31. ELECTRICAL DESIGN AND CONSTRUCTION

31.1 INTRODUCTION

It is uncommon for engineers to build their own controller designs. For example, once the electrical designs are complete, they must be built by an electrician. Therefore, it is your responsibility to effectively communicate your design intentions to the electricians through drawings. In some factories, the electricians also enter the ladder logic and do debugging. This chapter discusses the design issues in implementation that must be considered by the designer.

31.2 ELECTRICAL WIRING DIAGRAMS

In an industrial setting a PLC is not simply “plugged into a wall socket”. The electrical design for each machine must include at least the following components.

- transformers - to step down AC supply voltages to lower levels
- power contacts - to manually enable/disable power to the machine with e-stop buttons
- terminals - to connect devices
- fuses or breakers - will cause power to fail if too much current is drawn
- grounding - to provide a path for current to flow when there is an electrical fault
- enclosure - to protect the equipment, and users from accidental contact

A control system will normally use AC and DC power at different voltage levels. Control cabinets are often supplied with single phase AC at 220/440/550V, or two phase AC at 220/440V ac, or three phase AC at 330/550V. This power must be dropped down to a...
lower voltage level for the controls and DC power supplies. 110V ac is common in North America, and 220Vac is common in Europe and the Commonwealth countries. It is also common for a controls cabinet to supply a higher voltage to other equipment, such as motors.

An example of a wiring diagram for a motor controller is shown in Figure 31.1 (note: the symbols are discussed in detail later). Dashed lines indicate a single purchased component. This system uses 3 phase AC power (L1, L2 and L3) connected to the terminals. The three phases are then connected to a power interrupter. Next, all three phases are supplied to a motor starter that contains three contacts, M, and three thermal overload relays (breakers). The contacts, M, will be controlled by the coil, M. The output of the motor starter goes to a three phase AC motor. Power is supplied by connecting a step down transformer to the control electronics by connecting to phases L2 and L3. The lower voltage is then used to supply power to the left and right rails of the ladder below. The neutral rail is also grounded. The logic consists of two push buttons. The start push button is normally open, so that if something fails the motor cannot be started. The stop push button is normally closed, so that if a wire or connection fails the system halts safely. The system controls the motor starter coil, and uses a spare contact on the starter, M, to seal in the motor starter.
Figure 31.1
A Motor Controller Schematic

The diagram also shows numbering for the wires in the device. This is essential for industrial control systems that may contain hundreds or thousands of wires. These numbering schemes are often particular to each facility, but there are tools to help make wire labels that will appear in the final controls cabinet.

Aside: The voltage for the step down transformer is connected between phases L2 and L3. This will increase the effective voltage by 50% of the magnitude of the voltage on a single phase.
Once the electrical design is complete, a layout for the controls cabinet is developed, as shown in Figure 31.2. The physical dimensions of the devices must be considered, and adequate space is needed to run wires between components. In the cabinet the AC power would enter at the terminal block, and be connected to the main breaker. It would then be connected to the contactors and overload relays that constitute the motor starter. Two of the phases are also connected to the transformer to power the logic. The start and stop buttons are at the left of the box (note: normally these are mounted elsewhere, and a separate layout drawing would be needed).

Figure 31.2
A Physical Layout for the Control Cabinet

The final layout in the cabinet might look like the one shown in Figure 31.3.
Figure 31.3

Final Panel Wiring

L1
L2
L3

Starter

3 phase

AC

Motor

3 phase AC
When being built the system will follow certain standards that may be company policy, or legal requirements. This often includes items such as:

- **Hold downs** - these will secure the wire so they don't move.
- **Labels** - wire labels help troubleshooting.
- **Strain reliefs** - these will hold the wire so that it will not be pulled out of screw terminals.
- **Grounding** - grounding wires may be needed on each metal piece for safety.

A photograph of an industrial controls cabinet is shown in Figure 31.4.

When including a PLC in the ladder diagram still remains. But, it does tend to become more complex. Figure 31.5 shows a schematic diagram for a PLC based motor control system, similar to the previous motor control example.

This figure shows the E-stop wired to cutoff power to all of the devices in the circuit, including the PLC. All critical safety functions should be hardwired this way.
An Electrical Schematic with a PLC

ADD TO DIAGRAM
31.2.1 Selecting Voltages

When selecting voltage ranges and types for inputs and outputs of a PLC some care can save time, money and effort. Figure 31.6 that shows three different voltage levels being used, therefore requiring three different input cards. If the initial design had selected a standard supply voltage for the system, then only one power supply, and PLC input card would have been required.

