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AN-9742

Device Selection Guide for Half-Bridge Welding Machine (IGBT & Diode)

Summary

Various topologies; including two SW-forward, half-bridge and full-bridge, have been used for low-voltage / high-current DC-ARC welding machines for system minimization and efficiency improvement. Of these topologies, half-bridge is the most commonly used for small form factor, less than 230A capacity welding machines. Compared to full-bridge topology with the same power rating, half-bridge requires more transformer wiring and higher current capacity of inverter; but requires fewer power devices. Taking a Fairchild evaluation board as the example, this article presents a device selection guide for a half-bridge welding machine application.

Description of Welding Machine

Generally, based on the type of welding machine, the output voltage can be calculated as shown in Table 1.

Table 1. Welding Machine Output Voltage

Welding Machine	Output Voltage	Example
CO2	$0.04 \cdot I_{AC}+15$	0.04•200A+15=23V
TIG	$0.04 \cdot I_{AC}+10$	0.04•200A+10=18V
DC ARC	$0.04 \cdot I_{AC}+20$	0.04•200A+20=28V

Duty Cycle of a Welding Machine

In the welding industry; duty cycle refers to the minutes out of a 10-minute period a welder can be operated at maximum rated output without overheating or burning up the power source. For instance, a 140A welder with a 60% duty cycle must be "rested" for at least 4 minutes after 6 minutes of continuous welding at maximum rated output current 140A.

Allowable Duty Cycle

If actual current in use is smaller than a rated output current, the welder internal heating decreases. The welder then can be used at a higher rate than the specified duty cycle. Its allowable duty cycle can be calculated as:

$$= \left(\frac{\text{rated output current}}{\text{using output current}} \right)^2 \times \text{duty cycle of welding machine} \qquad (1)$$

For example, since only 80A to 130A current would be required to weld a 3.2 welding rod, a 140A welder with a 60% duty cycle can operate for a longer time for this application. Assuming 100A is used to weld a 3.2 welding rod, actual duty cycle is more than 78.4%.

Besides the actual output current, the temperature also affects the allowable duty cycle of a welding machine. Do NOT overheat welder machines.

Table 2. Feasible Welding Materials by Welding Machine

Welding Machine	Gas	Welding Type Steel
CO2	CO_2	Mild, High Tensile
MIG	He + Ar	Aluminum, SUS, Aluminum Alloy
MAG		Sheet Metal, Low Alloy, High Tensile
DC-TIG		Stainless, Mild, Copper Alloy, Nickel Alloy, Titanium Alloy, Low Alloy
AC-TIG		Aluminum Alloy, Magnesium Alloy, Bass
Mixed TIG		Light Alloy, Clad Plate
DC-ARC		Steel, Nonferrous Metals
AC-ARC		Aluminum

Fairchild DC-ARC Welding Machine Evaluation Board

Evaluation Board Features

- Input Stage: 50A Bridge Diode (600V, 50A, Square-Bridge Type)
- Input Filter Stage: Designed Under Consideration of Conductive Noise and Radiation Noise
- Controller: PIC16F716 (8-Bit ADC and 10-Bit PWM)
- Inverter Stage: FGH40N60SMD (within Co-Pak Diode) Single or Parallel
- Output Rectifier: FFA60UP30DN * Six Units (Three Ultra-Fast Diode in Parallel)
- Gate Driver: Opto-Coupler for the Isolation between Switching Devices and Controller Dual Power Supply +15V, -5V for IGBT Gate Voltage
- AUX Power Supply: Lower Standby Consumption Green Integrated PWM IC
- Input Voltage and Frequency: $220V_{AC}$ 60Hz
- Output Voltage (V_{OUT}) and Output Current (I_{WEL}): $26V_{DC}$, 140A
- Efficiency: > 80%
- Idle Power: < 4W
- Switching Frequency: 20KHz

Figure 2 shows the main block diagram of the welding machine evaluation board. The output current and output voltage of the DC-ARC welding machine evaluation board are 26V and 140A, which constitutes a 3kW-class welding machine. Various Fairchild Semiconductor components are used to meet the design requirements. The switching frequency of the machine is 20KHz. Due to their size; the transformer and inductor are installed beside the board. An air fan is attached for cooling.

