Appendix E: Electrical Standards

Contents

Appendix E: Electrical Standards and Wiring

E.1 Wire Sizing and Current Ratings

E.1.1 AWG (American Wire Gauge) Current Ratings

Copper Wire, 60°C Insulation (NEC Table 310.16), Chassis Wiring:

AWG Size	Diameter (mm)	Resistance (Ohms/km)	Max Current (A) @ 60°C	Typical CNC Use
24	0.511	84.2	3.5	Signal wires, limit switches, encoder
22	0.644	53.0	5	Control signals, relay coils, sensors
20	0.812	33.3	7.5	Limit switches, low-current 24V DC
18	1.024	20.9	10	24V DC power distribution, steppers (short runs)
16	1.291	13.2	13	Motor power (NEMA 17), 24V supplies
14	1.628	8.28	20	Motor power (NEMA 23), 48V supplies
12	2.053	5.21	25	Heavy motor power (NEMA 34), VFD output
10	2.588	3.28	40	Main power feeds, spindle motor
8	3.264	2.06	55	Large spindle VFD input/output

Note: For power transmission, derate by 80% for continuous duty (e.g., 14 AWG 16A continuous max).

90°C Insulation (THHN, THWN): Multiply current rating by 1.3× (e.g., 14 AWG 26A @ 90°C).

E.1.2 Metric Wire Sizing (IEC 60228)

Cross-Section (mm^2)	Diameter (mm)	Resistance (Ohms/km)	Max Current (A) @ 70°C	AWG Equivalent
0.5	0.80	39.0	3	~24 AWG
0.75	0.98	26.0	6	~22 AWG
1.0	1.13	19.5	10	~20 AWG
1.5	1.38	13.3	15	~18 AWG
2.5	1.78	7.98	21	~14 AWG
4.0	2.26	4.95	28	~12 AWG
6.0	2.76	3.30	36	~10 AWG

Cross-Section (mm^2)	Diameter (mm)	Resistance (Ohms/km)	Max Current (A) @ 70°C	AWG Equivalent
10.0	3.57	1.95	50	~8 AWG

E.1.3 Voltage Drop Calculation

Formula:

$$V_{drop} = \frac{2 \times I \times L \times R}{1000}$$

where: - V_{drop} = voltage drop (V) - I = current (A) - L = one-way length (m) - R = resistance (Ohms/km) from tables above - Factor of 2 accounts for return path

Example: 10A load, 20m cable run (one-way), 14 AWG copper

$$V_{drop} = \frac{2 \times 10 \times 20 \times 8.28}{1000} = 3.3 \text{ V}$$

On 48V system: 3.3V / 48V = 6.9% drop (borderline acceptable) On 24V system: 3.3V / 24V = 13.8% drop (excessive, use 12 AWG)

Maximum Recommended Voltage Drop: - **Power circuits (motors, VFD):** 3% max (2% preferred) - **Control circuits (24V DC logic):** 5% max - **Signal circuits (encoders, analog):** 1% max (minimize noise)

E.2 Electrical Standards and Codes

E.2.1 Voltage Classifications (IEC 60449, NEC)

Voltage Range	Classification	Insulation Requirements	Typical CNC Applications
<50V AC, <120V DC	Extra-Low Voltage (ELV)	Basic insulation	24V DC control, 48V stepper supplies
50-1000V AC, 120-1500V DC	Low Voltage (LV)	Double insulation or grounding	115V/230V AC mains, spindle motors
>1000V AC, >1500V DC	High Voltage (HV)	Special isolation, qualified personnel	Rare in CNC (plasma arc, EDM)

SELV (Safety Extra-Low Voltage): <=50V AC / <=120V DC with isolation from mains (transformer). Safe to touch under normal conditions.

Example: 24V DC control circuit powered by isolated 230V 24V transformer = SELV (safe).

