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Generation III Aluminizing Power Supplies – A Test Report

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Abstract: *The MMT Aluminizing power supply, as originally designed, is fragile, expensive, and has irreplaceable components. In 2004, MMT Engineering began a study project to find an acceptable replacement for that system. This report documents acceptance testing a candidate supply performed at the UA Sunnyside aluminizing facility.*

Historical Background

The MMT Aluminizing system consists of 200 tungsten heating filaments arranged in semi-concentric circles attached to a fixture inside the bell jar assembly. The filaments are bussed with aluminum bars into 10 electrical circuits that share a common return line. Ten power supplies are connected in a series/parallel combination so each power supply fires 20 filaments at a time. The interconnection of power supplies is arranged so that 5 of the power supplies have output current opposing the current from the other 5, eliminating all current flow in the common return line, known as the neutral bus.

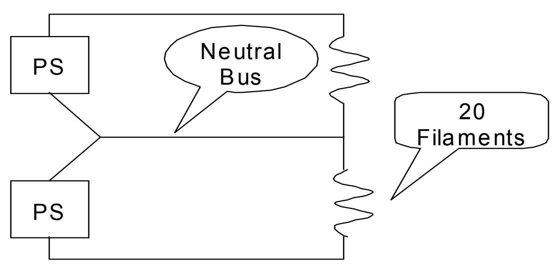

Figure 1 Typical Filament Circuit (1 of 5)

Karl Harrar, an MMTO engineer, was the lead designer for the original system. Given the high currents required for the aluminizing at low voltages, the system power supply was chosen to be truck starting batteries (Group 29 size, 880 cold-cranking amps), which gave high current density for a relatively small amount of space required. Two batteries are wired in series, giving a 24V bus for the power supplies. At 24V, very little loss in the power supply and cabling could be tolerated to meet the output current requirement. This led to the selection of low-loss MOSFETs as the switching elements in the power supply. A PWM (pulse-width modulation) circuit was designed to control the output duty cycle based on integration of the output current measured by a shunt in series with each power supply (current-source control). The PWM setpoint is manually controlled by the coating operator during the coating process. The circuit initiates the PWM cycle by turning on the MOSFETs from a master clock, and allowing the shunt voltage to integrate. The resultant ramp signal is compared to the setpoint, and once the integrator output equals the setpoint, the MOSFETs were switched off and the integrators reset until the next clock pulse. In this way, each of the 10 circuits remain synchronized, and given the careful matching of the circuit impedances, resulting in equal power delivery to each filament circuit while keeping all currents in the neutral bus cancelled.

Experience in the failure of the first attempt to coat the MMT primary highlighted a critical error in the system design: a current source, when connected to a tungsten load (or any load with a positive resistance-temperature coefficient), will run away. When a certain current is commanded, the PWM circuit will widen the output pulse width as the circuit resistance increases to maintain the given current. The increasing PWM duty cycle delivers more and more power to the load, resulting in thermal runaway. This is exactly what happened: the MMT mirror ended up coated with a mixture of aluminum, copper, and even some tungsten.

We redesigned the system as a voltage source and eliminated the failure-prone shunts from the circuit. We then fed back the voltage appearing at the bell jar feedthroughs and rescaled the integrator slope to match the circuit output and setpoint variation. Our next attempt at coating went much more smoothly.

In the years since the original design, the manufacturer of the MOSFETs discontinued their production, and no acceptable alternatives have ever been found. These were fairly unique devices with high rated drain currents and low $R_{ds(on)}$. The maximum drain-source voltage for these units was only 60V; 90% of the system engineering went into generating protection circuits to clamp the inductive switch-off spike across the devices, which destroys them instantly. A significant amount of work has also gone into cooling them during the coating so that they remain inside their operating temperature range and don't fail prematurely. Large amounts of battery power are also wasted by the inefficient protection circuits.

In 2004, while preparing for the next coating, we decided to look at alternatives for our MOSFET switching system, due to the complete lack of spares and the known fragility of the power supply. To this end, much time was spent pursuing alternate MOSFETs (unsuccessfully), and considering using IGBTs as the switching device. Two different vendors, Powerex Semiconductor and Dynex Semiconductor, declined to pursue a custom IGBT design, mainly due to the high losses occurred in switching at a bus voltage of only 24V. We realized during this search that high currents and low voltages are commonly available in commercial arc-welders.