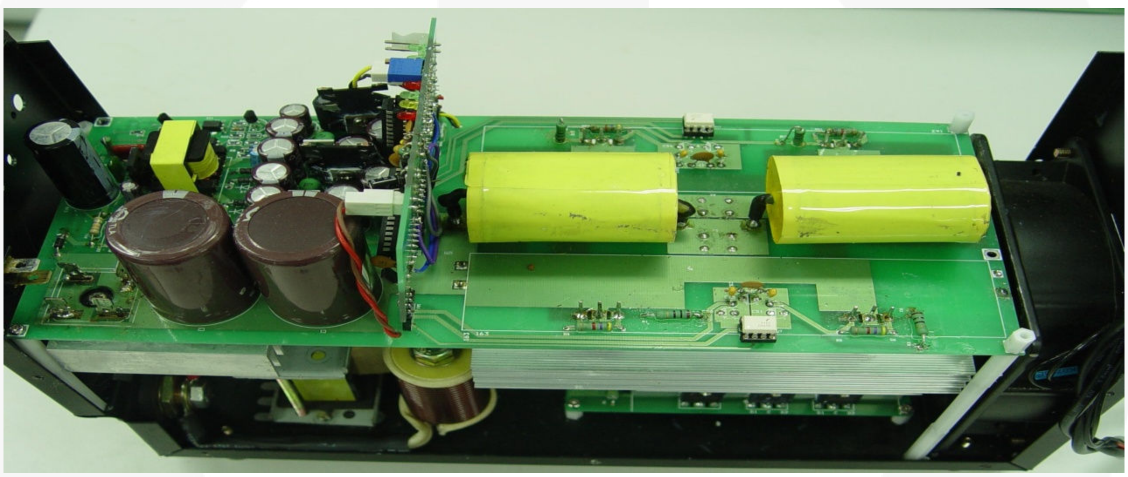

Figure 1. Evaluation Board

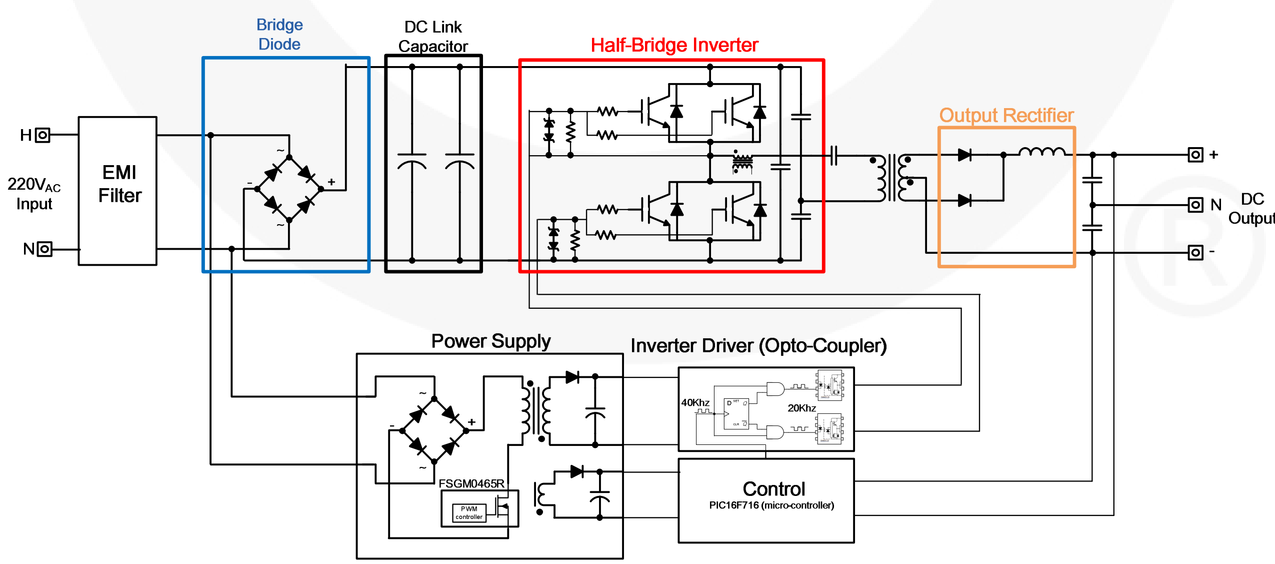

Figure 2. Main Block Diagram

Half-Bridge Inverter Design

The turn ratio of the primary and secondary of the transformer in a half-bridge topology can be obtained from the equation:

$$N_1 = \frac{V_{IN(MIN)} \times D_{MAX}}{4 \times B \times A_e * f_{SW}} \quad (2)$$

$$N_1 = \frac{(V_O + V_F + V_I) \times N_1}{D_{MAX} \times V_{IN(MIN)}} \quad (3)$$

where $V_I = V_S$, I_{WEL} = output current, I_{d1} & I_{d2} = diode current (output high side & output low side).

Output voltage under no load condition is given by:

$$V_{nolaod} = \frac{(V_O + V_F = V_I)}{D_{MAX}} \quad (4)$$

where:
V_O=output voltage;
V_F=diode drop voltage; and
V_I=inductor voltage drop.

Transformer's primary and secondary current can be obtained by:

$$I_{1rms} = \frac{N2}{N1} \times I_{WEL} \times \sqrt{(2 \times D_{MAX})} \quad (5)$$

$$I_{2rms} = \frac{1}{2} \times I_{WEL} \times \sqrt{(1 + 2 \times D_{MAX})} \quad (6)$$

Current running through the IGBT and secondary-side rectifier diode can be calculated by:

$$IGBT \text{ Current} : \mathrm{I_D} = \frac{\mathrm{N}_2}{N_1} \times I_{WEL} \quad (7)$$

Output rectifier diode voltage and current:

$$V_r = \frac{N2}{N1} \times V_{IN(MAX)}, I_{WEL} = \sqrt{I_{d1}^2 + I_{d2}^2} \quad (8)$$

IGBT Selection for Welding Machine

Among various power switching components, Insulated Gate Bipolar Transistor (IGBT) is the most suitable device for welding machines thanking for its high current handling capability and high switching speed. IGBT is a voltage-controlled power transistor, similar to the power MOSFET in operation and construction. This device offers superior performance to the bipolar-transistors. It is the most cost-effective solution for high power and wide frequency-range applications. Table 3 shows the characteristics comparison of IGBT with BJT and MOSFET.

Table 3. Device Characteristics Comparison

Features	BJT	MOSFETS	IGBT
Drive Method	Current	Voltage	Voltage
Drive Circuit	Complex	Simple	Simple
Input Impedance	Low	High	High
Drive Power	High	Low	Low
Switching Speed	Slow(µs)	Fast(ns)	Middle
Operating Frequency	Low	Fast (less than 1MHz)	Middle
S.O.A	Narrow	Wide	Wide
Saturation Voltage	Low	High	Low

Power losses of an IGBT include conduction loss and switching loss. The conduction loss is determined by IGBT's $V_{ce(sat)}$ value and the duty rate. The switching loss is determined by turn-on and turn-off action during IGBT's switching transient. For IGBTs, there are technical trade-off characteristics between the $V_{ce(sat)}$ and the switching loss. If $V_{ce(sat)}$ is high, switching loss becomes low and vice versa. Therefore, the designer should select an IGBT based on the system configuration and its switching frequency. The total loss of an IGBT can be expressed as:

Total Loss	=	1 Pulse Switching Loss (E_{ON} + E_{OFF})	X	Switching Frequency	+	Conduction Loss ($V_{CS(SAT)}$ X I_C X Duty)	(9)

Figure 3 curves show the characteristics comparison between PT IGBT and field-stop IGBT. PT IGBT has NTC temperature characteristic: as temperature rises, $V_{ce(sat)}$ decreases. Field-stop IGBT has PTC temperature characteristic: as temperature rises, $V_{ce(sat)}$ increases. Therefore, PT IGBT with NTC characteristic is more suitable for the application where IGBT is operated solely. However, if parallel operation of IGBTs is required for current sharing, field-stop IGBT with PTC characteristic would be more appropriate.

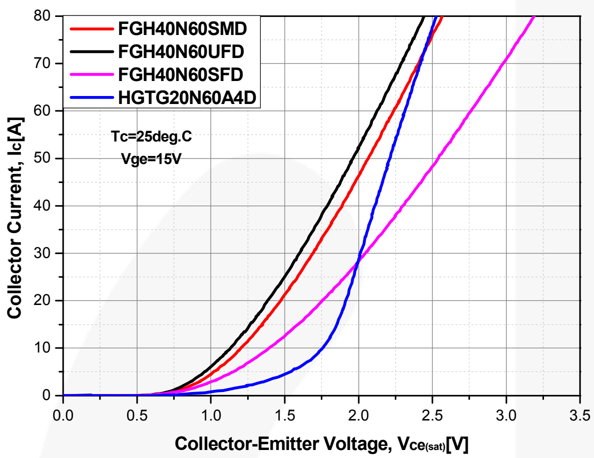

Figure 3. HGTG20N60A4D(PT) vs. FGH40N60UFD/SFD (Field-Stop Gen1)

