Universal DRSSTC Controller

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Introduction

The Universal DRSSTC Controller is a fully integrated, high current intelligent IGBT and MOSFET driver, designed for use with Double Resonant Solid State Tesla Coils (DRSSTCs) of all power levels. It is 100% universal with the ability to drive both IGBT and MOSFET based half-bridges and full-bridges for both low power DRSSTCs as well as high power DRSSTC coils utilizing full-bridge switching circuits comprised of 1200V, 600A CM600 IGBT modules. The controller provides the intelligent logic necessary to drive both IGBT and MOSFET based power bridges as well as provide the fault processing circuit necessary to ensure safe, reliable operation of a DRSSTC system. The controller includes both peak current limiting circuitry as well as an Under Voltage Lock-Out (UVLO) protection circuit on the output stages of the integrated high current gate drivers. The UVLO circuit is especially useful for long pulsewidth applications, such as Quasi-Continuous Wave (QCW) Tesla Coils where the gate bus voltage may droop excessively during long pulses which could cause IGBTs to desaturate and operate in their linear regions which would ultimately cause them to fail due to overheating.

The controller receives its modulator (interrupter) input via a standard connectorized ST fiber optic input. The controller will accept both a standard modulator (interrupter) input as well as a musical MIDI based input from a modulator such as our Universal MIDI Handheld Controller. There are also two current sense inputs which connect to standard 1000:1 current transformers. The feedback current sense monitors the current in the primary circuit of the DRSSTC and uses the scaled current signal to synchronize the output gate drivers of the controller to the primary current to ensure the gate drivers switch at the exact resonant frequency of the DRSSTC system. The second current sense also monitors peak primary current and is used in a peak current limiting circuit. When this monitored peak primary current exceeds a set threshold limit programmed into the controller by the end user, it will disable the output pulsing, and thus protect the switching devices from excessive current. Current limit programming is set using two (2) externally accessible potentiometers. Using one potentiometer for coarse adjustment and one for fine adjustment, current limits can be set accurately in real time by simply looking at the arrow designators on the potentiometer knobs. A multimeter to read the current limit setpoints is not necessary. Overcurrent thresholds of 50A-2000A can be set visually by the end user with great ease.

The controller is designed with two integrated high current gate drive channels which can drive up to four (4) CM600 (or similar) IGBTs or MOSFETs in a full-bridge configuration. Each output channel features a very low impedance output drive which is capable of switching up to 50A peak current. This is necessary to drive large CM300 and CM600 IGBT modules very quickly and efficiently. An externally accessible phase select switch allows the user to select the polarity of the gate drive outputs with respect to the phase of the primary current.

To ensure proper synchronized and Zero Voltage Switching (ZVS) switching of the IGBT or MOSFET bridges with the primary current waveform, a phase delay circuit is provided. This adjustment allows the delay of the output gate drivers to be adjusted so that perfect ZVS soft-switching is occurring within the half-bridge of full-bridge switching circuit. This minimizes the switching losses of IGBTs or MOSFETs and allows the system to run efficiently and deliver maximum power to the primary circuit of the DRSSTC system. As the amount of inductance required to shift the phase of the current waveform varies with the type and size of the IGBT or MOSFET being used, a wide array of variable inductor modules are available which can be socketed directly onto the PCB board allowing the user to easily swap from one range of inductance to another.

Finally, the controller is enclosed in an EMI shielded two-piece enclosure that features four (4) #8 mounting holes. This allows the user to easily mount the controller in almost any location. Four (4) high-intensity LEDs provide real-time status to the health and operation of the controller.

Features:

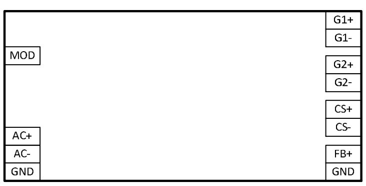
- Operates from 20VAC 50/60Hz or 27VDC
- Low power consumption: 5.5W Max at 20VAC
- Number gate driver channels: 2
- Gate drive output: 50A peak drive per channel
- Compatible with low to high power IGBTs including CM300 and CM600 IGBT modules
- Bridge configurations: Half-bridge or full-bridge
- Overcurrent protection to 2000A
- Under voltage lock-out (UVLO) protection
- Coarse / fine overcurrent setpoint adjustments
- Four (4) status LEDs
- Variable phase lead compensation circuit
- Phase select switch for gate drive outputs
- Plug-in inductor modules – allows range of values
- Modulator input – Fiber optic ST
- EMI shielded enclosure
- Four (4) #8 mounting holes
- Fully assembled and tested
- All units subjected to 1 hour burn-in testing
- Built and tested in the USA

Technical Performance

The following table summarizes the technical performance of the Universal DRSSTC Controller:

Technical Performance	
Input voltage range	20VAC 50/60Hz (tested) 27V ± 0.5VDC (tested)
Output frequency	10kHz to 1Mhz (tested)
Gate Drive Channels	2 Channels
Gate Drive Current	> 50A peak per channel
Max. FB Current	1000A (standard) or 2000A
Bridge Configurations	Half-bridge or full-bridge
Compatible Devices (Typical)	MOSFETs (TO-220 / TO-247) MOSFETs (SOT-227) IGBTs (TO-220 / TO-247) IGBTs (SOT-227) FGA60N65SMD IXFN60N60C2D1 CM200 IGBT Modules CM300 IGBT Modules CM600 IGBT Modules CM1200 IGBT Modules