We then acquired a test unit from Lincoln Electric, a major manufacturer of welders, and took it to the UA coating facility at Sunnyside. This unit, a MIG welder supply (Lincoln V-350) was connected to a sample load of 20 filaments in the 18" bell jar and tested. We were disappointed to discover this unit barely supplied the power to bring the filaments up to the melting point, and not much more.

After looking over the data from this first failure and refining our circuit models, we identified another candidate power supply from a competing manufacturer, Miller Electric. This was a model 652 constant-voltage (CV) unit capable of 650A at 44V, well over our modeled power requirement. We acquired two units from Miller, along with some ancillary test equipment, and proceeded to test them at Sunnyside.

Sunnyside Testing

The 652s, as delivered, are designed to operate as welders in an industrial setting. Modifications were required to bring them to a state usable for aluminizing; they have an internal circuit that forces their minimum output voltage to 10V. This is so that an arc can be struck with a welding rod reliably without sticking to the work surface. However, the MMT load voltage during coating maxes out at about 14V (known from previous MMT coatings), and we wanted more control range. We changed the minimum output voltage on these two test units to 3.5V. We also built telemetry electronics to capture the output voltage, current, and power from the units during the test. The electronics also accept input from a standard Miller remote control to turn the outputs on and control the output voltage setpoint on both units.

Bill Kindred fabricated a test fixture that fits inside the 18” bell jar that holds a complete 20-filament circuit pair (40 filaments total). Each pair is powered from a welder supply, and is equivalent to 1 out of the 5 filament/power supply combinations required on the MMT bell jar, allowing us to test the system under controlled conditions.

Figure 2. Test Fixture Before Firing

The filaments were loaded with aluminum in the same manner as used in the actual aluminizing; wrapped tightly around the filament coils to eliminate shorts and cold spots when the aluminum melts and "wets" the filament.

To collect the data, we built two differential-amplifier front ends for each welder with analog signal isolation that passes the output voltage and current signals to a Measurement Computing PMD-1208LS connected to a laptop PC. The setpoint voltage is likewise transmitted to each welder with the same isolation and differential amplifier circuitry. A simple control GUI was written with SoftWire and Visual Basic to collect and present the data in real time, as well as write it to a file. The individual signals were scanned at 100Hz, with an average over 50 samples output as a data point. The total signal throughput is then 2Hz. We collected the system setpoint as a reference, as well. We plan to continue with the Softwire/Measurement Computing GUI environment, extended to 10 Welder I/Os for the final MMT system. We will collect welder output voltage/current, load voltage, and system setpoint for a total of 31 input channels.

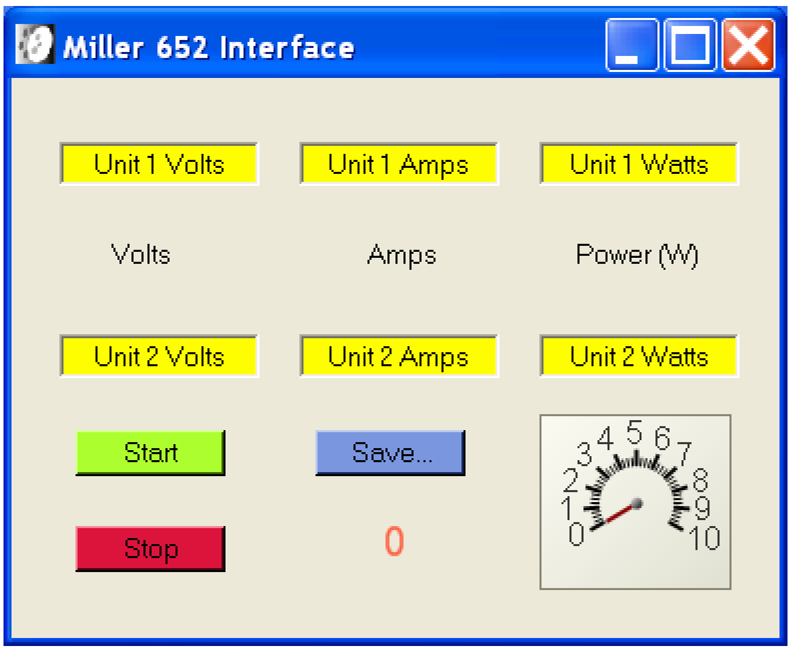

Figure 3. Miller Welder Data Collection GUI

For the first set of tests, we powered up the welders on the brand-new filaments completely cold, then after shutting down and checking things over, powered again and increased the setpoint until the filaments wetted. We then stopped and checked things over again, then proceeded to try to go for evaporation. At this point, the diesel generator began to have problems with its output voltage regulation, and went over/under voltage. The Miller welders handled the power variations without hiccupping; they simply shut themselves down when the power fell out of specification. During this period, we also happened to increase the setpoint to a point beyond the welders' full output current specification – nearly 870A! The welders again survived the abuse, and after some tweaking on the generator, we went to full evaporation, shown in the data below:

