself if allowed to continue.
- **When using Controlled Current, choose the right compensation network!**
 - While CC1 and CC2 can be used for different loads, the resultant of selecting the wrong compensation can cause oscillations and damage to the amplifier and possibly the load.
 - For the purposes of this guide, please only use CC1 or CC2.
 - Operating without either CC1 or CC2 activated or without compensation can result in oscillations as the control loop will react too quickly resulting in damage.
- **Do not allow the Amplifier to oscillate for longer than a few seconds!**
 - While tuning the compensation network, the amplifier may experience dangerous oscillations if the compensation network component values are not sufficient to counteract the effects of load inductance.
 - Use caution when powering on the system and be prepared to turn off the front breaker, or place the amplifier in standby mode, quickly should oscillations occur.
 - **Note:** *stopping the signal IS NOT sufficient to stop a oscillations and should not be relied upon. Only "Stop" or removing system power is guaranteed to stop oscillations.*
- **The Amplifier may react to noise on the signal line, which can result in immediate oscillations upon the amplifier being powered ON and/or upon entering an Enabled/Ready state.**
 - Before powering on the amplifier, check for and minimize all potential sources of radiated or conducted noise or potential ground loops.
 - Ensure that an inductive load is connected to the amplifier's output and that Dipswitch settings are configured correctly, with either CC1 or CC2 enabled (not both or neither).
 - See below for diagrams of dipswitch settings for each model of amplifier.
- **Ensure that the signal source is not outputting a significant DC offset.**

Controlled Current Gain and Monitoring Options

“Input signal to output current” gain while operating in CC mode is specific to the model. This gain level may be different for modified or otherwise non-standard units.

Please contact AE Techron Technical Support (tech@aetechron.com) with any questions regarding CC mode gain. If possible, please provide any available data and/or oscilloscope pictures to assist with the troubleshooting process.

CC mode Gain by model:

7200 Series:

1 V input = 5 A output

7500 and 7700 Series:

1 V input = 20 A output

8000 Series:

1 V input = 20 A output

9105, 9205, and 9305:

1 V input = 10 A output

9110:

1 V input = 20 A output

9115:

1 V input = 30 A output

Calculating Compliance Voltage Requirements

Many controlled current applications are driven by a square or trapezoid signal waveshape. In order to achieve the correct current slew rate to achieve the desired rise time, the voltage will overshoot the current level in a behavior called “preemphasis”. Likewise, the negative current slew requires a negative voltage spike to accurately draw down the current in a linear fashion. This behavior is necessary to provide the initial energy required to “charge” the magnetic field of the inductive load.

An example of these preemphasis voltage spikes can be seen in *Figure 1* (below), with the **Voltage graphed in green** and the **Current in Orange**:

[Insert preemphasis image here]

While operating in controlled current mode, the amplifier will deliver the necessary compliance voltage to output the requested current, up to the limits of the amplifier’s voltage rails. When the required compliance voltage is limited by voltage rail limits, the voltage waveform can be seen to clip, resulting in a slower and less precise current rise or fall, as seen in *Figure 2* (below):

[Insert Image of voltage clipping during preemphasis]

The required compliance voltage can be calculated based on the following formula:

[Insert Compliance Voltage Formula Here]

Note: *There is a calculator available on the AE Techron website for your convenience:*

<https://aetechron.com/calculators/compliance-voltage/>

If your amplifier is not capable of reaching the required compliance voltage, slowing down the rise time or decreasing the load inductance will reduce the voltage needs.

If neither adjusting rise time nor changing the load characteristics is a viable option for your testing needs, please reach out to AE Techron Technical support at tech@aetechron.com.

Step 1: Confirming Amplifier Operation in Controlled Voltage Mode

This step will confirm that your amplifier is operating correctly and rule out any other sources of setup-related issues that would get in the way of compensation network tuning.

Procedure:

- Start by disconnecting the load from the amplifier's output terminals. This first test will be performed into an open circuit.
- Monitor the following on an oscilloscope:
Note: All oscilloscope channels should be DC coupled with 1 M Ω input impedance (or any "High impedance" setting greater than 100 k Ω).
 - Input signal
 - Output Voltage
 - May be monitored with VMON BNC connection (7000 and 8000 series amplifiers), DB9 voltage monitoring pins, or with a differential probe connected to amplifier output terminals.
- Send Signal:
 - Waveshape: 1 kHz square wave
 - Amplitude: 1 Vp (giving 20 Vp amplifier output for all 7000 and 9000 series amplifier, or 40 Vp amplifier output for all 8000 series amplifier)
- Check for proper voltage output shape and amplitude, as well as monitoring for excessive noise on the signal or monitoring lines.

(Optional):

- After verifying proper output connect a known load, with appropriate Wattage rating and repeat the test to verify proper behavior while the amplifier is outputting current/power rather than just voltage.
 - Monitor Amplifier Current output on the oscilloscope.
 - May be monitored with IMON BNC connection, DB9 voltage monitoring pins, with an external current clamp, or by using a differential voltage probe across a shunt.

