Introduction to Designing Machine Control Systems, Part 2

by

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Introduction:

This course is the second part of a two part series, as an introduction for designing Machine Control Systems for the design Engineer. Part 1 presents overall system design techniques up to Control Cabinets design. Part 2 presents Control Cabinet design and field wiring issues.

While this presentation is not comprehensive, the goal is to provide enough background for further in-depth studies in a wide range of related topics. The reader should have at least a working understanding of electricity.

The three major goals for every control system should be safety, reliability, and the ease of troubleshooting. To meet these goals, seven basic steps (see outline below) are presented to help guide the design engineer through the design and implementation of Control Systems. The Steps for Part 1 and Part 2 are outlined below.

Disclaimer: This course is not intended to provide an in-depth treatment of the subject matter or to provide engineering advice applicable to specific designs; you therefore should consult with appropriately qualified, licensed engineer/s to evaluate how applicable codes, regulations, rules, statutes and practices may apply to your particular project/s.

Part 1, System Design and Power up to the Control Cabinet:

1 Process I/O Diagrams:
   1.1 Define all machine motions/ functions
   1.2 Define the Operator Interface
   1.3 Identify the Safety issues

2 Supply Power Selection:
   2.1 Codes
   2.2 Determine if Single or Three Phase is needed.
   2.3 Determining System Voltage.
   2.4 Determining Maximum Current required.
Part 2, Control Cabinet Design and beyond:

3 Control Cabinet Design:
   3.1 Internal power distribution
   3.2 Control of heater Loads
   3.3 Types of motor control
   3.4 Line balancing
   3.5 Control power
   3.6 Power On/Off
   3.7 Instrumentation Power
   3.8 DC and Low Voltage Wiring
   3.9 E-Stop Circuits
   3.10 PLC wiring basics
      3.10.1 Discrete I/O
      3.10.2 Sinking and Sourcing
      3.10.3 Sinking and Sourcing Inputs
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      3.10.5 Analog I/O
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      3.10.9 Distributed Architecture
      3.10.10 Modular vs. Integrated Systems
      3.10.11 Control Valves
   3.11 Terminal Strips
   3.12 Wire numbers

4 Component Selection

5 Panel Design
   5.1 NEMA rated Panels
   5.2 Good wiring practices and EMI issues
   5.3 Interlocks
   5.4 Control Panel Accessories
6 Software Development
   6.1 Ladder Logic
   6.2 Special control modules
   6.3 General Programming
   6.4 Math
   6.5 E-Stop Events
   6.6 Reset Buttons
   6.7 Stop Buttons

7 Installation and Startup
   7.1 Electrical Shock Safety
   7.2 Multiple Power Sources
   7.3 Arc Flash Safety
   7.4 Lockout and Tag-out Procedures

8 Documentation
   8.1 Maintenance Manual basics.
   8.2 Safety Warnings Page
   8.3 Facilities Requirements
   8.4 Equipment Setup
   8.5 Equipment Operation
   8.6 Recommended Documents
3 Control Cabinet Design:

If Part 1 of this two part series has been completed, the next step after completing the Process I/O diagram and determining the supply power to the systems is to develop the wiring diagrams or wiring schematics.

In review, before the wiring can be designed, it is very important to understand and apply all appropriate codes.

3.1 Internal power distribution: Once the choice between single phase and three phase, the maximum current, and the supply voltage have all been determined, the supply power for the system can be specified. Code/ NEC dictate the wire sizes and the main disconnect switch/ CB or fuses, etc.

For most control systems, power conductors enter the main cabinet and are connected directly and only to the main disconnect switch. Fuses would directly follow the main disconnect switch but a main Circuit Breaker (CB) is often used as it can also fulfill the function of the main disconnect switch.

Main Disconnect Switch mechanisms usually prevent the door from being opened unless the switch is in the "off" position. However, given the need that some work may need to be performed while a system is energized, over ride devices are incorporated into main disconnect switch mechanisms.

When the Main Disconnect Switch is in the "off" position, it must be remembered that there is still live voltage entering into the switch. Therefore, these switches should be mounted towards the top of the cabinet and it should always be remembered that there is an unsafe "zone" around the main disconnect switch.

