A CONTROL SCHEME FOR HIGH POWER DENSITY MULTI-UNIT POWER SUPPLIES

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Abstract

A control scheme for high-power density multi-unit constant current power supplies based on compact high-speed PLC is proposed. The scheme adopts a hybrid analog-digital dual-loop control approach. The power supplies utilize mature commercial customized modules with internal analog voltage control loop, while a single PLC constructs the current feedback loop for multiple power modules. This scheme has been successfully applied to multi-unit klystron solenoid power supplies and industrial Linac power supplies, achieving very high power density, simple interlocking and communication interfaces, and high operational reliability.

INTRODUCTION

In particle accelerators, microwave tubes, and other beam devices, multi-unit solenoid constant current power supplies are widely used. Typically, each coil of the focusing magnet is powered by an independent power supply. When the number of coils is large, the number of power supplies increases accordingly, leading to larger overall volume and weight, as well as more complex communication interfaces and interlocking circuit. This is unfavorable for achieving miniaturization of the entire accelerator system and improving its simplicity and reliability.

We adopt a hybrid analog-digital dual-loop control method [1], where power units use mature and commercially customized modules as internal analog voltage control loops. In [1], the stability of the outer current loop is provided by a Proportional-Integral compensation circuit, while in our scheme, a compact high-speed PLC is used to construct the current feedback loops for multiple power modules.

The internal analog loop of the power modules offers high bandwidth and fast response speed, effectively suppressing fast disturbances such as power grid fluctuations. The outer loop utilizes a digital controller to form a digital feedback current loop, which compensates for slow variations caused by temperature changes and load variations. The combination of both loops enables excellent dynamic performance and high static stability.

Unlike the dedicated digital controller solutions in [2] or the large-scale system designs in [3–5], our scheme prioritizes compactness and convenience by leveraging commercial modules, following a design similar to [6] but extended to multi-unit PLC-based control.

This scheme has been successfully applied to multi-unit klystron solenoid power supplies and industrial Linac power supplies. It achieves a very high power density, along with simplified interlocking and communication interfaces, greatly simplifying the design of the upper-level control network. The entire power supply system exhibits very high operational reliability.

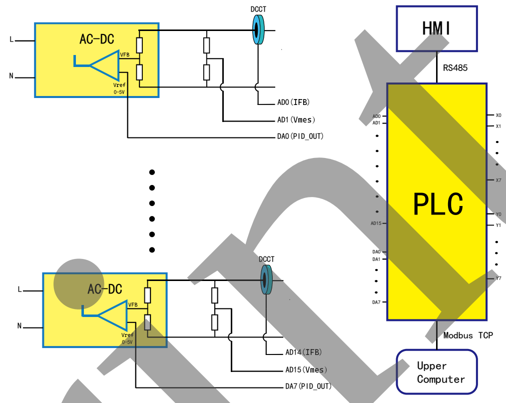


Figure 1: Overall Control Scheme.

DESIGN ARCHITECTURE

Overall Control Scheme

As shown in Fig. 1, the left side shows a group consisting of 8 commercial regulated power modules (each with a rated power of 1000 W), all uniformly installed within the same chassis. All of the eight modules are controlled by a single compact high-speed PLC. Current and voltage signals from the load side of each power supply are sampled and input through ADC channels (A0–A15, totaling 16 channels) of the analog input module GL20-8AD.

Inside the PLC, a closed-loop compensation control program based on the PID algorithm is executed, with a digital control sampling period of 1 ms for the system. The deviation between the current setpoint and the actual feedback value is processed by PID calculation to generate 8 channels of control voltage signals (0–5 V). These signals are sent to the regulation ports of each module via channels DA0–DA7 of the GL20-8DA analog output module, thus achieving stable control of load currents.