External Connections



The following external connections are required for proper operation of the Universal DRSSTC Controller:

Pin	Function
AC+	Input voltage + (AC or DC)
AC-	Input voltage – (AC or DC)
GND	Earth ground
CS+	Current sense +
CS-	Current sense -
FB+	Feedback +
GND	Feedback -
G1+	Gate Drive Channel 1 +
G1-	Gate Drive Channel 1 -
G2+	Gate Drive Channel 2 +
G2-	Gate Drive Channel 2 -
MOD	Modulator Input (Fiber optic)

Powering the Universal DRSSTC Controller

The Universal DRSSTC Controller can be powered via both AC and DC, although it is typically powered through the use of a 20VAC 50/60Hz control transformer which is available from Eastern Voltage Research. The following tables lists the various methods which can be employed to provide power to the controller.

Input	Description
AC	20VAC 50/60Hz Transformer Rated at least 10VA (500mA) Connects to AC+ and AC-
DC	27V ± 0.5VDC (>500mA) Connect DC+ to AC+ Connect DC- to GND

Signal / Power Segregation

There are two (2) wire cut-outs in the enclosure for wires to pass through. Power connections shall use one cut-out while the current, feedback, and gate drive wires should use the other cut-out. It is important to segregate these connections to minimize the effect of noise and interference between power and signal connections. Rubber grommets are provided to ensure wires are not damaged due to chafing.

Grounding for Safety

The Universal DRSSTC Controller should be grounded to earth (chassis) ground through the internal GND pad. This is necessary for safety purposes and ensures that the controller is never floating at a potential above earth ground.

Fuse Protection

It is recommended to use a 1A fuse for input protection. Both standard 1 ¼" x ¼" and 5x20mm fast blow fuses are acceptable for this and should be placed at the input to the AC control transformer or DC power supply.

Modulator Input (Interrupter)

The modulator input uses a fiber optic ST port which accepts a modulator (interrupter) input to control and pulse the DRSSTC system. The Universal DRSSTC Controller utilizes an HFBR2412TC fiber optic receiver. We recommend using the Eastern Voltage Research Universal Handheld MIDI Controller or one of our Universal MIDI 1.0 Interface boards. However, other modulators (interrupters) may be used. Be sure to verify that the type of fiber optic output used on third party modulators (interrupters) is compatible with the HFBR2412TC fiber optic receiver.

Current Sense Input

Input pads CS+ and CS- connect to a 1000:1 current sense transformer which samples primary current and is used for peak overcurrent protection. It is recommended to use an Eastern Voltage Research 1000:1 current sense transformer for this application. Be sure the wires between the current sense transformer and the controller are twisted tightly together to maximize coupling and reduce inductance.

Feedback Input

Input pads FB+ and GND connect to a 1000:1 current sense transformer which samples primary current and is used for primary current feedback for the controller. It is recommended to use an Eastern Voltage Research 1000:1 current sense transformer for this application. Be sure the wires between the current sense transformer and the controller are twisted tightly together to maximum coupling and reduce inductance.

Gate Drive Outputs

The Universal DRSSTC Controller has two identical gate drive output channels. Each channel has an output drive capability of greater than 50A peak current and can be used to drive nearly any size MOSFET or IGBT module through the use of an isolation gate transformer. Each output drive channel can drive an individual bridge or be paralleled to drive a larger bridge. Please see our application figures in the end of this document for an example of the different types of gate drive configurations which are possible. Please note that the gate drive outputs are not isolated, and cannot drive IGBTs directly. They must be isolated through the use of an appropriate gate drive transformer to ensure proper electrical isolation between the Universal DRSSTC Controller and the switching bridge circuit.

Be sure that your wiring between the controller and gate transformer, as well as gate drive transformer and MOSFETs or IGBTs, is twisted tightly together. This will ensure maximum coupling between the gate drive and return leads and minimize leakage inductance which can have an adverse effect on the performance of the gate drive circuit.

Gate Drive Transformer Wire Type

The purpose of the gate drive transformer (GDT) in a high voltage bridge is to provide electrical isolation between the controller and the high voltage bridge. Wire should be rated for at least the maximum voltage present on the bridge. The following table provides recommendations for gate drive wire vs. maximum bridge DC bus voltage:

DC Bus Voltage	GDT Wire Type
0-600VDC	Alpha 1854 Series 24AWG, Stranded PVC Insulation, 600V
600-1000VDC	Alpha 1550 Series 24AWG, Stranded PVC Insulation, 1000V

Eastern Voltage Research sells several different gate drive transformer kits for various configurations.

LED Indicators

There are four (4) LED indicators which are used to provide status to the user. They are defined in the table below:

LED	Status
ENABLED	The controller is powered and passes all self-checks.
GATE POWER	24V gate power is enabled and within operational limits.
MOD ACTIVE	When a valid modulator (interrupter) signal is detected by the controller, this LED will illuminate. The brightness of this LED is directly proportional to the duty cycle of the modulator signal.
FAULT	The fault LED will illuminate during peak overcurrent detection as well as if a general fault is detected in the unit. As a self-check, the fault LED will always illuminate when the unit is first powered up and will reset when a valid modulator pulse is detected. This feature aids in the troubleshooting of the system in that it can be used to determine if the problem lies in the modulator and/or fiber optic cable.