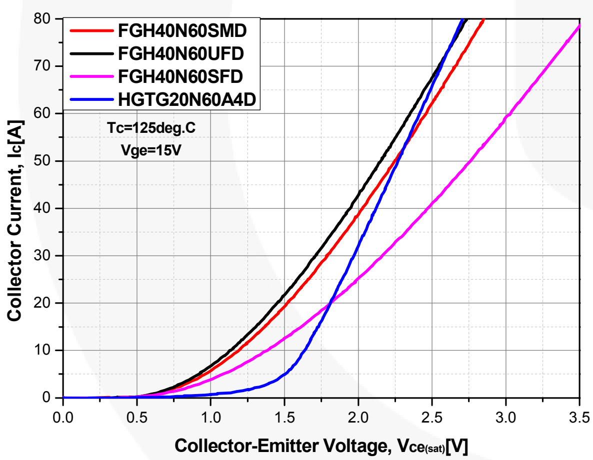

Figure 4. FGH40N60SMD (Field-Stop Gen2)

Reduction of conduction loss and total device cost with better thermal performance would be the advantage of the parallel operation of IGBTs. However, for such kind application, the following must be considered:

- Using high-temperature PTC characteristic IGBT
- Using gate resistor with ≤1% tolerance for each IGBT
- Proper gate PCB layout for symmetrical current paths
- Identical heat sink size and airflow for each IGBT
- Same threshold voltage and saturation voltage characteristics

The following figures show that the switching loss becomes the dominant factor over conduction loss in 25kHz and above switching frequency area.

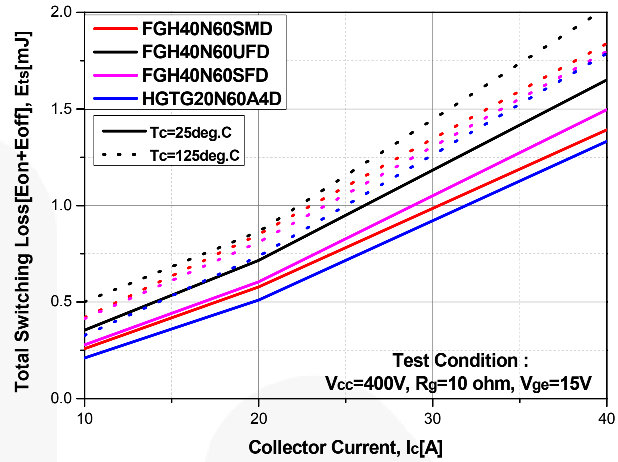

Figure 5. Total Switching Loss E_{ts} vs. Collector Current I_C

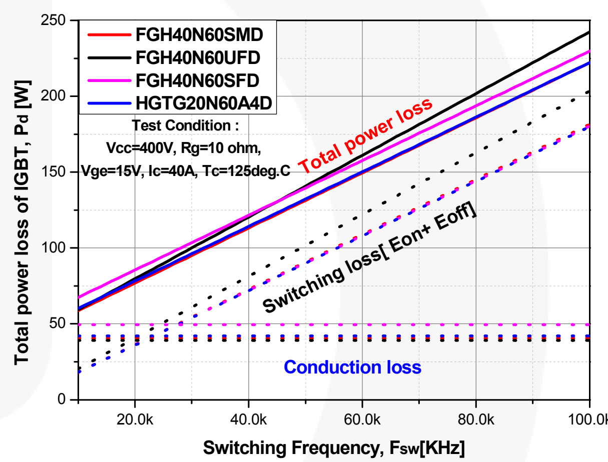

Figure 6. Total Power Loss of IGBT P_d vs. Switching Frequency

The gate resistor is also very critical to the switching loss. High gate resistance results in high switching loss. On the other hand, high gate resistance improves EMI performance as the di/dt is lower during the switching transient. A properly selected gate resistor should minimize the switching loss without sacrificing system EMI performance.

Below are the IGBT turn-off characteristics measurements with JIG testing. Under the same conditions, FS Planar Gen2 IGBT FGH40N60SMD shows faster switching characteristic, lower $V_{ce(sat)}$, and tremendously lower turn-off loss compared to previous technology devices - PT and FS Planar Gen1 IGBT.

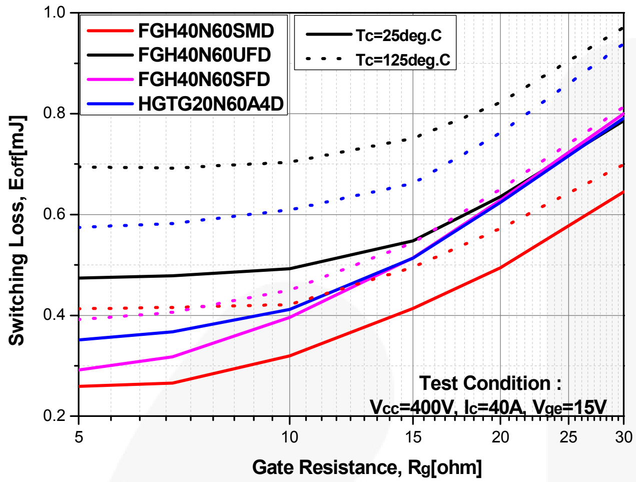

Figure 7. Turn-Off Loss E_O vs. Gate Resistance R_g

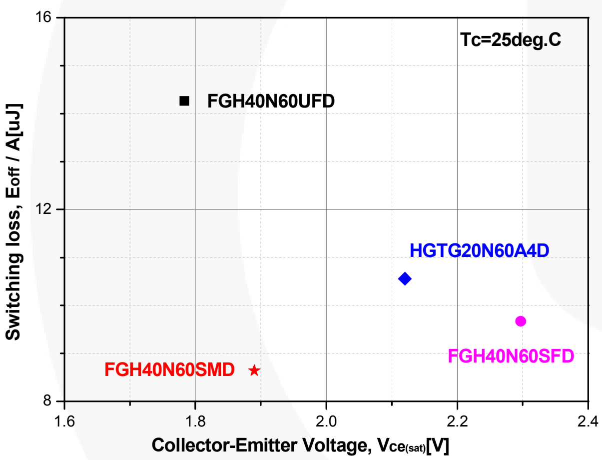

Figure 8. Turn-Off Loss E_{OFF} vs. Collector-Emitter $V_{ce(sat)}$

Figure 9 and Figure 10 show the IGBT operation waveforms of the evaluation board with R-load and welding load. These waveforms reveal that welding load consumes three times the current that R-load consumes. Therefore, it is important to select IGBT with suitable I_{cm} parameter to avoid saturation at peak-current condition.