![Figure 31.6: Standardized Voltages](image-url)
The terms ground and common are often interchanged, but they do mean different things. The term, ground, comes from the fact that most electrical systems find a local voltage level by placing some metal in the earth (ground). This is then connected to all of the electrical outlets in the building. If there is an electrical fault, the current will be drawn off to the ground. The term, common, refers to a reference voltage that components of a system will use as common zero voltage. Therefore the function of the ground is for safety, and the common is for voltage reference. Sometimes the common and ground are connected.

The most important reason for grounding is human safety. Electrical current running through the human body can have devastating effects, especially near the heart. Figure 31.7 shows some of the different current levels, and the probable physiological effects. The current is dependant upon the resistance of the body, and the contacts. A typical scenario is, a hand touches a high voltage source, and current travels through the body and out a foot to ground. If the person is wearing rubber gloves and boots, the resistance is high and very little current will flow. But, if the person has a sweaty hand (salty water is a good conductor), and is standing barefoot in a pool of water their resistance will be much lower. The voltages in the table are suggested as reasonable for a healthy adult in normal circumstances. But, during design, you should assume that no voltage is safe.

<table>
<thead>
<tr>
<th>current in body (mA)</th>
<th>effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>negligible (normal circumstances, 5VDC)</td>
</tr>
<tr>
<td>1-5</td>
<td>uncomfortable (normal circumstances, 24VDC)</td>
</tr>
<tr>
<td>10-20</td>
<td>possibility for harm (normal circumstances, 120V AC)</td>
</tr>
<tr>
<td>20-50</td>
<td>muscles contract (normal circumstances, 220V AC)</td>
</tr>
<tr>
<td>50-100</td>
<td>pain, fainting, physical injuries</td>
</tr>
<tr>
<td>100-300</td>
<td>heart fibrillates</td>
</tr>
<tr>
<td>300+</td>
<td>burns, breathing stops, etc.</td>
</tr>
</tbody>
</table>
Figure 31.8 shows a grounded system with a metal enclosure. The left-hand enclosure contains a transformer, and the enclosure is connected directly to ground. The wires enter and exit the enclosure through insulated strain reliefs so that they don't contact the enclosure. The second enclosure contains a load, and is connected in a similar manner to the first enclosure. In the event of a major fault, one of the "live" electrical conductors may come loose and touch the metal enclosure. If the enclosure were not grounded, anyone touching the enclosure would receive an electrical shock. When the enclosure is grounded, the path of resistance between the case and the ground would be very small (about 1 ohm). But, the resistance of the path through the body would be much higher (thousands of ohms or more). So if there were a fault, the current flow through the ground might "blow" a fuse. If a worker were touching the case their resistance would be so low that they might not even notice the fault.

Aside: Step potential is another problem. Electron waves from a fault travel out in a radial direction through the ground. If a worker has two feet on the ground at different radial distances, there will be a potential difference between the feet that will cause a current to flow through the legs. The gist of this is - if there is a fault, don't run/walk away/towards.

Current can flow two ways, but most will follow the path of least resistance, good grounding will keep the worker relatively safe in the case of faults.
When improperly grounded, a system can behave erratically or be destroyed. Ground loops are caused when too many separate connections to ground are made, creating loops of wire. Figure 31.9 shows ground wires as darker lines. A ground loop caused because an extra ground was connected between device A and ground. The last connection creates a loop. If a current is induced, the loop may have different voltages at different points. The connection on the right is preferred, using a tree configuration. The grounds for devices A and B are connected back to the power supply, and then to the ground.

Problems often occur in large facilities because they may have multiple ground points at different ends of large buildings, or in different buildings. This can cause current to flow through the ground wires. As the current flows, it will create different voltages at different points along the wire. This problem can be eliminated by using electrical isolation systems, such as optocouplers.

Note: Always ground systems first before applying power. The first time a system is activated, it will have a higher chance of failure.
When designing and building electrical control systems, the following points should prove useful.

Avoid ground loops
- Connect the enclosure to the ground bus.
- Each PLC component should be grounded back to the main PLC chassis.
- The PLC chassis should be grounded to the backplate.
- The ground wire should be separated from power wiring inside enclosures.
- Connect the machine ground to the enclosure ground.

Ensure good electrical connection
- Use star washers to ensure good electrical connection.
- Mount ground wires on bare metal, remove paint if needed.
- Use 12AWG stranded copper for PLC equipment grounds and 8AWG stranded copper for enclosure backplate grounds.
- The ground connection should have little resistance (<0.1 ohms is good).