Under Voltage Lock-out (UVLO)

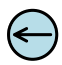
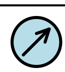
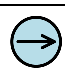
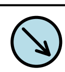
The Under Voltage Lock-out (UVLO) circuit is an important safety feature which can prevent your MOSFET or IGBT from failing during operation. The UVLO accomplishes this by inhibiting the output drive whenever the 24V gate drive voltage falls below a threshold of 20.5V. This ensures that if the 24V gate drive voltage ever falls below 20.5V, that the MOSFET or IGBT will not desaturate and operate within the device's linear region which would cause premature failure of the device.

Overcurrent Protection

The Universal DRSTTC Controller monitors peak current in the primary circuit of a DRSSTC via an external current transformer on a pulse-by-pulse basis. If the measured current exceeds a threshold set by the end user, output switching of the gate drive circuits will be inhibited and thus protect the MOSFET or IGBT switching devices from excessive current which could lead to premature failure. The Universal DRSSTC Controller is available with two maximum peak current capabilities: 1000A or 2000A depending on model. The end user can set the overcurrent trip threshold through the use of two (2) externally accessible potentiometers which is described in more detail in the next section.

Configuring Overcurrent Setpoint

Setting the overcurrent trip threshold is done by adjusting two (2) externally accessible potentiometers. There is both a COARSE and FINE adjustment potentiometer to provide the end user with maximum flexibility and ease when setting the overcurrent threshold. When setting the overcurrent threshold, the values programmed via the potentiometers are added together. For example, if the COARSE adjustment knob is set to 500A current and the FINE adjustment knob is set to 50A, then the overcurrent trip threshold would be 500A + 50A = 550A. The following table shows the approximate current setpoints for various knob positions. The numbers in parentheses are for the 2000A controller option.

POSITION	FINE	COARSE
	0 A	0 A
	17 A (33 A)	167 A (333 A)
	33 A (67 A)	333 A (667 A)
	50 A (100 A)	500 A (1000 A)
	67 A (133 A)	667 A (1333 A)
	83 A (167 A)	833 A (1667 A)
	100 A (200 A)	1000 A (2000 A)

Note: Please note that the current numbers in parentheses are the current setpoints for the 2000A controller units. As an example, if I have a 2000A version of the controller and the FINE potentiometer knob is set at 12 o'clock and the COARSE potentiometer knob is set at 3 o'clock, then the resulting current trip setpoint would be 100A + 1667 A = 1767 A. Please note that the setpoint values in the table above are approximate only and may vary depending on tolerances in components within the controller.

Phase Lead Compensation

Phase lead compensation allows one to add a small amount of "phase lead" to the input current feedback signal. This results in the ability for the switching device (i.e. IGBT or MOSFET) to switch earlier than it would typically during operation and allow the device to switch closer to its ideal Zero Voltage Switching (ZVS) point which is also known as "soft switching." This is highly desirable as if the device switches when current is passing through it, you will end up having to switch the devices during their conduction phase (current >> zero) which will result in large voltage spikes and ringing across those devices which overstresses the devices and ultimately causes them to fail. Although in reality, there will always be a small amount of current flowing through the IGBTs during switching transitions. By having the ability to vary the phase lead compensation, the end user is able to precisely tune the DRSSTC system so that the bridge is always switching in its ideal "soft switching" or ZVS state.

Selecting Plug-in Inductor Module

When selecting a plug-in inductor module, it is important to note that in general, the larger the IGBT, the more inductance is required to achieve the proper tuning point. The following chart provides some example inductor plug-in modules which can be utilized to achieve proper tuning. All inductor modules are available through Eastern Voltage Research.

Inductor Module	Switching Devices
IND-1 9-15uH	TO-247 IGBT
IND-2 10-20uH	CM200/CM300
IND-3 15-30uH	CM200/CM300
IND-4 30-50uH	CM200/CM300
IND-5 35-60uH	CM200/CM300
IND-6 40-70uH	CM600 / CM1200
IND-7 50-85uH	CM600 / CM1200
IND-8 60-100uH	CM600 / CM1200

Please note the table above should only be used as a starting point. Your actual DRSSTC system may require an inductor module different than that specified in the chart. Empirical (trial and error) testing and tuning will be required to determine what value works best for your DRSSTC system.

How to Tune Phase Lead

Adjusting the phase lead compensation for your DRSSTC system involves choosing the appropriate inductor module for your particular switching devices and tuning the switching point to minimize ringing and switch at a point as close to perfect to Zero Voltage Switching (ZVS) or "soft switching" as possible. The best approach to use when tuning a DRSSTC system is to remove the secondary coil, and test with a dummy load. An empty steel coffee can is a very good dummy load and readily available. The coffee can should be placed instead of the secondary coil centered within the primary coil. Please note, that the coffee can may get excessively hot during operation and filling it with water may help this by providing additional thermal mass. DRSSTCs can be tuned at either the full operational DC bus voltage of the DRSSTC or at reduced voltage using a variac.