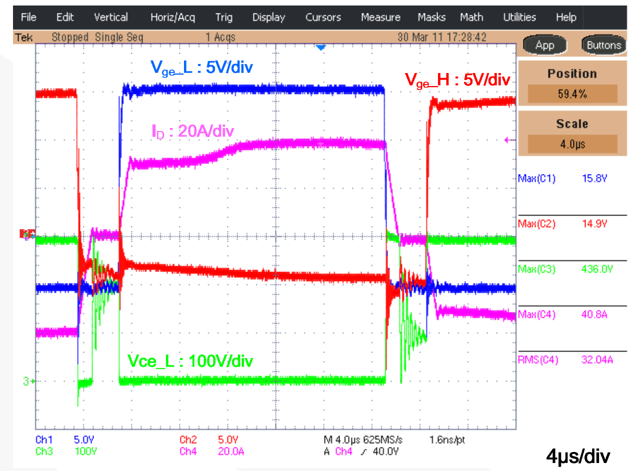

Figure 9. R-Load Test at I_{OUT}=14A

Figure 10. Welding-Load Test at 3.2 Pie Welding Rod

Figure 11 through Figure 16 show turn-off switching loss E_{OFF} measurement with welding load and R-load. Due to the leakage inductance and capacitor element, there is huge difference in E_{OFF} measurement compared with the JIG test result. The E_{OFF} of FGH40N60SMD shows the lowest loss from the test.

Figure 11. E_{OFF} Comparison Under R-Load (FGH40N60SMD)

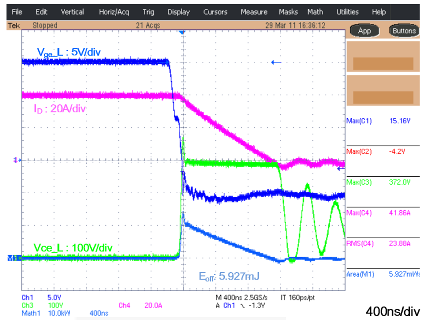

Figure 12. E_{OFF} Comparison Under R-Load (FGH40N60UFD)

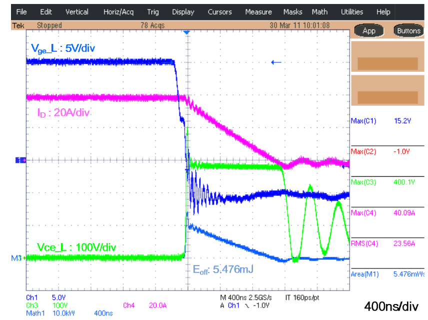

Figure 13. E_{OFF} Comparison Under R-Load (FGH40N60SFD)

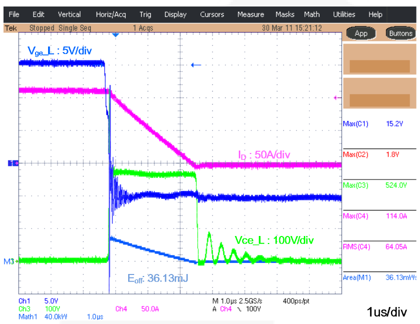

Figure 14. E_{OFF} Comparison Under Welding Load (FGH40N60SMD)

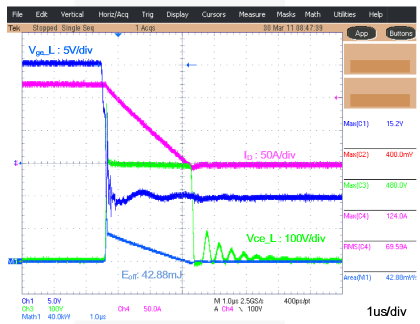

Figure 15. E_{OFF} Comparison Under Welding Load (FGH40N60UFD)

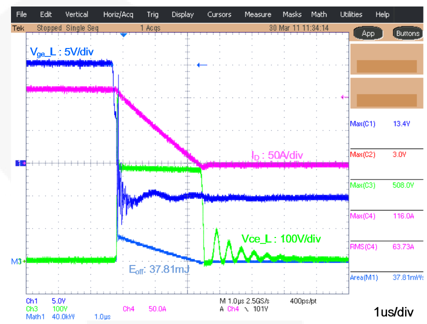

Figure 16. E_{OFF} Comparison Under Welding Load (FGH40N60SFD)

Rectifier Diode for Welding Machine

Fairchild Semiconductor provides five kinds of diodes that cater to different applications. Diodes with lower V_f, I_{rr}, and T_{rr} characteristics are ideal for welding applications; however, the common P_N theory dictates that the lower the V_f, the longer the T_{rr} and vice versa. A designer chooses a diode with a trade-off point where V_f and T_{rr} benefit the system efficiency the most. The following figures show performance comparisons for 600V/8A diodes from each Fairchild Semiconductor diode technology.