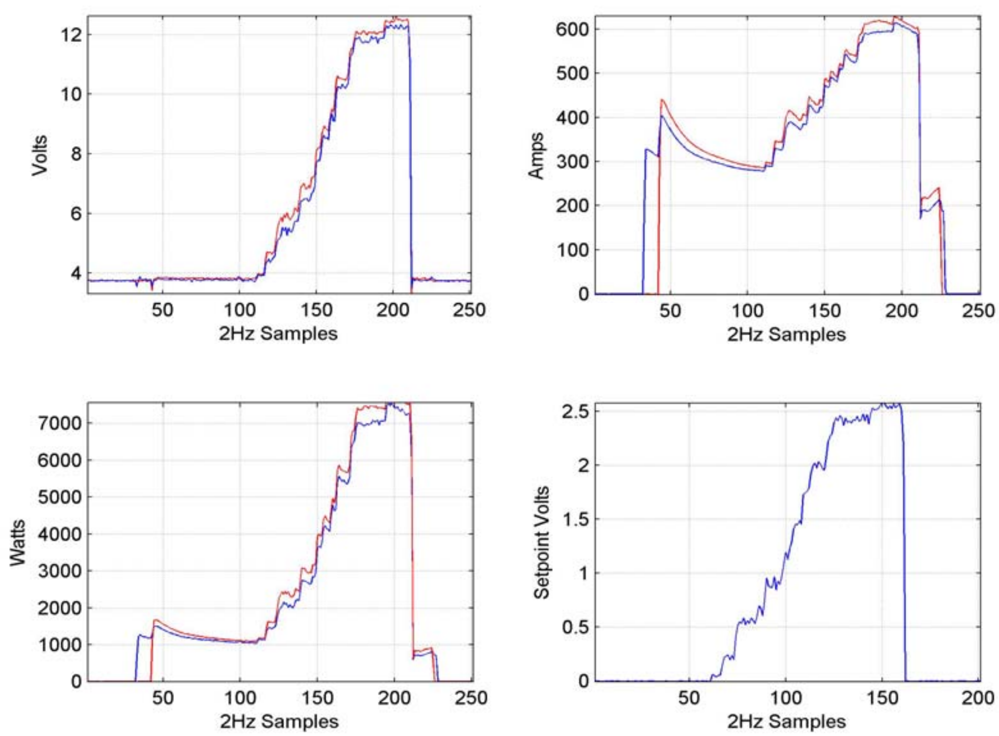

Figure 4. Sunnyside Test Run #1 Data

The delay in output current turning on between the two is due to manually enabling their outputs on the front panel switches to avoid bogging the generator down. We also made an effort to keep setpoint demands below the 650A rated output current of the welders.

A few interesting items are worth pointing out on the graphs above:

1. We never demanded more than 25% of the available setpoint swing (10V).
2. The output current overshoots and settles to a lower value when the setpoint is unchanged. This is consistent with the power heating the thermal mass of the

filaments and then radiating the input power away according to the Boltzmann Radiation Law, as suggested by our models.

3. We remained well within the welder output rating during the entire time. The aluminum was vaporizing at an enormous rate at the upper end. During an actual coating, we would probably not drive the filaments this hard.

Figure 5. Test Fixture After Firing

As can be seen above the filaments show nearly complete evaporation of the aluminum load, with some droplets and blobs remaining. The filaments at this point have a thin layer of aluminum and have had heat stress, and so are now much more brittle and lower resistance than before.

For our next step, we decided to clean the vacuum equipment up and reload the filaments with slugs. This is a worst-case scenario, as this would only be done in case of a coating failure and a need to retry immediately, without installing freshly loaded and wrapped filaments. With this arrangement, the aluminum is folded up across the filament coils instead of being wrapped around the filament loops. The aluminum is then shorting out most of the length of the filament and it will develop hot ends and a cold center, risking drips of molten aluminum and filament breakage due to the additional stress on the brittle centers. The combination of the thin wetted coating of aluminum from the previous firing and the shorted coils present the lowest possible resistance load to the welders.