To properly tune the phase lead compensation, a method to be able to properly and safely measure the primary current and primary voltage at the output of the bridge circuit is required. Primary current can be measured using commercially available high bandwidth current transformers made by Pearson or Ion Physics or using one of the current transformer kits available through Eastern Voltage Research. Primary voltage can be measured using differential scope measurement techniques using two oscilloscope probes. **Make sure that your oscilloscope probes are rated for the proper voltage and NEVER connect the ground clip from**

an oscilloscope probe directly to any point on a power bridge circuit.

Actual tuning techniques are outside the scope of this document and additional assistance can be provided by contacting Eastern Voltage Research.

The following scope shots are provided as reference for tuning. Figure 1 below shows the primary voltage (red) and current (green) waveforms of the bridge output with the inductor module removed from the controller (no phase lead.) As one can see, there is a large delay between the voltage switching transitions and the zero crossing of the current. This causes large voltage spikes to occur on the voltage waveform as shown below. These large voltage spikes are typically what will cause and IGBT or MOSFET to fail and great effort must be made to reduce them.

Figure 1 – No Phase Lead

The waveforms in Figure 2 below show the initial waveforms with a properly selected inductor module installed. Initially, one can see that the current (green) waveform has shifted to the left and the voltage spikes on the voltage (red) waveforms have been reduced slightly, although they are still quite large in magnitude. At this point, the DRSSTC system still requires tuning to further shift the phase lead and reduce the overvoltage spikes on the voltage waveform.

Figure 2 – Inductor Module Installed

During the tuning process, the end user will want to minimize those voltage spikes and achieve as close a switching point as possible to perfect ZVS or "soft switching." This is accomplished by incrementally adjusting the phase inductance and evaluating the resulting scope waveforms. Since there may be a slight phase offset between the voltage and current measurements due to the measuring devices themselves, the best method to achieve optimal tuning is to look at the voltage spikes on the voltage waveforms and try to minimize them as best as possible. The scope capture below shows an optimally tuned system. Note that the voltage spikes on the voltage (red) waveform have been reduced to nearly zero and the current (green) waveform basically intersects the voltage waveform at its zero voltage transition points.

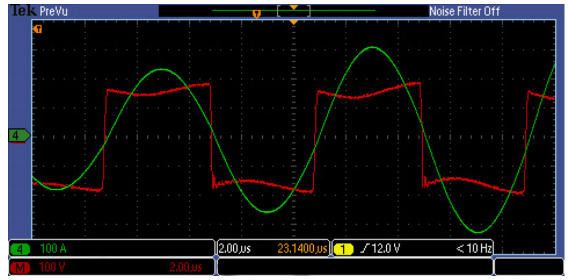


Figure 3 – Optimally Tuned DRSSTC System

Phase Select Switch

The phase select switch allows the user to reverse the phase of the output gate drive with respect to the phase of the primary feedback current. This function has the same effect as reversing the wires (or direction of the primary lead) of the feedback current transformer. Recognize that a DRSSTC system will only self-oscillate and work properly if the phasing is correct. So, if during initial testing, you find your DRSSTC system is not self-oscillating and switching, to simply power down the system and change the phasing of the output gate drive by moving the phase select switch into the opposite position.

Typical Applications

Figures 4 through 7 on the following pages show some example configurations of how the Universal DRSSTC Controller would be wired up with a DRSSTC system. Different input power and gate drive output configurations are shown.

Example DRSSTC Systems

Figures 8 through 10 at the end of this document show several example DRSSTC systems using Eastern Voltage Research supplied components including the Universal DRSSTC Controller. Please note that these are only examples and the values used for various components in the diagrams may not be accurate and should not be used for an actual DRSSTC design.