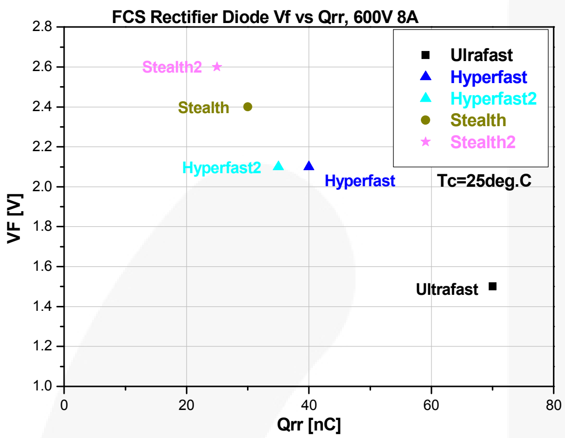

Figure 17. V_F vs. Q_{rr} Trade-Off

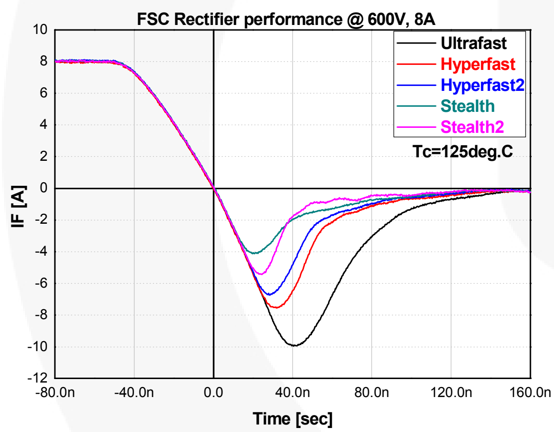

Figure 18. Reverse Recovery Performance

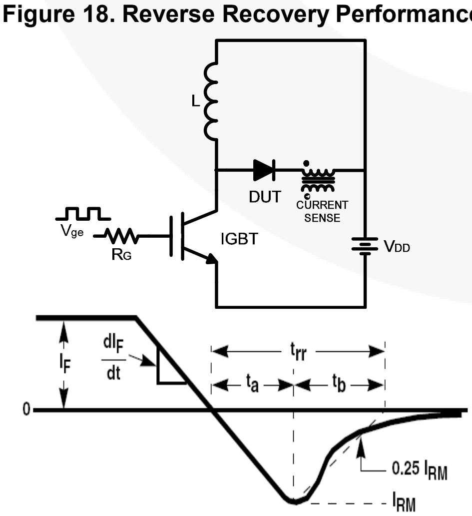

Figure 19. Test Circuit and Waveforms

$$Q_{rr} = \frac{1}{2} \times I_{rr} \times t_{rr} \qquad (10)$$

Generally, the rectifier diode of welding machine has higher conduction loss than reverse recovery loss. Therefore, the diode V_F value is more critical for a welding application. For this reason, ultra-fast diode FFA60UP30DN (30A dual diode) is used for this evaluation board. Three diodes are used in parallel for each tap of transformer to lower the V_F.

The figures below show the performance of diodes used in single and parallel configuration. Although the reverse recovery loss increases, V_f is reduced with parallelized diodes and better thermal performance can be expected. Designer caution is required for parallel diode application to ensure that the air flow does not cause unbalanced current conditions, as the V_f of diode tends to decrease when the temperature rises.

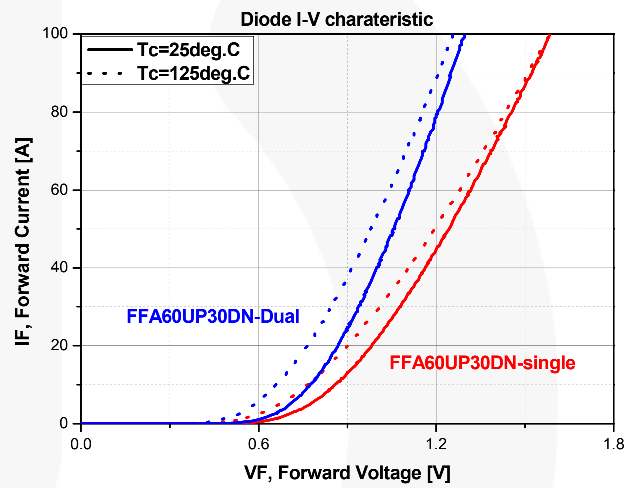

Figure 20. Diode I-V Characteristic

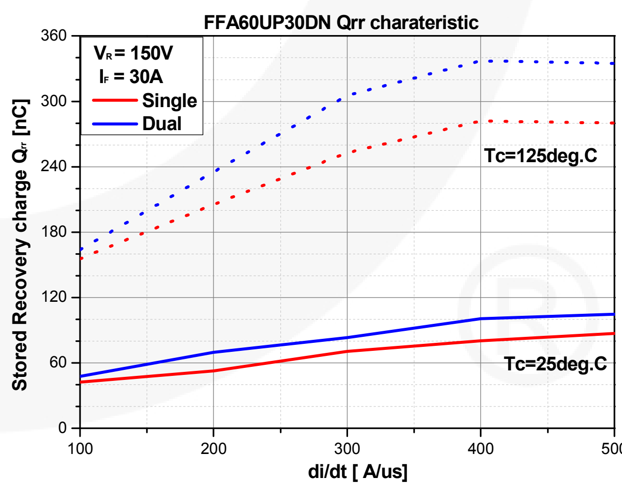

Figure 21. Stored Recovery Charge Q_{rr} vs. Diode Current Slop di/dt

Figure 22 shows the diode switching loss when the board is operating at 20KHz. The conduction loss is about 336μJ, while the reverse recovery loss is only about 4μJ.

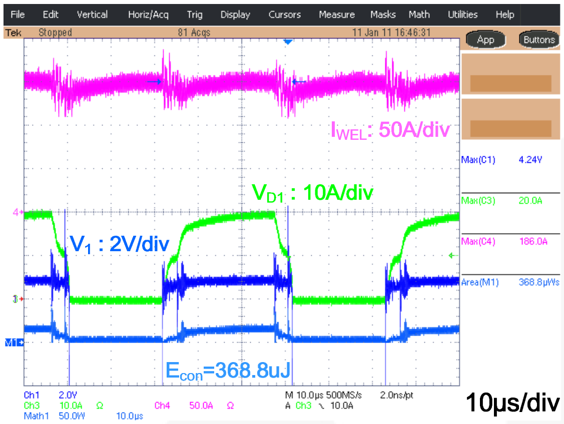

Figure 22. Diode Conduction Loss During Welding

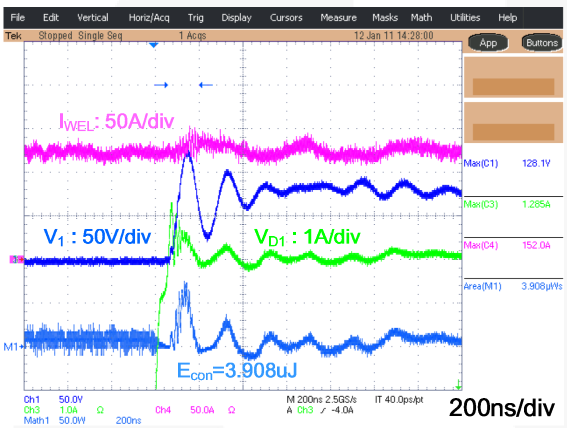

Figure 23. Diode Reverse Recovery Loss During Welding

Avalanche occurs in a diode with sudden current increase when the voltage across a diode exceeds the specified V_r value. Here, the area ($V_{r(AVL)}$*I_{sa}) that diode does not fail is called avalanche energy and the equation is:

$$E_{AVL} = \frac{1}{2} \times L \times I_{sa}^{2} \times [\frac{V_{r(AVL)}}{(V_{r(AVL)} - V_{DD})}] \quad (11)$$

$$\therefore Q_1 = IGBT(BV_{ces}) > DUT(V_{r(AVL)})$$

Avalanche energy is occurred by the second output inductor, as shown in the equation. The immunity capability is proportional to the inductance. The inductance of a welding machine is generally designed as small value as several μH, and diode immunity capability value becomes an important factor for choosing a device.

Avalanche can occur in the secondary-side rectifier of a welding machine; especially when the welding work is completed and the reverse pass occurs by inductor. Immunity capability is measured using a circuit as shown in Figure 24 with the graph in Figure 25 showing avalanche energy test result waveform.