E.2.2 IP (Ingress Protection) Ratings (IEC 60529)

Format: IP XY - X = Solid particle protection (0-6) - Y = Liquid ingress protection (0-9)

Rating	Solid Protection	Liquid Protection	CNC Applications
IP20	>12.5mm (finger)	None	Indoor electronics enclosure (standard)
IP54	Dust protected	Splash-proof	Machine control cabinet (light industrial)
IP65	Dust-tight	Water jet proof	Outdoor enclosures, washdown areas
IP67	Dust-tight	Immersion 1m	Sensors in cutting zone (waterjet, coolant)

Recommendation: - **Main control cabinet:** IP54 minimum (keep dust out, survive accidental liquid splash) - **Pendant/HMI:** IP65 (operator handling, coolant splash) - **Limit switches in cutting zone:** IP67 (continuous coolant exposure)

E.2.3 UL, CE, and Safety Certifications

UL (Underwriters Laboratories - North America): - UL 508A: Industrial Control Panels - UL 61010-1: Electrical Equipment for Measurement, Control, Laboratory Use

CE Marking (European Conformity): - Low Voltage Directive (LVD) 2014/35/EU: 50-1000V AC equipment safety - EMC Directive 2014/30/EU: Electromagnetic compatibility - Machinery Directive 2006/42/EC: Machine safety (includes E-stop, interlocks)

CSA (Canadian Standards Association): - CSA C22.2 No. 142: Process Control Equipment

Recommendation for DIY/Small Production: - Use UL-listed components (power supplies, circuit breakers, contactors) - Follow NEC/IEC wiring practices - CE marking not required for single machines (own use), but recommended for sale in EU

E.3 Power Distribution and Protection

E.3.1 Circuit Breaker Selection

Thermal-Magnetic Circuit Breakers:

Rating (A)	Trip Curve	Magnetic Trip (A)	Applications
C-Curve (Standard)	5-10×	50-100A @ 10A breaker	General CNC circuits, motors
D-Curve (Motor)	10-20×	100-200A @ 10A breaker	Inductive loads, VFD input, high inrush

Sizing: - **Continuous load:** Breaker rating >= 1.25× max continuous current - **Motor circuits:** Breaker rating = 2.5× motor full-load current (FLC) typical

Example: 2.2 kW spindle motor, 230V single-phase - FLC = 2200W / 230V / 0.85 PF = 11.2A - Breaker: 11.2 × 2.5 = 28A use 30A D-curve breaker

E.3.2 Residual Current Device (RCD) / GFCI

Purpose: Detect ground fault (leakage current), trip to prevent electrocution.

Types: - **Type AC:** Detects AC fault current (standard, lowest cost) - **Type A:** Detects AC + pulsating DC (VFD compatible) - **Type B:** Detects AC + DC (high-frequency drives, medical)

Trip Current: - **30 mA:** Personnel protection (required on circuits with portable equipment, operator contact) - **100-300 mA:** Fire protection (main panel)

Recommendation for CNC: - **30 mA Type A RCD** on operator circuits (pendant, HMI, 115V outlets) - VFDs may cause nuisance tripping with RCD (use Type A or B, or isolate VFD on separate circuit without RCD)

E.3.3 Fuses vs. Circuit Breakers

Device	Response Time	Reusability	Cost	Best For
Fast-Blow Fuse	<0.001s	Single-use	$	Semiconductor protection (drivers, PSU)
Slow-Blow (Time-Delay) Fuse	0.1-10s	Single-use	$	Motor circuits (tolerates inrush)
Circuit Breaker	0.01-1s	Reusable	$$	Panel distribution, easy reset

Fuse Sizing: - **Electronics (PSU, drivers):** 1.5× max continuous current, fast-blow - **Motors (VFD, steppers):** 2.0× FLC, slow-blow

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E.4 Grounding and Shielding

E.4.1 Grounding Schemes

Single-Point Ground (Star Ground): - All grounds connect to one central point (typically main panel ground bus) - Prevents ground loops (multiple return paths causing noise) - **Recommended for CNC controls**

Multi-Point Ground: - Grounds connected at multiple locations (chassis, cabinet, earth) - Lower impedance at high frequencies - Used for RF/EMI shielding (enclosure bonding)

Grounding Conductor Sizing (NEC):

Circuit Breaker Size (A)	Minimum Ground Wire (AWG)
15-20	14
30	10
40-60	10
100	8
200	6