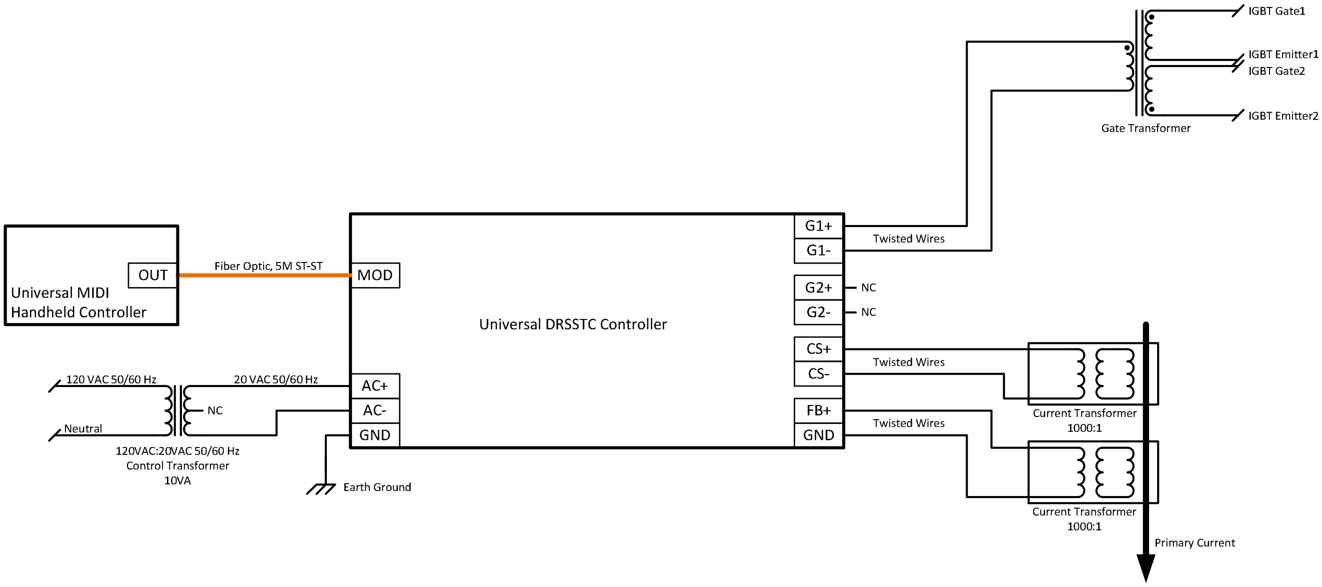

IGBT Gate1
IGBT Emitter1
IGBT Gate2
IGBT Emitter2
Gate Transformer
G1+
G1-
Twisted Wires
Universal MIDI
Handheld Controller
OUT
Fiber Optic, 5M ST-ST
MOD
G2+
G2-
NC
NC
Universal DRSSTC Controller
CS+
CS-
Twisted Wires
120 VAC 50/60 Hz
20 VAC 50/60 Hz
AC+
AC-
GND
NC
Neutral
FB+
GND
Twisted Wires
Current Transformer
1000:1
120VAC:20VAC 50/60 Hz
Control Transformer
10VA
Earth Ground
Current Transformer
1000:1
Primary Current