Power Module

The commercialized industrial power module is UHP-1000-48, made by MEAN WELL ENTERPRISES CO.,LTD. The principle of the power module is illustrated in Fig. 2. The main circuit of the power module adopts a two-phase interleaved forward converter topology. Its front stage consists of a dual interleaved Booster-type PFC circuit, achieving a

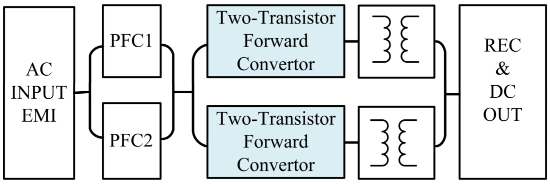


Figure 2: The principle of the commercialized industrial power module.

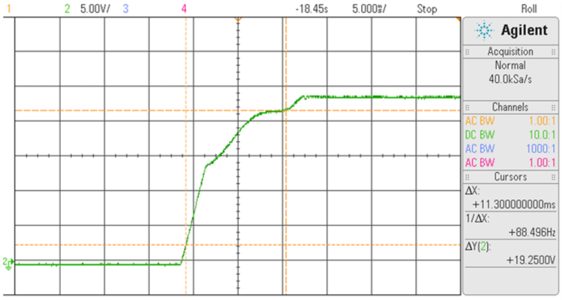


Figure 3: Step response of the power module.

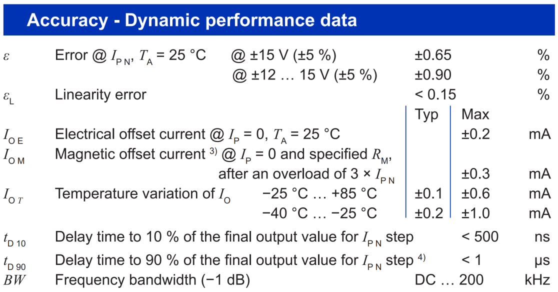
power factor close to 1. This reduces harmonic interference from the power supply, minimizes disturbance to the grid, and supports a wide input AC voltage range. The PFC stage converts AC 100 V–240 V to DC 400 V, which is then fed to the forward converter.

The forward converter operates in PWM closed-loop voltage regulation mode at a switching frequency of approximately 100 kHz. A high-voltage transformer at the output stage steps the voltage down to the required low level, followed by rectification and filtering to produce the final desired DC output voltage.

The power modules should have a step response of 10 ms level at full load, which is required to compensate for input line changes and transients. Figure 3 shows the step response of the power module in full-load conditions. When the set voltage steps up from 0 to 5 V, the rise time of the module's output voltage is approximately 11 ms.

PLC and Analog I/O Modules

- PLC: The Inovance EASY series PLC is a compact high-performance PLC with a tightly designed host structure (83 × 90 × 95 mm). It features 16 built-in input points and 14 output points. It supports RS485, Ethernet, CAN and EtherCAT interfaces, and the Ethernet interface supports Modbus TCP protocol communication.
  We select the Ethernet interface with the Modbus TCP protocol for upper control communication.
  In the actual control scheme, the PLC scan rate is set to 1000 Hz.
- Analog Modules: The GL20-8AD and GL20-8DA blade-style expansion modules provide 16-bit resolution. The conversion time of each channel is 60 µs.
- Current Sensors: LA55 is a widely recognized closed-loop Hall effect current transducer. The dynamic performance data of LA55 are shown in Fig. 4.



Accuracy - Dynamic performance data

ε	Error @ I_{PN}, T_A = 25 °C	@ ±15 V (±5 %)	±0.65		%
		@ ±12 … 15 V (±5 %)	±0.90		%
ε_L	Linearity error		< 0.15		%
			Typ	Max	
I_{OE}	Electrical offset current @ I_P = 0, T_A = 25 °C			±0.2	mA
I_{OM}	Magnetic offset current 3) @ I_P = 0 and specified R_M, after an overload of 3 × I_{PN}			±0.3	mA
I_{OT}	Temperature variation of I_O	−25 °C … +85 °C	±0.1	±0.6	mA
		−40 °C … −25 °C	±0.2	±1.0	mA
t_{D10}	Delay time to 10 % of the final output value for I_{PN} step			< 500	ns
t_{D90}	Delay time to 90 % of the final output value for I_{PN} step 4)			< 1	µs
BW	Frequency bandwidth (−1 dB)		DC … 200		kHz

Figure 4: Dynamic performance data of the current sensor.