Step 2: Controlled Current Mode using CC1 compensation network

This step will observe the behavior of the amplifier into an average default compensation network. Based on the behavior seen here, we will determine the best initial values for the Capacitor and Resistor of CC2. (“normal” loads are 100 to 500uH, with 1 to 10 ohms in series, with a load similar it is generally stable)

These tests will be performed with a low duty cycle, square (or trapezoidal) pulse signal, regardless of your actual signal waveshape. Correctly compensating the amplifier to your load with this signal will result in ideal behavior for any waveshape or will be close enough to ideal behavior that it can be corrected with minor resistance value adjustments.

Procedure:

Warning!

Please read all warnings before beginning this section!

If at any time the amplifier is seen outputting erratic, high-amplitude oscillations – remove system power immediately using the rocker-switch power breaker on the front of the amplifier.

1. To begin, remove power from the amplifier and connect your inductive load.
2. Configure Dipswitch settings for Controlled Current with CC1 activated (or CC2 with parts installed).
3. Monitor the following on an oscilloscope:
 - Input signal
 - Output Voltage
 - May be monitored with VMON BNC connection (7000 and 8000 series amplifiers), DB9 voltage monitoring pins, or with a differential probe connected to amplifier output terminals.
 - Output Current
 - May be monitored with IMON BNC connection, DB9 voltage monitoring pins, with an external current clamp, or by using a differential voltage probe across a shunt.(Do not ground “-Imon”, use care to not create ground loops with scope connections)

4. Next, Power on the amplifier while observing the output of the amplifier. Be prepared to turn the power back off if there are any indications of oscillations seen on the oscilloscope.
 - If the compensation of CC1 is too far from ideal, and the output voltage has too much noise, then the amplifier may have entered an oscillation.
 - If you do see oscillations, Press “Stop” or “Power Off”, move on to the next section – “Selecting Initial component values for CC2”.
 - If the amplifier is stable, continue to step 5 in this section.

5. With the amplifier output stable upon power-up, send the following signal while observing the behavior of your load with the CC1 compensation network:
 - Send Signal:
 - Waveshape¹: Low duty-cycle, square pulse.
 - High level²: +1 V_{DC} (or lower, to a safe level for your load)
 - Low level: 0 V_{DC}
 - Durations:
 - High for 10 ms
 - Low for 90 ms (or longer)

[Insert Image of Square Pulse]

Note 1: A trapezoid wave may be used in place of a square wave if your desired rise times are low, or if you are hitting compliance voltage limits (see below).

Note 2: High level may be lower than 1 V_{DC} depending on the power rating of your coil, or any other necessary constraint.

6. Observe behavior and immediately turn off the amplifier if any oscillations develop.
 - If your amplifier output is stable, Capture the waveshape on the oscilloscope and stop the input signal.
 - Look for the following characteristic behaviors to determine if your amplifier is underdamped or overdamped with CC1, or if you are encountering other issues:

[Insert Picture of Compliance Voltage Clipping]

Figure A: Insufficient Compliance Voltage causing a slow and rounded Current slew.

- If you notice that the Voltage waveform trace is clipping (showing a flat top, rather than a clean spike during the rising/falling current transitions), then you may be limited by compliance voltage.
 - It is possible for clipping to occur during this test, but not with your actual signal, since a square wave is requesting an extremely quick rise time, which requires a higher compliance voltage to achieve.
 - For example, the required compliance voltage for sinusoidal signals will be much lower than those for square or trapezoidal pulse signals.
- For the purpose of this test, you can remedy voltage clipping with any of the following methods:
 - You may slow down the rise time of the signal by substituting the square wave pulse signal with a trapezoidal signal.
 - You may lower the amplitude of the input signal until the voltage waveform is no longer clipping.
 - Any combination of the above.

[Insert Picture of Underdamped with Ringing]

Figure B: Underdamped waveshape with characteristic “ringing-down” behavior.

- An Underdamped waveshape will show ringing-down behavior as seen above in Figure B.
 - This behavior is due to the amplifier repeatedly overshooting the target current.
 - Oscillations occur when the ringing is not fully suppressed and builds to instability through positive reinforcement.
- This behavior indicates that the damping of the compensation network needs to be increased, either through an increased capacitor value or a decreased resistor value.
 - (See section – “Selecting Initial Component Values for CC2”).

[Insert Picture of Overdamped Waveshape]

Figure C: Overdamped waveshape with rounded Current slew.

- An Overdamped waveshape will show a very rounded corner on the current trace, as seen above in Figure C.
 - This behavior is due to the amplifier suppressing the voltage overshoot to the point where the current reaches the target level too slowly.
 - Despite not reaching target slew rate or bandwidth, this is safe and stable behavior as a starting point for tuning the CC2 compensation network (the first step of which is to achieve overdamping) and the process of tuning CC2 will be much easier when starting from this state with CC1.