Figure 4

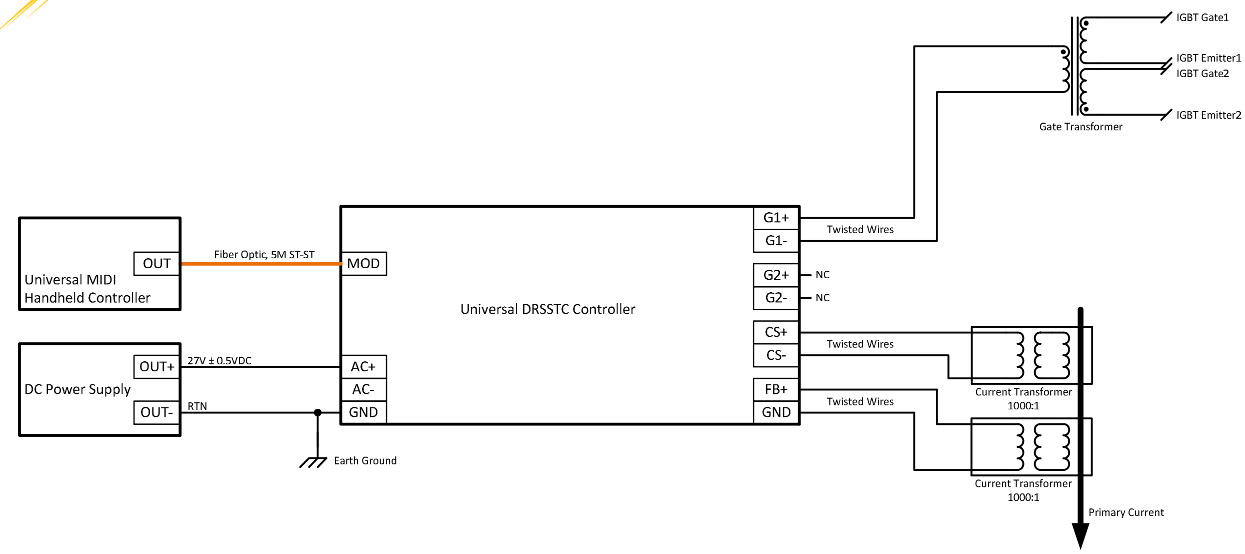


Figure 5

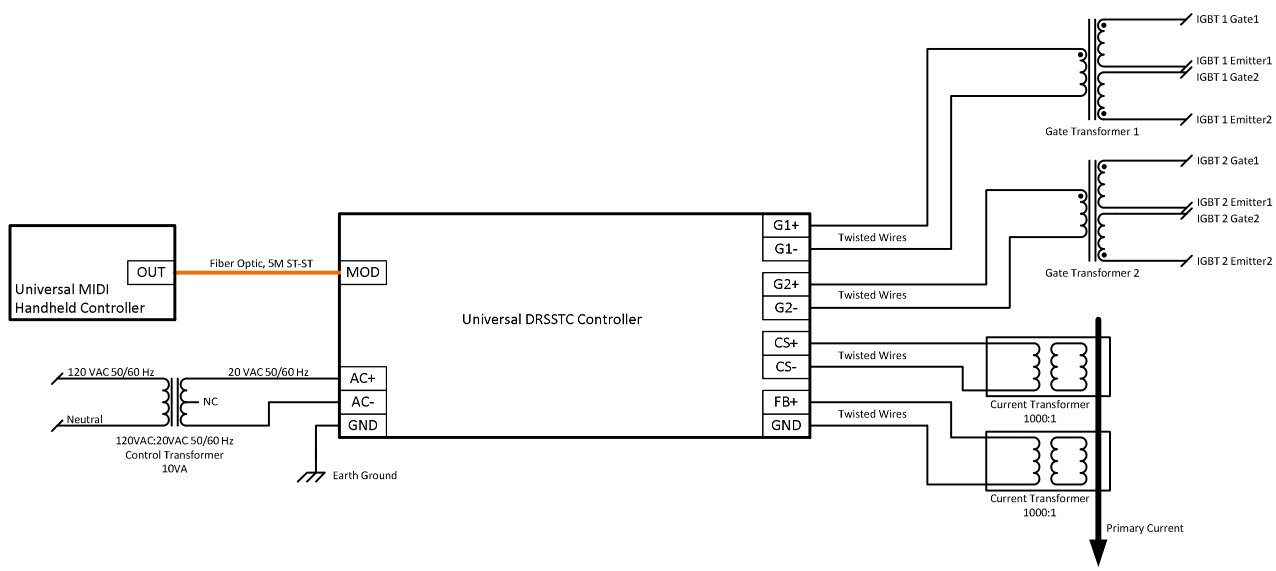


Figure 6

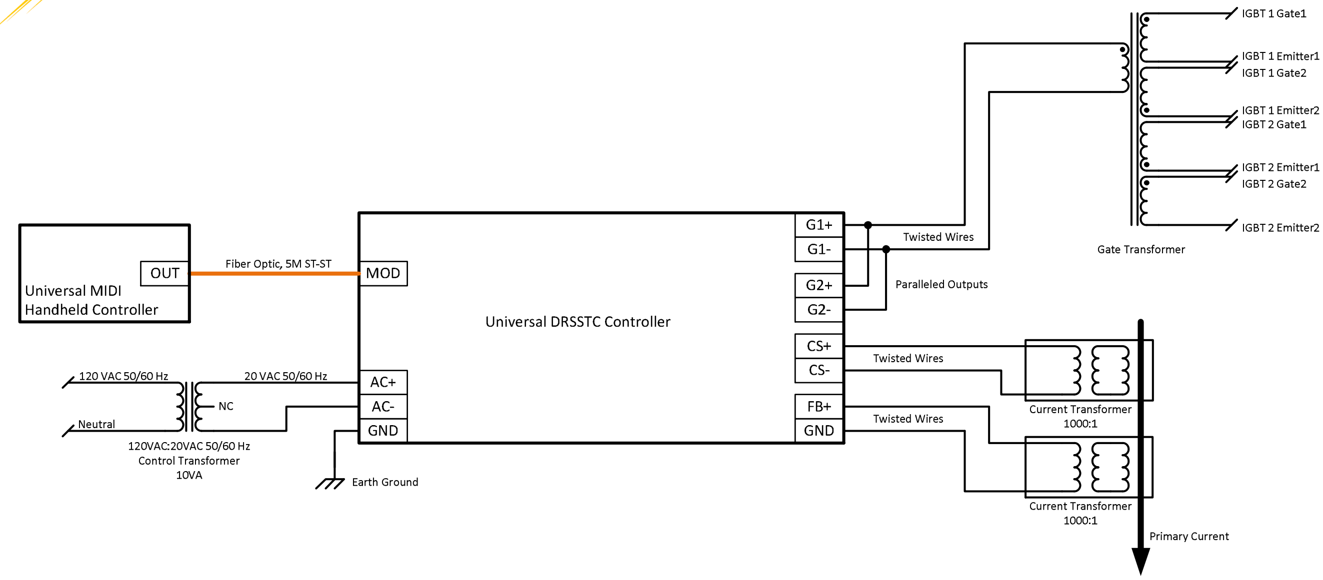
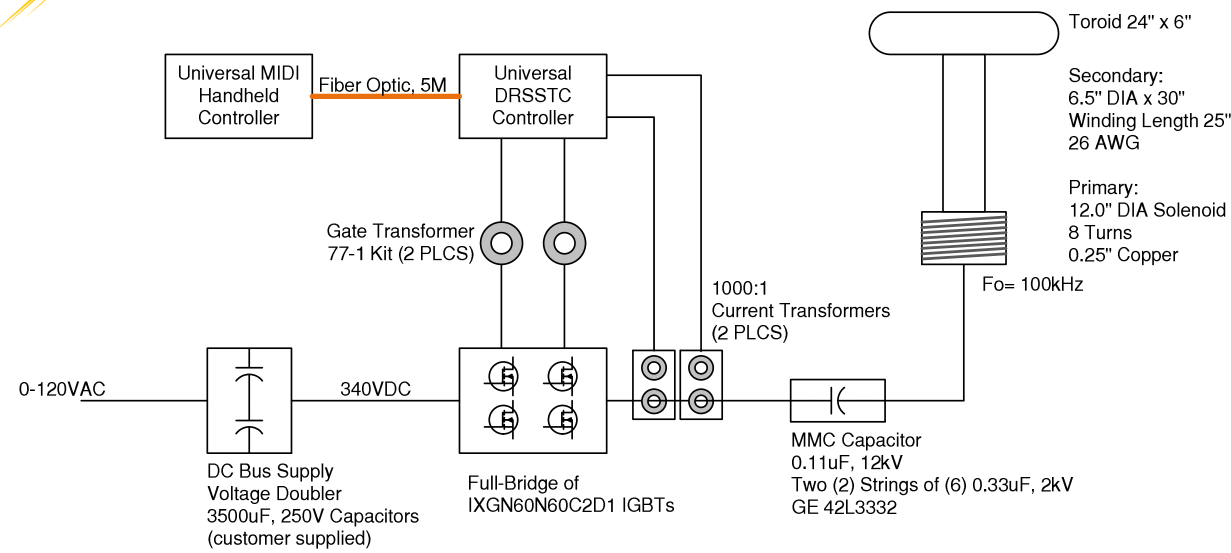