After the main disconnect switch, power is then internally distributed to devices controlling major loads in/from the cabinet. Code requirements will determine the
wiring and circuit protection devices that will need to be specified for each of the major loads that will be controlled.

The primary purpose of Circuit Breakers (CB’s) or fuses is to protect wires from over current, overheating and causing a fire. The NEC will dictate the minimum size of wires and CB’s or fuses that will be needed.

The choice between specifying CB’s vs. fuses requires an in-depth discussion and is not presented here. The reader may want to pursue further study on this topic. In general, fuses usually provide faster protection but they must be replaced after being overloaded. CB's only need to be mechanically reset after being tripped. **Note:** When an overload occurs, it is important to determine and correct the cause before "resetting" the overload device.

Below are a few situations that deserve additional comments regarding the control of various types of loads:

3.2 Control of heater loads: Before solid state devices, heaters were controlled by cycling the power on and off with a mechanical contactor. As an example, if the contactor was off for 30 seconds out of every minute, the heat produced would be 50% of maximum available heat. The down side of these older devices was that since many mechanical contactors only have a rating of 100,000 or 1,000,000 cycles, after a few years of operation the contacts in mechanical contactors would often fail.

Because Solid State (SS) devices have virtually unlimited life cycle ratings, SS heater controllers were developed. However, the down side of SS heater controllers is that their failure mode is often to fail "closed". In such a failure mode the heating coils will be driven at full power which can results in a melt down and fire. The typical solution to solve both of these issues has been to install a mechanical contactor ahead of the SS controller. In these applications the mechanical contactor will usually only operate a few times per day, and not even come close to their rated number of cycles during the expected life of most system. The mechanical contactor should be controlled by a separate redundant temperature sensor and high limit controller so that in the case of a SS failure, the high limit safety sensor/ switch will drop out the mechanical contactor, removing the power to the SS controller and the heater. High temp safety sub-systems
should also initiate an E-Stop event through the use of an auxiliary contact.

Note: One of the causes of failures of SS devices is power spikes. Filters can be used to help eliminate power spikes. A good rule of thumb is to double the current ability of SS devices. As an example, if the load is expected to need 20 amps, the SS device should be specified that is capable of 40 amps or greater. Because of the basic costs of SS devices, the cost for a higher rated device is usually not very expensive.

3.3 There are two basic types of motor control configuration, direct powered or through a motor controller.

In the case of "direct powered" motors, there should be a contactor and an overload sensing device. Overload devices are designed to protect motors from over current which will result in overheating (in most cases). The maximum expected current rating of a motor will be stamped on the motor nameplate. This current value can then be used to set adjustable overload devices or to select specific "heater elements" that will need to be installed for non-adjustable overload devices.

Note: It should be remembered that fuses and CB's are typically sized to protect the wires and related components, while motor over current devices are designed to protect motors from overheating. The purpose and application of these two types of devices should never be confused.

If motors are powered through a mechanical contactor, they will run at their fundamental operating speed. If the speed of motors needs to be controlled, then motor controllers should be incorporated. There are two basic categories of motor controllers, Alternating Current (AC) and Direct Current (DC). DC drives convert the AC line power into variable voltage DC which controls the speed of DC motors. Variable Frequency Drives (VFD's) are designed to control the speed of AC motors, primarily by changing the output frequency. Note: Only AC motors which have been designed and rated specifically for VFD applications should be driven by VFD drives.

Most DC drives do a good job at controlling the speed of motors. However, VFD's usually provide considerable more control than just the speed, including the
acceleration/ de-acceleration and even holding torque when a motor is not turning. Because of all of the potential capabilities of various motor controllers, it is recommended that the manufacturer's application engineering department be contacted. These departments are usually very good sources of how to implement their equipment. All motor controllers should be implemented strictly per the manufacturer's instructions.

Servo and stepping motor controllers are advanced versions of a number of motor technologies. The advantage of these types of controllers/ motors is that shaft positions and speeds can be accurately controlled which results in the ability to move loads to precise positions through required velocity profiles. Again, manufacturer applications departments are extremely helpful and should be contacted.