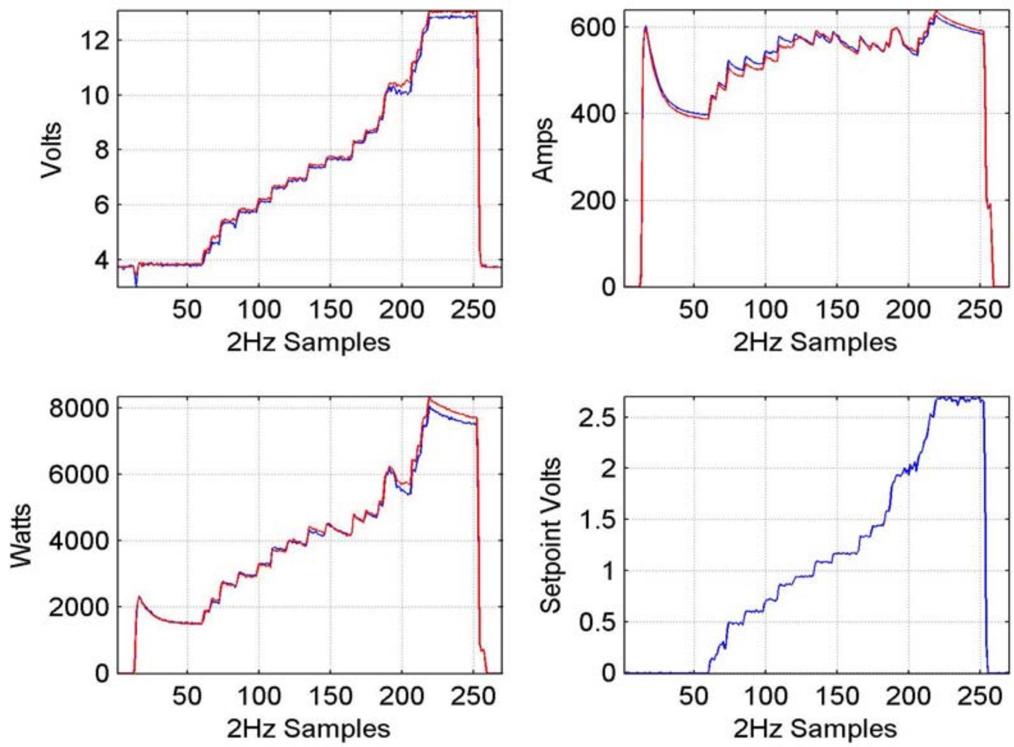

Figure 6. Sunnyside Test Run #2 Data

As can be seen here, we again remained within the welder ratings, but the load required almost 1kW more power than with aluminum wrapping the coils. The welder output also dipped to zero volts when turned on as well, but held up to the load and delivered the demanded output. The filaments again completely evaporated their aluminum loads, except for the expected drips and blobs here and there.

Conclusions

The Miller 652 welders have proven to be robust, easy to set up and use, and of sufficient power output to drive the MMT aluminizing load. We discovered during this series of tests:

1. The cold load minimum resistance is of order 10mΩ. Any lower than this and we run the risk of demanding more current than can be supplied by the welders at the cold starting temperatures.
2. The low-end output voltage of 3.5V is a bit too high; we get a little more heating than we want for good preheating control. We will set them up in future for a 2.5V minimum output.

3. Cable resistance is a significant part of the cold-circuit load. The filament circuit alone measures 2.5mΩ. At the welder terminals, this becomes 10mΩ. This implies 80% of the output power developed when cold is lost in the welder leads!
4. The hot-circuit resistance is of order 20mΩ. The cable resistance is still a fair amount of the load.
5. The room required to install the welders at the MMT will certainly lead to unequal cable lengths. This means we must have an equalizing circuit to force the load voltages at the bell jar to the same level to help guarantee even coating on the mirror. This is not difficult, as we have done this already for the old switching electronics.
6. When going toward evaporation, we can get up near the rated output current of the welders. We will have to implement a clamp circuit to clip the welder setpoints so the coating operator cannot demand a potentially damaging amount of power.
7. Even with unequal cable lengths and output clipping, more than enough power is available from the welders to drive the MMT filaments.
8. A fair amount of facility electrical service work will be required to power up the welders. We will need 480VAC three-phase service at 500A to meet the rated welder input power.
9. The welders must have their chassis isolated from one another and other grounds to safely power the neutral bus.
10. The coating operator will need a remote control with less-sensitive swing to avoid accidentally going over the evaporation rate desired (for once, we have too much power available!).