Wiring

As the amount of current carried by a wire increases, it is important to use a wire with a larger cross section. A larger cross section results in a lower resistance, and less heating of the wire. The standard wire gages are listed in Figure 31.10.

**Figure 31.10**

<table>
<thead>
<tr>
<th>AWG #</th>
<th>Diameter (mil)</th>
<th>Resistance 25°C (ohm/1000 ft)</th>
<th>Rated Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>204</td>
<td>0.25</td>
<td>5000</td>
</tr>
<tr>
<td>6</td>
<td>162</td>
<td>0.40</td>
<td>3500</td>
</tr>
<tr>
<td>8</td>
<td>128</td>
<td>0.64</td>
<td>2000</td>
</tr>
<tr>
<td>10</td>
<td>102</td>
<td>1.0</td>
<td>1000</td>
</tr>
<tr>
<td>12</td>
<td>81</td>
<td>1.6</td>
<td>750</td>
</tr>
<tr>
<td>14</td>
<td>64</td>
<td>2.6</td>
<td>500</td>
</tr>
<tr>
<td>16</td>
<td>51</td>
<td>4.1</td>
<td>300</td>
</tr>
<tr>
<td>18</td>
<td>40</td>
<td>6.5</td>
<td>200</td>
</tr>
<tr>
<td>20</td>
<td>32</td>
<td>10</td>
<td>150</td>
</tr>
<tr>
<td>22</td>
<td>25</td>
<td>17</td>
<td>100</td>
</tr>
<tr>
<td>24</td>
<td>20</td>
<td>26</td>
<td>75</td>
</tr>
</tbody>
</table>

Note: The table shows the diameter and resistance for each wire gage, as well as the rated current capacity.
3.2 Suppressors

Most of us have seen a Vandegraaf generator, or some other inductive device that can generate large sparks using inductive coils. On the factory floor there are some massive inductive loads that make this a significant design problem. This includes devices such as large motors and inductive furnaces. The root of the problem is that coils of wire act as inductors and when current is applied they build up magnetic fields, requiring energy. When the applied voltage is removed and the fields collapse the energy is dumped back out into the electrical system. As a result, when an inductive load is turned on it draws an excess amount of current (and lights dim), and when it is turned off there is a power surge. In practical terms this means that large inductive loads will create voltage spikes that will damage our equipment.

Surge suppressors can be used to protect equipment from voltage spikes caused by inductive loads. Figure 31.11 shows the schematic equivalent of an uncompensated inductive load. For this to work reliably we would need to over design the system above the rated loads. The second schematic shows a technique for compensating for an AC inductive load using a resistor-capacitor pair. It effectively acts as a high pass filter that allows a high frequency voltage spike to be short circuited. The final surge suppressor is common for DC loads. The diode allows current to flow from the negative to the positive. If a negative voltage spike is encountered it will short circuit through the diode.
31.2.5 PLC Enclosures

PLCs are well built and rugged, but they are still relatively easy to damage on the factory floor. As a result, enclosures are often used to protect them from the local environment. Some of the most important factors are listed below with short explanations.

Uncompensated

\[
\begin{align*}
\text{output} & \quad \text{common} \\
+ & \quad - \\
\text{Power supply} & \quad \text{Relay or Transistor}
\end{align*}
\]

Compensating

\[
\begin{align*}
\text{output} & \quad \text{common} \\
+ & \quad - \\
\text{Power supply} & \quad \text{Relay or Triac}
\end{align*}
\]

- In DC loads,\( R = \frac{Vs}{Adc} \) ohms
- \( C = \frac{.5}{Adc} \) microfarads
- \( V_{\text{capacitor}} = 2(V_{\text{switching}}) + (200 \text{ to } 300) \text{ V} \)
- \( Adc \) is the rated amperage of the load
- \( Vs \) is the voltage of the load/power supply
- \( V_{\text{switching}} \) may be up to 10\( \times \)\( Vs \)
Dirt - Dust and grime can enter the PLC through air ventilation ducts. As dirt clogs internal circuitry, and external circuitry, it can effect operation. A storage cabinet such as Nema 4 or 12 can help protect the PLC.

Humidity - Humidity is not a problem with many modern materials. But, if the humidity condenses, the water can cause corrosion, conduct current, etc. Condensation should be avoided at all costs.