Grounding Recommendations: - Motor frame ground: Same gauge as power conductors - Chassis ground: 14 AWG minimum to earth ground (green/yellow wire) - VFD PE (protective earth): Same gauge as input power, <0.1Ohms to cabinet ground

E.4.2 Shielded Cable and Grounding

Shield Types: - **Foil shield (aluminum polyester):** 85-90% coverage, lightweight, low cost - **Braided shield (tinned copper):** 90-98% coverage, flexible, higher cost - **Spiral/serve shield:** 80-85% coverage, very flexible, low coverage

Shield Grounding: - **Single-end grounding:** Shield grounded at source (driver) only, prevents ground loops - **Both-ends grounding:** Shield grounded at both source and load, better for high-frequency EMI (>1 MHz)

CNC Signal Recommendations: - **Encoder cables:** Shielded twisted-pair, shield grounded at driver end only - **Stepper/servo motor cables:** Shielded, both ends grounded (motor frame + driver PE) - **Analog signals (0-10V, +/-10V):** Shielded twisted-pair, single-end ground, differential if possible - **Limit switches:** Unshielded OK for short runs (<3m), shielded for long runs or high-noise environments

E.4.3 Cable Routing and Separation

Separation Distances (IEC 61800-3):

Cable Type	Separation from Power Cables (cm)
Low-voltage power (<50V DC, signal)	30 cm minimum
Shielded signal (encoder, analog)	15 cm minimum
Motor power cables (unshielded)	50 cm from signal cables
High-frequency VFD output	100 cm from sensitive signals

Cable Tray/Routing: - Separate trays for power and signal (or metal divider in same tray) - Cross power/signal cables at 90° (minimize coupling) - Avoid running cables parallel for >1m

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E.5 Control Voltage Standards

E.5.1 Common Control Voltages

Voltage	Type	Typical Use	Safety	Distribution
24V DC	Extra-low	Logic, PLC I/O, relays, sensors	Touch-safe	Standard industrial
24V AC	Extra-low	Older PLCs, some sensors	Touch-safe	Less common (legacy)
12V DC	Extra-low	Cooling fans, LED indicators	Touch-safe	Automotive-style
5V DC	Extra-low	TTL logic, microcontrollers	Touch-safe	Modern electronics
3.3V DC	Extra-low	Modern microcontrollers, FPGA	Touch-safe	High-speed digital

CNC Standard: 24V DC (most common, compatible with industrial components)

E.5.2 24V DC Power Supply Sizing

Formula:

$$P_{PSU} = \sum P_{devices} \times 1.3 \text{ (safety factor)}$$

Example CNC System: - PLC/controller: 5W - HMI touchscreen: 15W - Limit switches (10×): 2W total - Relay coils (5×): 10W total - Cooling fans (3×): 12W total - LED indicators: 3W total

$$P_{total} = (5 + 15 + 2 + 10 + 12 + 3) \times 1.3 = 61 \text{ W}$$

Select 100W (24V, 4.2A) power supply for margin

Inrush Current: PSU should handle 5-10× rated current for 10-100ms (capacitor charging). Most modern PSUs handle this automatically.

E.6 Connectors and Terminations

E.6.1 Industrial Connector Standards

Connector Type	Pins	Current/Pin (A)	IP Rating	Mating Cycles	Applications
M12 (A-coded, 5-pin)	3-5	4	IP67	500	Sensors, encoders, actuators
M12 (B-coded, 5-pin)	5	4	IP67	500	Profibus, DeviceNet fieldbus

Connector Type	Pins	Current/Pin (A)	IP Rating	Mating Cycles	Applications
M8 (3-pin)	3	2	IP67	500	Compact sensors, proximity switches
M23 (12-pin)	12-19	3-5	IP67	500	Multi-signal (motor power + encoder)
Han (Harting)	10-108	10-16	IP65	500	Heavy-duty motor, panel interconnect
D-Sub (DB9, DB25)	9, 25	1-5	IP20	100	Parallel port (obsolete), RS232/422
RJ45 (8P8C)	8	1.5	IP20	1000+	Ethernet, Modbus RTU (not recommended for motor cables)