IGBT 1 Gate1
IGBT 1 Emitter1
IGBT 1 Gate2
IGBT 1 Emitter2
IGBT 2 Gate1
IGBT 2 Emitter1
IGBT 2 Gate2
IGBT 2 Emitter2
Gate Transformer
Twisted Wires
Paralleled Outputs
G1+
G1-
G2+
G2-
CS+
CS-
FB+
GND
OUT
Universal MIDI
Handheld Controller
Fiber Optic, 5M ST-ST
MOD
Universal DRSSTC Controller
120 VAC 50/60 Hz
20 VAC 50/60 Hz
NC
Neutral
AC+
AC-
GND
120VAC:20VAC 50/60 Hz
Control Transformer
10VA
Earth Ground
Twisted Wires
Current Transformer
1000:1
Twisted Wires
Current Transformer
1000:1
Primary Current

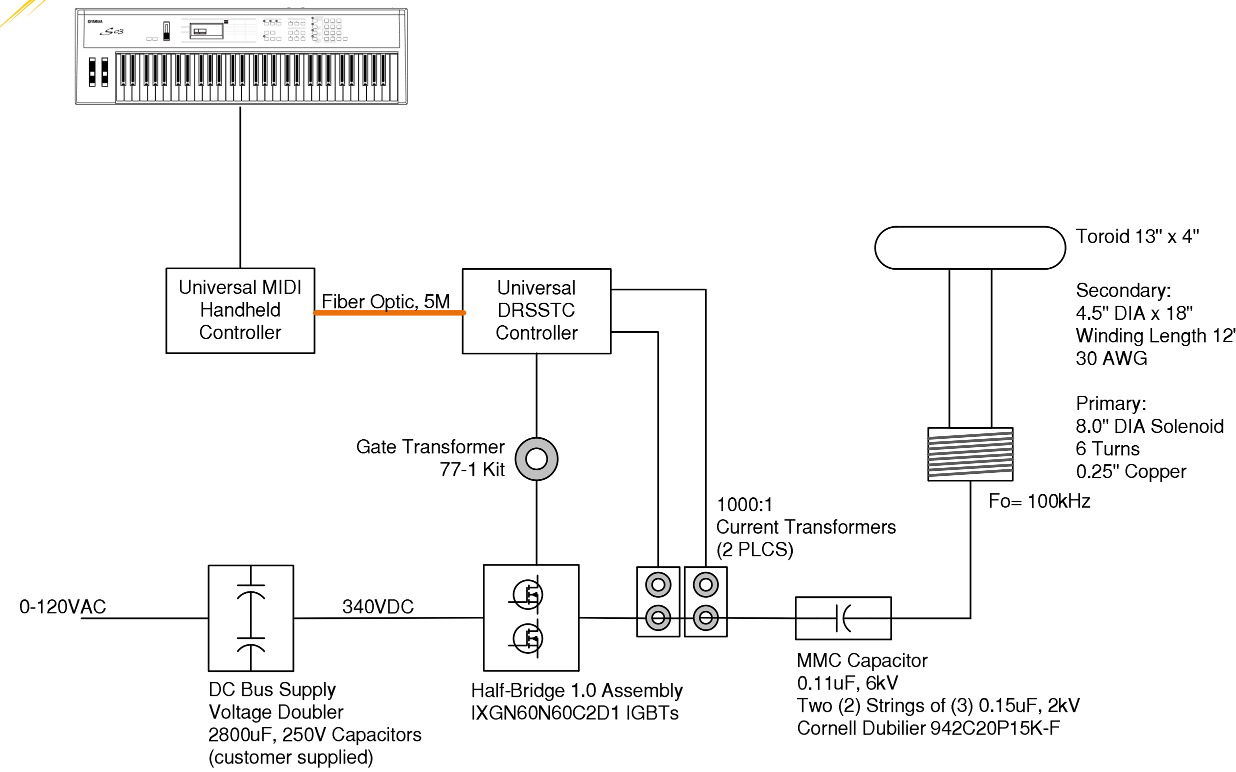
Figure 7



Eastern Voltage Research Components	QTY
Universal MIDI Handheld Controller (Interrupter)	1
Universal DRSSTC Controller	1
Gate Transformer 77-1 Kit	2
1000:1 Current Transformer Assembly	2
IXGN60N60C2D1 IGBTs	4
Toroid, 24" x 6", Aluminum	1
Fiber Optic Cable, 5M, ST-ST	1

Eastern Voltage Research purchased components for this specific application.