Temperature - The semiconductor chips in the PLC have operating ranges where they are operational. As the temperature is moved out of this range, they will not operate properly, and the PLC will shut down. Ambient heat generated in the PLC will help keep the PLC operational at lower temperatures (generally to 0°C). The upper range for the devices is about 60°C, which is generally sufficient for sealed cabinets, but warm temperatures, or other heat sources (e.g. direct irradiation from the sun) can raise the temperature above acceptable limits. In extreme conditions heating, or cooling units may be required. (This includes "cold-starts" for PLCs before their semiconductors heat up).

Shock and Vibration - The nature of most industrial equipment is to apply energy to change workpieces. As this energy is applied, shocks and vibrations are often produced. Both will travel through solid materials with ease. While PLCs are designed to withstand a great deal of shock and vibration, special elastomer/spring or other mounting equipment may be required. Also note that careful consideration of vibration is also required when wiring.

Interference - Electromagnetic fields from other sources can induce currents.

Power - Power will fluctuate in the factory as large equipment is turned on and off. To avoid this, various options are available. Use an isolation transformer. A UPS (Uninterruptable Power Supply) is also becoming an inexpensive option, and are widely available for personal computers.

A standard set of enclosures was developed by NEMA (National Electric Manufacturers Association). These enclosures are intended for voltage ratings below 1000V ac. Figure 31.12 shows some of the rated cabinets. Type 12 enclosures are a common choice for factory floor applications.
31.2.6 Wire and Cable Grouping

In a controls cabinet the conductors are passed through channels or bundled. When dissimilar conductors are run side-by-side problems can arise. The basic categories of conductors are shown in Figure 31.13. In general category 1 conductors should not be grouped with other conductor categories. Care should be used when running category 2 and 3 conductors together.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type 1 - General purpose - indoors</th>
<th>Type 2 - Dirt and water resistant - indoors</th>
<th>Type 3 - Dust-tight, rain-tight and sleet (ice) resistant - outdoors</th>
<th>Type 3R - Rainproof and sleet (ice) resistant - outdoors</th>
<th>Type 3S - Rainproof and sleet (ice) resistant - outdoors</th>
<th>Type 4 - Water-tight and dust-tight - indoors and outdoors</th>
<th>Type 4X - Water-tight and Dust-tight - indoors and outdoors</th>
<th>Type 5 - Dust-tight and dirt resistant - indoors</th>
<th>Type 6 - Waterproof - indoors and outdoors</th>
<th>Type 6P - Waterproof submersible - indoors and outdoors</th>
<th>Type 7 - Hazardous locations - class I</th>
<th>Type 8 - Hazardous locations - class I</th>
<th>Type 9 - Hazardous locations - class II</th>
<th>Type 10 - Hazardous locations - class II</th>
<th>Type 11 - Gas-tight, water-tight, oiltight - indoors</th>
<th>Type 12 - Dust-tight and drip-tight - indoors</th>
<th>Type 13 - Oil-tight and dust-tight - indoors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevent human contact</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Falling dirt</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Liquid drop/light splash</td>
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<td>X</td>
<td>X</td>
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<td>airborne dust/particles</td>
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<td>wind blown dust</td>
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<td>X</td>
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<td>X</td>
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<tr>
<td>liquid heavy stream/splash</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>oil/coolant seepage</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>oil/coolant spray/splash</td>
<td>X</td>
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<td>X</td>
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<td>corrosive environment</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>temporarily submerged</td>
<td>X</td>
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<td>X</td>
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<td>X</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>prolonged submersion</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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</tbody>
</table>

In Figure 31.13, the categories of conductors are shown and the factors that each category protects against are listed. The table above shows the different types of enclosures and their corresponding levels of protection.
Figure 31.13 Wire and Cable Categories

Types of wire pathways - channels - raceways/trays - conduit

Conductor types enter and exit the controls cabinet separately

When conductors must be near incompatible types, they should cross at right angles

31.3 FAIL-SAFE DESIGN

All systems will fail eventually. A fail-safe design will minimize the damage to people and equipment. Consider the selection of electrical connections. If wires are cut or connections fail, the equipment should still be safe. For example, if a normally closed stop button is used, and the connector is broken, it will cause the machine to stop as if the stop button has been pressed.

NO (Normally open) - When wiring switches or sensors that start actions, use normally open connections. More sensitive category 3 low voltage DC power local communications

Category 2 analog IO signals low power AC/DC IO

Category 1 AC power lines high power AC/DC IO remote communications
plc electrical - 31.18

Mally open switches so that if there is a problem the process will not start.