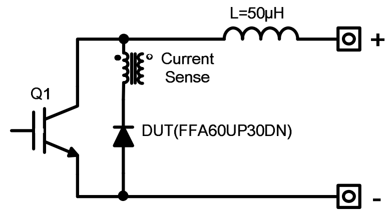

Figure 24. UIS Test Circuit

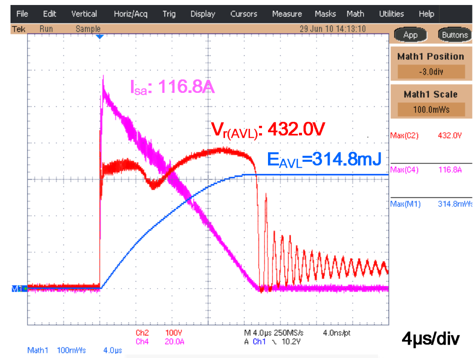

Figure 25. FFA60UP30DN Immunity Capability

Blocking Capacitor

For half-bridge topology; if the two series DC bank capacitors or the turn-on time of IGBTs are not matched, DC flux occurs in the transformer. The accumulated DC flux eventually drives transformer into saturation. The IGBTs can be destroyed by sharply increased current due to the saturated transformer. To block the DC flux in the transformer core, a small DC blocking capacitor is placed in series with the transformer primary. The value of the DC blocking capacitor is given by:

$$C_{blocking} = \frac{D_{max} \times I_D}{\Delta V_P \times F_{sw}} \quad (12)$$

where ΔV_P is the permissible droop in primary voltage due to the DC blocking capacitor.

Below is the waveform of the transformer primary current. The current abruptly rise due to the saturated transformer caused by DC bias.

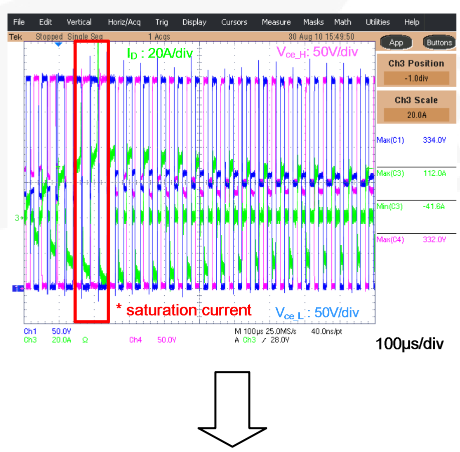

Figure 26. IGBT Saturation Current

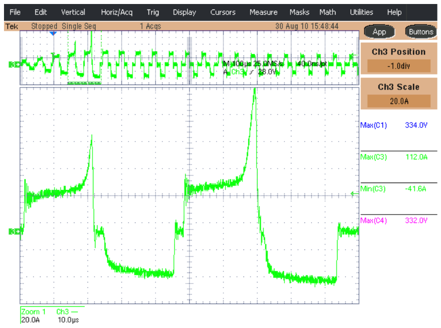

Figure 27. Zoom of IGBT Saturation Current

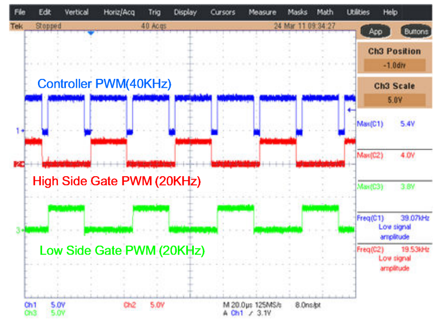

Figure 28. PWM Convert 40KHz to 20KHz

Power Supply Structure and Design

MOSFET integrated IC FSMG0465R is used for power supply. Its simple peripheral circuit and 66KHz switching frequency reduce the PCB and transformer size. In addition, the efficiency of power has been maximized by the minimization of idling power that can be achieved from low power consumption in Standby Mode (<1W at 230V_{AC} input at 0.5W load). There are transformer type and SMPS type for the substitute power supply. SMPS type, compared to linear transformer type, has stable output power over the influence of input serge, sag, and noise; and minimal design of size and weight is possible. In addition, transformer type has a fixed input voltage, whereas SMPS has a wide input voltage range of 80V_{AC}~264V_{AC}, which can be used for free voltage welding machine without additional operation. However, it is necessary to consider counter measures for noise as the switching noise may affect main inverter. For further information about Fairchild Power Switches (FPS™), refer to the application note AN-4150 found at: *http://www.fairchildsemi.com/an/AN/AN-4150.pdf*.

Controller Design

The evaluation board uses PIC16f716 for the control circuits. PIC16f716 controller consists of four ports of 8-bit AD converter and one port PWM timer with 9-bit, 40KHz resolution. To generate two PWM pulses from one PWM signal, a D flip-flop and an AND gate are used to divide the 40KHz PWM into 20KHz PWM pulse *(see Figure 28)*.

Gate Driver Design

A transformer, opto-coupler, or HVIC can be used for a gate driver. Necessary supply voltages for different gate drivers are listed as:

- HVIC Driver: +15V, 0V (High and Low Gate),
  + 24V, 0V (Output Detect), +5V, 0V (Controller)

  Otpo-Coupler Driver : +15V, 0V, -5V (High-Side Gate), +15V, 0V, -5V (Low-Side Gate), +24V, 0V (Output Detect), +5V, 0V (Controller)

  Pulse Transformer: +24V, 0V (Output Detect),
  +5V, 0V (Controller)

The opto-coupler and transformer provide isolation between the control circuit and IGBTs. However, a transformer may cause half bridge cross-conduction due to the offset voltage of gate-pulse dead-time stage. Through an by integrated high-voltage MOSFET, the HVIC provides isolations between the control circuit and the high-side IGBT. This does not work with negative supply voltage. A negative supply voltage is necessary for HVIC during a fast commutation in a half-bridge topology to prevent dv/dt shoot-through. The shoot-through is linked to a fast voltage variation across one of the two IGBTs. A current flowing through collector-emitter capacitor can bring the gate voltage of an IGBT, when turned off, to rise due to Miller effect and obtain a cross conduction into the leg.