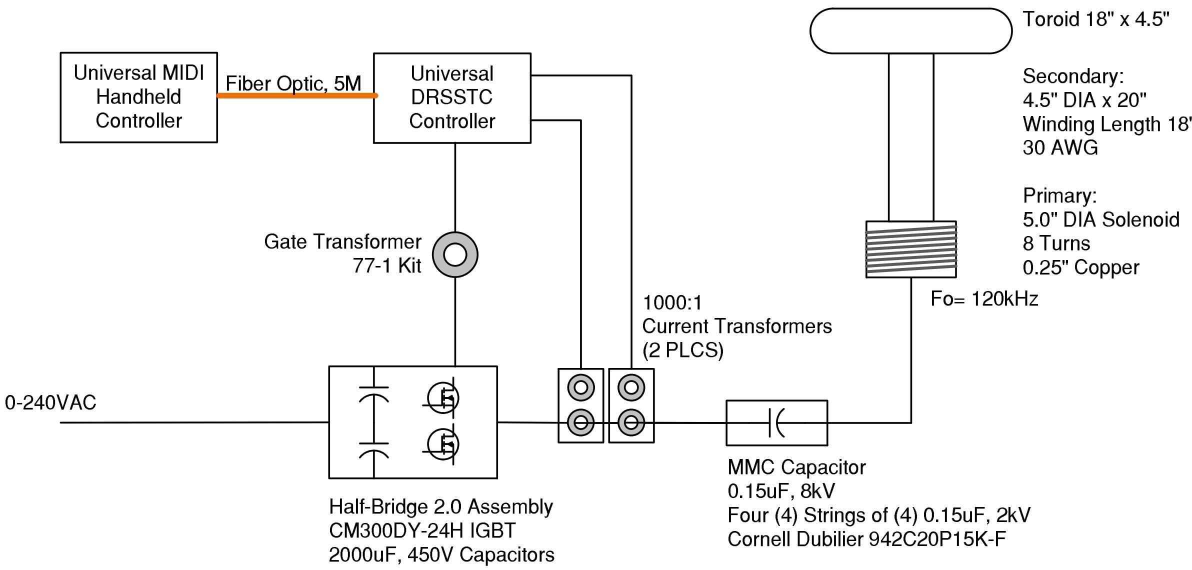
Figure 8



Component	QTY
Universal MIDI Handheld Controller	1
Universal DRSSTC Controller	1
Gate Transformer 77-1 Kit	1
1000:1 Current Transformers	2
IXGN60N60C2D1 IGBTs	4
942C20P15K-F 0.15uF, 2kV Capacitors	6
Toroid, 13" x 4", Aluminum	1
Half-Bridge 1.0 Assembly	1
Fiber Optic Cable, 5M, ST-ST	1

Eastern Voltage Research purchased components for this specific application.

Figure 9



Component	QTY
Universal MIDI Handheld Controller	1
Universal DRSSTC Controller	1
Half-Bridge 2.0 Assembly (For CM300)	1
Gate Transformer 77-1 Kit	1
1000:1 Current Transformer Assembly	2
CM300DY-24H IGBT	1
942C20P15K-F, 0.15uF, 2kV Capacitors	16
Secondary Coil, 4.5" x 20", 30 AWG	1
Toroid, 18" x 4.5", Aluminum	1
Fiber Optic Cable, 5M, ST-ST	1

Eastern Voltage Research purchased components for this specific application.

Figure 10

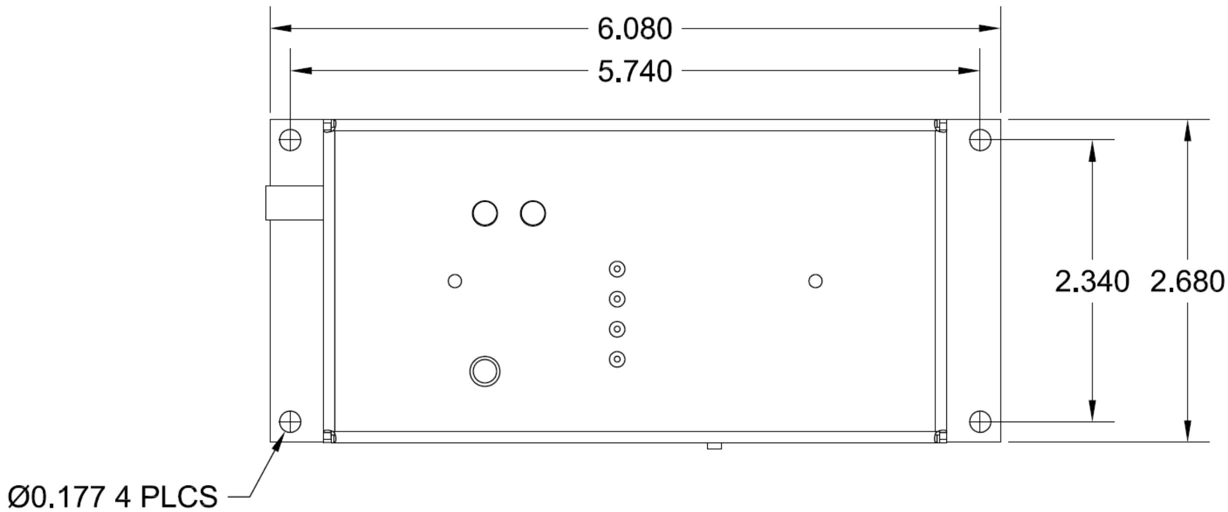


Figure 11- Mounting Dimensions (inches)