- This behavior indicates that the damping of the compensation network needs to be decreased, either through a lower capacitor value or an increased resistor value.
 - (See section – “Selecting Initial Component Values for CC2”).

Other Possible Common Behavior:

[Insert Picture of Rising/Falling Current plateau]

***Figure D:** Rising Current trace plateau due to CC1 capacitor being too small.*

- If the plateau of the current waveform trace is increasing rather than flat, this indicated that the selected capacitor is too small.

Step 3:

Selecting Initial Component Values for CC2

Based on the behavior observed during Step 2, initial component values will be selected in order to intentionally create an Overdamped condition. From that state, the capacitor value will be lowered and/or the resistance will be increased to achieve ideal compensation.

This tuning process may be performed with discrete, fixed-value components, but will be far easier if a full-range potentiometer is used in place of a fixed value resistor.

Optionally, an “RC Box” with selectable resistance and capacitance values may also be used for the first pass tuning, but it may be impossible to achieve ideal behavior due to the remote connection to the PCB. When the RC Box is replaced with the actual discrete components, their values may need to be adjusted slightly to account for the difference.

Normal Component Ranges:

The following component value ranges can be used for the capacitor and resistor in CC2:

Capacitor:
1 nF – 1 μ F

Resistor:
100 Ω – 100 k Ω

Note: *If you are unable to achieve stable compensation with components in this range, please contact AE Techron Technical Support (tech@aetechron.com).*

Procedure:

Start with the section below that best describes your observed behavior from Step 2.

Oscillations when using CC1:

- Observing oscillations when using CC1 is an indication that the default component values are not providing sufficient damping.
- In order to achieve an over damped state, CC2 should be initially populated with the following, based on the range of your load inductance (L) and model of amplifier:

| Initial CC2 Component Values | | | | | |
|------------------------------|---------------------------|---------------------------------------------------------------------------------------------------------------------------|-----------------------|----------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| Inductance (L): | 5 μ H to 50 μ H | 50 μ H to 1 mH | 1 mH to 5 mH | L greater than 5 mH Or L less than 5 μ H | |
| Model Series: | 7000 or 9000 | 22 nF + 1 k Ω | 100 nF + 1 k Ω | 470 nF + 1 k Ω | Please Contact AE Techron Technical support for assistance (tech@aetechron.com) |
| | 8000 | 100 nF + 500 Ω | 100 nF + 500 Ω | 220 nF + 500 Ω | |
| | Custom and Modified Units | Please Contact AE Techron Technical support for assistance (tech@aetechron.com) | | | |

Underdamped when using CC1:

- Observing current overshoot and “ringing-down” when using CC1, without the amplifier going into full oscillation, is an indication that the default component values are close, but not providing sufficient damping.
- In order to increase damping, CC2 should be initially populated with the following component values:

| Initial CC2 Component Values (all models) | |
|-------------------------------------------|--------------|
| Capacitor | 100 nF |
| Resistor | 1 k Ω |

- Repeat the test from Step 2 with the same input signal and observe the change in waveforms.
- If the current trace is overdamped, Step 3 is complete, and you may continue with Step 4.
- If the current trace is still underdamped (but not oscillating) and the behavior has improved, then double the capacitor value and run the test again.
 - Repeat this process until the behavior is no longer overshooting and ringing, or if you have run out of values in the Safe Component range table earlier in this section.

Overdamped when using CC1:

- Observing a rounded corner on the current trace when using CC1 is an indication that the default component values are providing too much damping.
- As this is already the desired outcome of step 3, please continue on to Step 4.

Step 4:

Tuning CC2 Component Values

Following step 3, your current waveform should now be overdamped.

Procedure:

- Slowly increase the resistor value until the corners are sharp, but not overshooting and ringing.
- If you are unable to get the desired behavior by the time you reach 100 k Ω :
 - Stop and replace the capacitor with one that is 10%-50% larger
 - Reset the resistance to 1 k Ω .
 - Repeat the performance tests while increasing the resistor value.
- When you are unable to improve the corner response without causing the current to overshoot, then you have achieved the optimal component configuration for this load.

Step 5:

Confirming Operation at Full Power

Procedure:

- Test the system output with your desired signal, starting with 10%-25% of the target amplitude.
- If the amplifier output is behaving correctly, repeat this test with 50%, 75%, then full power.

Troubleshooting:

- If during these tests, you encounter any unexpected overdamping, check the output voltage waveform for evidence of clipping.
- If the output becomes underdamped, as seen by overshoot or ringing, decrease the resistor value slightly and see if the behavior improves.
- If at any point the system enters oscillation, immediately turn the amplifier OFF and start Step 5 over again with a slightly larger capacitor and lower resistance value.