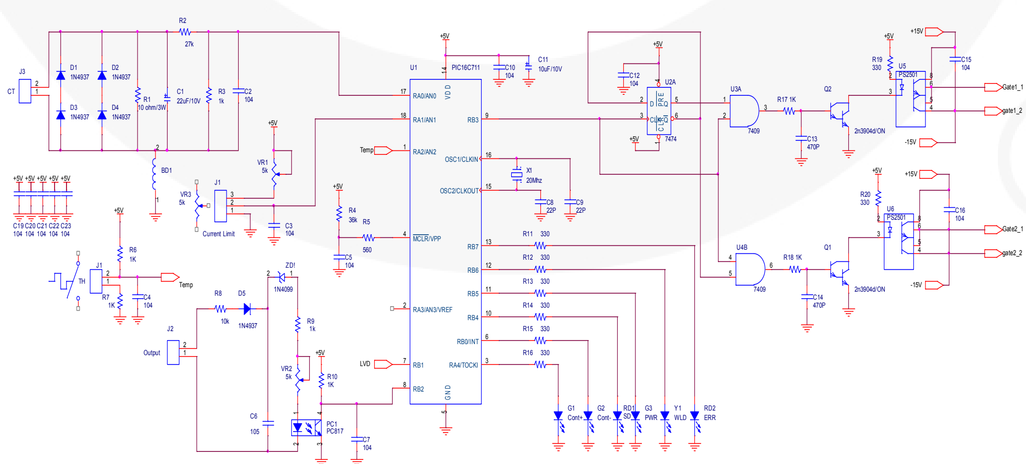

Figure 29. Controller Schematic

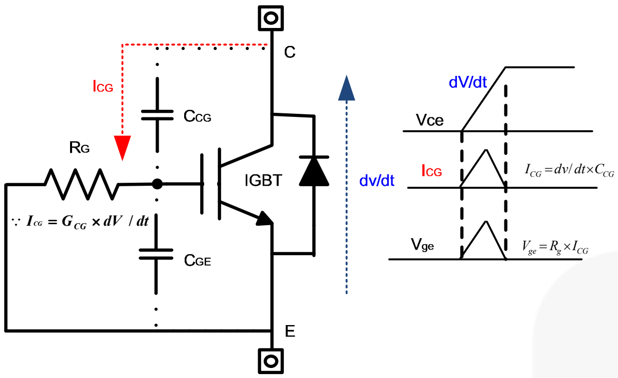

Figure 30. Effect on dv/dt to V_{GE}

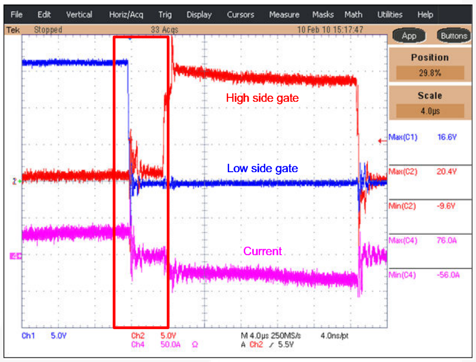

Figure 31. Effect on dV/dt to Gate Wave

Based on the above considerations, an opto-coupler is used for this welding machine evaluation board. Figure 32 and Figure 33 present the gate waveforms captured with different types of gate drivers. It is clear the opto-coupler is the best choice for this welding application.

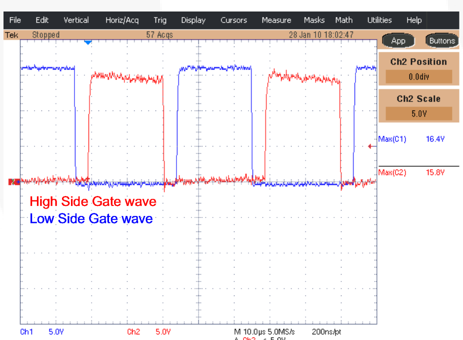

Figure 32. HVIC Gate Waveform

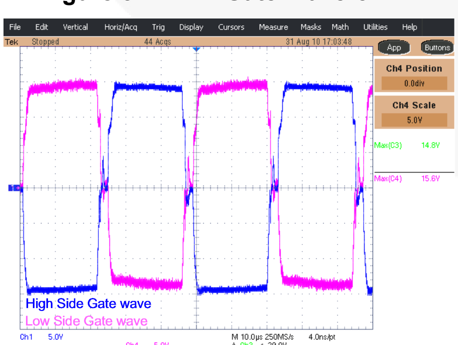

Figure 33. Transformer Gate Waveform

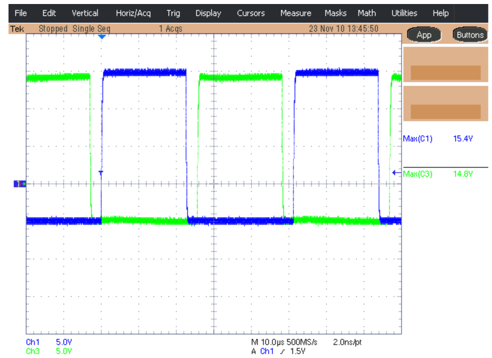

Figure 34. Opto-Driver Gate Waveform

DC Reactor Design

DC reactor helps stabilize arc current during welding operation. As DC reactance grows, specter occurs smaller. On the contrary, if the mobility of arc is lowered and the L_{DC} value gets too large, it is harder to create an arc. Therefore, an appropriate reactor choice is necessary. If considering V_{OPEN} as output no-load voltage, V_{WEL} and I_{WEL} as rated output voltage or current; the maximum L_{DC} value can be obtained from the equation:

$$\because L_{DC} \leq \frac{-R \times t_R}{In\left(1 - \frac{I_{WEL}}{V_{open}} \times R\right)} \qquad (13)$$

where R is the equivalent resistance of welding load and T_r is the rising time of the output current from 0 to the rated current. Once the maximum L_{DC} value is obtained; the optimum L_{DC} value can be finalized through testing.

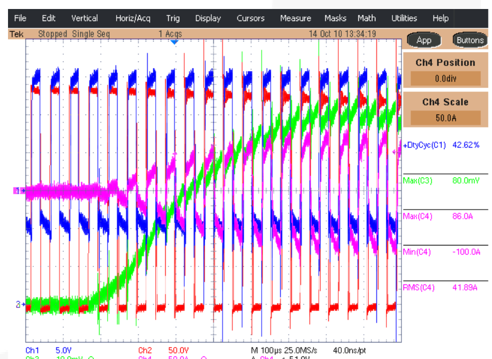

Figure 35. Soft-Start During Welding Operating

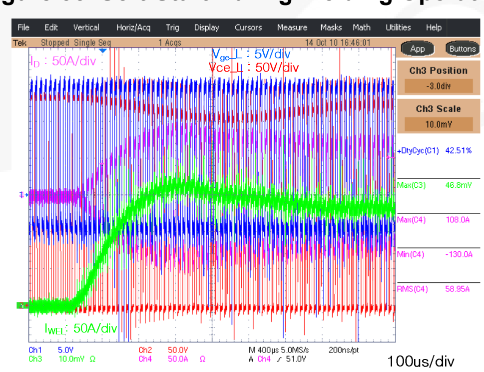

Figure 36. Welding Operating

Conclusion

Better performance is expected for a DC-ARC welding machine when the inverter devices are selected properly based on the inverter topology and its switching frequency. This article presents a power device selection guide for a half-bridge welding machine application.