Figure 5: Chassis front panel.

Assembly and Commissioning

The assembled power supply is shown in Fig. 5, Fig. 6, and Fig. 7. The chassis is a standard 19-inch 4U height unit with a depth of 500 mm. It uses a three-phase AC input. Each module accepts single-phase power, allowing the three-phase lines (L1, L2, L3) and the neutral (N) to be evenly distributed among the eight modules.

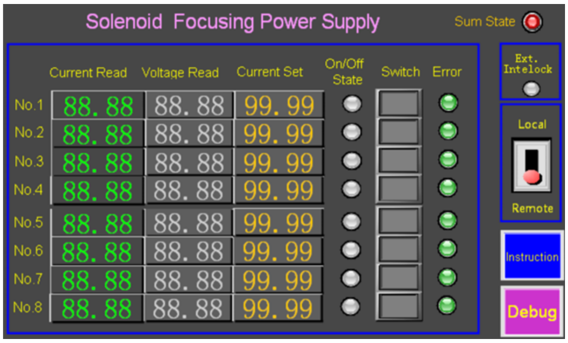
After assembly and commissioning, the output current stability was measured using a high-precision DCCT. Connected in series with the load, the DCCT sends the measured signal to the Agilent 34401A, a high-precision digital voltmeter, then read by a PC, and finally stored in CSV format. After a half-hour warm-up, continuous measurements were taken over 8 hours. Analysis of these data showed that the 8-hour stability of the power supply is under ±100 ppm, as in Fig. 8. Measurement equipment included:

- Electronic Load: Model IT8818, CR mode, $R = 0.8\,\Omega$, $I_{\mathrm{out}} = 20$ A.
- Digital Voltmeter: Agilent 34401A.
- DCCT: HITEC TOPACC, with 1 V / 1 turn corresponding to 100 A; the actual configuration uses 31 turns.

CONCLUSION

The high-power-density, multi-channel constant-current power supply utilizes mature industrial voltage-regulated modules and a PLC controller. It complies with relevant electrical and electromagnetic compatibility standards, is suitable for harsh operating environments, and offers a long service life. This solution enables the rapid construction of constant-current power supplies at different power levels. It provides simple, flexible communication ports and

Figure 6: Chassis rear view.



	Current Read	Voltage Read	Current Set	On/Off State	Switch	Error
No.1	88. 88	88. 88	99. 99	○	☐	●
No.2	88. 88	88. 88	99. 99	○	☐	●
No.3	88. 88	88. 88	99. 99	○	☐	●
No.4	88. 88	88. 88	99. 99	○	☐	●
No.5	88. 88	88. 88	99. 99	○	☐	●
No.6	88. 88	88. 88	99. 99	○	☐	●
No.7	88. 88	88. 88	99. 99	○	☐	●
No.8	88. 88	88. 88	99. 99	○	☐	●

Figure 7: HMI control interface.

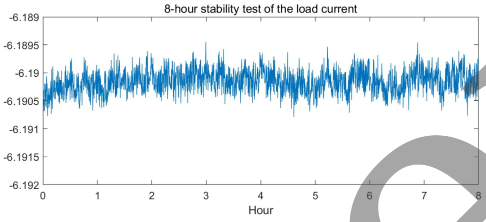


Figure 8: 8-hour stability test of the load current.

safety interlock interfaces, reducing hardware costs associated with communication equipment. This scheme has been successfully applied to accelerator multi-channel focusing coil constant-current power supplies, yielding excellent results.

The multi-channel power supplies present in this work utilize conventional, cost-effective current sensors and 16-bit AD conversion modules, which are sufficient for most general-purpose applications. For scenarios demanding higher current stability, higher precision current sensors and higher resolution AD converters-such as 24-bit modules-can be substituted. A prototype using a 24-bit AD module has already been built and tested, with results confirming that current stability below ±50 ppm can be achieved.

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