NC (Normally Closed) - When wiring switches that stop processes use normally closed so that if they fail the process will stop. E-Stops must always be NC, and they must cut off the master power, not just be another input to the PLC.

Hardware

Use redundancy in hardware.

Directly connect emergency stops to the PLC, or the main power supply.

Use well controlled startup procedures that check for problems.

Shutdown buttons must be easily accessible from all points around the machine.

31.4 SAFETY RULES SUMMARY

A set of safety rules was developed by Jim Rowell (http://www.mrplc.com, “Industrial Control Safety; or How to Scare the Bejesus Out of Me”). These are summarized below.

Grounding and Fuses

Always ground power supplies and transformers.

Ground all metal enclosures, casings, etc.

All ground connections should be made with dedicated wires that are exposed so that their presence is obvious.

Use fuses for all AC power lines, but not on the neutrals or grounds.

If ground fault interrupts are used they should respond faster than the control system.

Hot vs. Neutral Wiring

Use PNP wiring schemes for systems, especially for inputs that can initiate actions.

Loads should be wired so that the ground/neutral is always connected, and the power is switched.

Sourcing and sinking are often confused, so check the diagrams or look for PNP/NPN markings.

AC / DC

Use lower voltages when possible, preferably below 50V.

For distant switches and sensors use DC.

Devices

Use properly rated isolation transformers and power supplies for control systems. Beware autotransformers.

Use Positive or Force-Guided Relays and contacts can fail safely and prevent operation in the event of a failure.

Some 'relay replacement' devices do not adequately isolate the inputs and output and should not be used in safety critical applications.
Use NO buttons and wiring for inputs that start processes. Select palm-buttons, and other startup hardware carefully to ensure that they are safety rated and will ensure that an operator is clear of the machine.

When two-hand start buttons are used, use both the NO and NC outputs for each button. The ladder logic can then watch both for a completed actuation.

Stops
E-stop buttons should completely halt all parts of a machine that are not needed for safety. E-stops should be hard-wired to kill power to electrically actuated systems. Use many red mushroom head E-stop buttons that are easy to reach. Use red non-mushroom head buttons for regular stops. A restart sequence should be required after a stop button is released. E-stop buttons should release pressure in machines to allow easy ‘escape’.

An ‘extraction procedure’ should be developed so that trapped workers can be freed. If there are any power storage devices (such as a capacitor bank) make sure they are disabled by the E-stops. Use NC buttons and wiring for inputs that stop processes.

Use guards that prevent operation when unsafe, such as door open detection. If the failure of a stop input could cause a catastrophic failure, add a backup.

Construction
Wire so that the power enters at the top of a device. Take special care to review regulations when working with machines that are like presses or brakes. Check breaker ratings for overload cases and supplemental protection. A power disconnect should be located on or in a control cabinet. Wires should be grouped by the power/voltage ratings. Run separate conduits or raceways for different voltages. Wire insulation should be rated for the highest voltage in the cabinet. Use colored lights to indicate operational states. Green indicates in operation safely, red indicates problems. Construct cabinets to avoid contamination from materials such as oils. Conduits should be sealed with removable compounds if they lead to spaces at different temperatures and humidity levels. Position terminal strips and other components above 18” for ergonomic reasons. Cabinets should be protected with suitably rated fuses. Finger sized objects should not be able to reach any live voltages in a finished cabinet, however DMM probes should be able to measure voltages.
Electrical schematics used to layout and wire controls cabinets. JIC wiring symbols can be used to describe electrical components. Grounding and shielding can keep a system safe and running reliably. Failsafe designs ensure that a controller will cause minimal damage in the event of a failure. PLC enclosure are selected to protect a PLC from its environment.

1. What steps are required to replace a defective PLC?

1. In a rack the defective card is removed and replaced. If the card has wiring terminals these are removed first, and connected to the replacement card.

1. Where is the best location for a PLC enclosure?
1. What is a typical temperature and humidity range for a PLC?
1. Draw the electrical schematic and panel layout for the relay logic below. The system will be connected to 3 phase power. Be sure to include a master power disconnect.

A
B
C
B

O

1
4. Why are nodes and wires labelled on a schematic, and in the controls cabinet?

5. Locate at least 10 JIC symbols for the sensors and actuators in earlier chapters.

6. How are shielding and grounding alike? Are shields and grounds connected?

7. What are significant grounding problems?

8. Why should grounds be connected in a tree configuration?