When to chose an IGBT, its $V_{ce(sat)}$, E_{off} turn-off loss, gate driver resistor, and I_{cm} characteristics are the critical factors that require a designer's careful attention.

For the secondary -side rectifier diodes, it is important to determine which is the dominant factor, V_f or reverse recovery loss, based on system switching frequency. The evaluation board uses three ultra-fast diodes (FFA60UP30DN) in parallel for each tap of the transformer to lower the V_f and therefore the conduction loss.

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Related Resources

FGH40N60SMD — 600V, 40A Field Stop IGBT

FFA60UP30DN — 300V Ultrafast Recovery Power Rectifier

FSGM0465R — SMPS Power Switch, 4A, 650V (Green)

Appendix — Circuit Diagrams

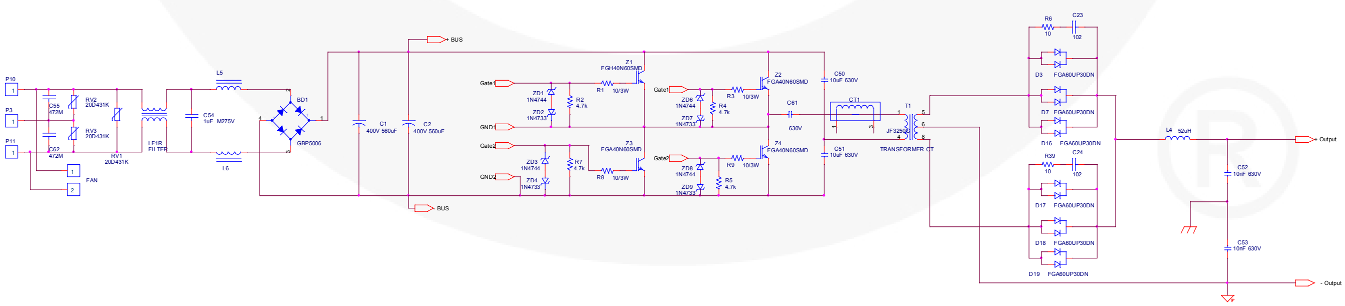

Figure 37. Main Circuit

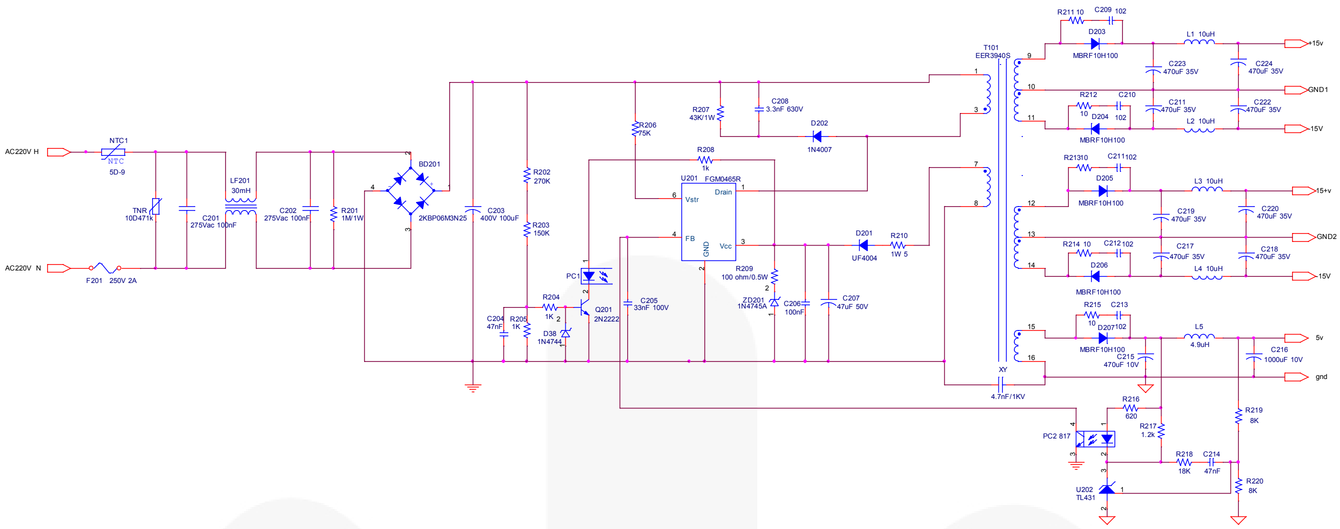

Figure 38. Auxiliary Power Supply

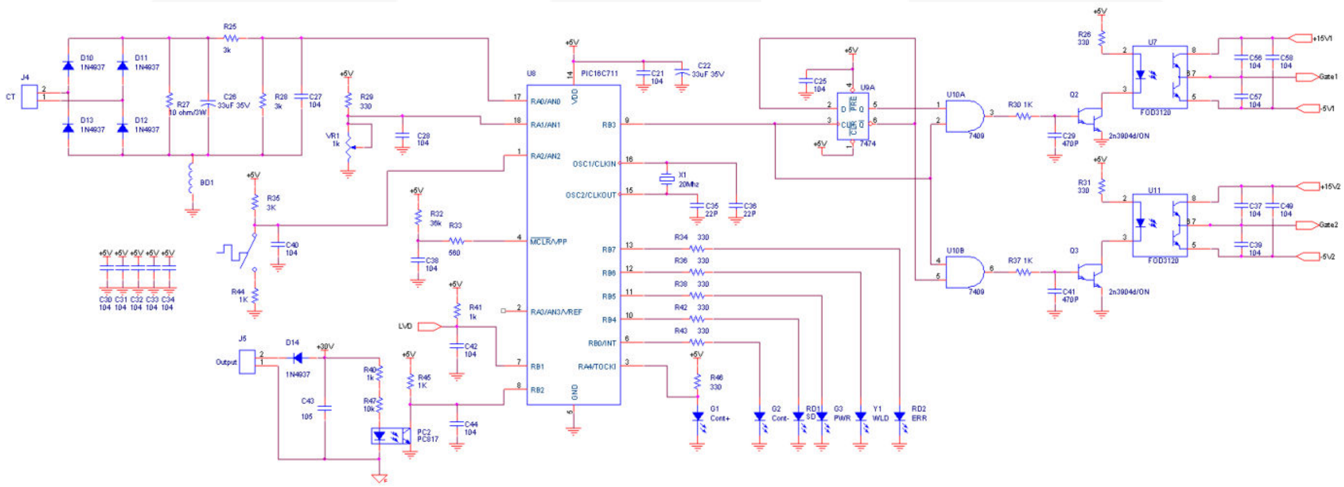

Figure 39. Controller

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