Recommendation: - **Limit switches, sensors:** M12 or M8 (field-installable, waterproof) - **Stepper/servo motors:** Pre-wired cables with specific connectors (vendor-supplied) or terminal blocks - **Control cabinet interconnect:** Phoenix Contact PCB terminal blocks or Wago lever-lock connectors

E.6.2 Wire Termination Methods

Crimp Terminals (Ferrules): - Twin ferrules for two wires in one terminal block hole - Insulated ferrules (color-coded: 0.5mm^2 = white, 1.0mm^2 = red, 2.5mm^2 = blue) - Requires crimping tool (ratcheting recommended for consistent crimp quality)

Solder: - Acceptable for low-vibration environments - **NOT recommended** for terminal blocks (solder creeps, connection loosens over time) - OK for PCB connections, low-current signal wires

Wire Nuts (Twist-On Connectors): - **NOT suitable for CNC** (vibration loosens, not industrial-rated) - Use Wago lever-lock connectors instead (tool-less, vibration-proof, reusable)

Terminal Block Torque Specifications:

Wire Gauge (AWG)	Terminal Screw Size	Torque (N·m)
24-22	M2.5	0.4
20-18	M3	0.6
16-14	M3.5	0.8
12-10	M4	1.2

Use calibrated torque screwdriver to prevent under/over-tightening (common failure mode).

E.7 Emergency Stop (E-Stop) Circuits

E.7.1 E-Stop Requirements (ISO 13850, IEC 60204-1)

E-Stop Button: - Red mushroom head, yellow background - Latching (stays pressed until manually reset) - Break-before-make contacts (NC contact opens before any NO contact closes)

E-Stop Circuit: - Hardwired (not through software) - Series circuit (all E-stop buttons in series) - Redundancy: Dual-channel (two independent circuits) - Monitoring: Safety relay monitors both channels for faults

Categories (ISO 13849-1): - **Category 0:** Uncontrolled stop (power removed immediately) - **Category 1:** Controlled stop (controlled deceleration, then power removed)

CNC Recommendation: Category 0 (immediate power cut to motors, close spindle contactor)

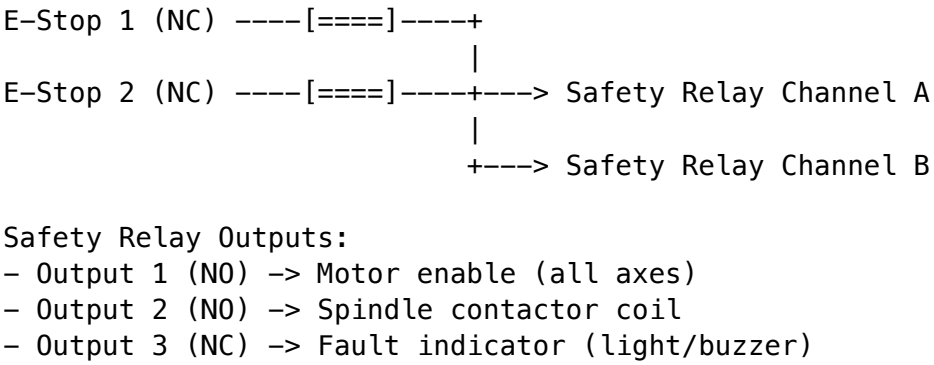
E.7.2 Safety Relay Selection

Function: - Monitors E-stop circuit for faults (contact welding, wire short) - Provides redundant outputs (typically 2 or 4 safety outputs) - Self-testing (checks own operation on each cycle)

Safety Integrity Level (SIL): - **SIL 1:** 10^{-5} to 10^{-6} failures/hour (basic automation) - **SIL 2:** 10^{-6} to 10^{-7} failures/hour (standard industrial) - **SIL 3:** 10^{-7} to 10^{-8} failures/hour (critical safety, large machines)

CNC Recommendation: SIL 2 safety relay (Pilz PNOZ, Phoenix Contact PSR series)

E-Stop Circuit Example:



End of Electrical Standards and Wiring Appendix