3.4 Standard practice dictates that the incoming wiring and circuit protection are the same size for all three phases. Therefore, the incoming supply must be sized for the largest current of each of the three phases. Three phase motors and loads draw close to the same power from all three phases so they don't impact line balancing. The current for all three phase loads need to be added together. However, as single phase motors and loads only draw power from one of the three phases, if they are all connected to the same phase the incoming power requirement will be the largest of the three phase loads. Larger current require more expensive wiring and components so line balancing is important.

Example, if a three phase systems powers a three phase 20 amp heater and a 2 amp control circuit, all three phases of the incoming supply current must be sized for 22 amps. Note: Since the ampacity of wire and components are only available in specific sizes, as 22 amp components are not available, the next available size for the incoming power will be 25 amps.
Diagram G: Example of "internal" power distribution.

In the diagram above, the three phase heater has no effect on line balancing as the same current will be drawn from all three phases. Since the two 5 hp motors, M1 and M2 are single phase they are connected to two different phases. The control transformer is also a single phase load. While the...
transformer is relatively small compared to the other single phase loads, the best practice is to connect the transformer to remaining unbalance phase.

M1 is connected between lines 1&2. M2 is connected to lines 1&3. And the 2 amp transform is connected between lines 2&3. Due to the mixture of loads, it is not possible to obtain a perfect balance. In such cases the goal is to balance all three phases as closely as possible.

Review from Part 1:

As an example, a 30Kw single phase heater will produce the same amount of heat as a 30Kw three phase heater. However, depending on the configuration of the 3 phase system, the current per each phase may be different. Therefore it is important to determine the amps per phase when detering the required wire and circuit protection supply current.

To convert Kilowatts to Amps, per phase, the Kw load is divided by the supply voltage and multiplied by 1000. Example: A 10Kw load supplied by 240 VAC would be equal to approximately 42 amps (10 / 240 x 1000 = 41.7).

In the case of motors, because hp is describing the energy, the current for a 5 hp single phase motor will not be equal to 3 times the current of a 5 hp three phase motor. As an example, at 230 VAC, a 5 hp single phase motor will typically draw about 28 full load amps while a 5 hp three phase motor will typically draw 15.2 full load amps per phase.

For single phase, the relationship between Kw and hp is: 1.341 hp = 1 Kw.

To determine the amps for hp, one of the easiest methods is to use a "paper calculator". These charts/calculators will take into consideration if motors are single or three phase and the operating voltage. These calculators can also be easily found on the internet (by searching for "horsepower to amps calculator").

3.5 The last load that is usually connected to the internal power distribution
supply is the control transformer (see Diagram G above). The output of most control transformers is usually 120 VAC. Code/ NEC clearly specify how control transformers are to be wired and protected. Generally, the grounded wire should never be fused.

Since control transformers are single phase devices, which usually only demand relatively small current loads, they don't have a significant impact on line balancing. However, it is recommended that the control transformer not be connected to Phase 1. This is not a hard and fast rule, but since the tendency is to connect these "minimal" loads to the first phase, the overall impact of having all of the control transformers, each relatively small load, connected to the same phase within the entire facilities can become significant.

The 120 VAC control circuit will power a wide range of instruments, sub-controllers (such a heater controller), the Program Logic Control (PLC) and any lower voltage DC power supplies. Probably the most common DC supply is 24 VDC for powering a wide range of sensors, control valves, sub-controllers, etc., and even some PLC's.

The power grid in the United States is a grounded system, which means that power systems are tied to earth "ground". It is very important to thoroughly understand grounding and the associated code requirements. The NEC and NFPA 79 should be the first sources to refer to for more information. The advantage of a grounded system is that the power is not "floating". In a floating system, the voltage between two supply conductors is determined by the transformer or power supply. However, the voltage potential between either of the conductors and "earth" is undetermined. A floating system allows for the possibility of static build up. Sometimes the static build up can be hundreds of volts, resulting in a potential shock hazard and damage to sensitive equipment. Electronic equipment is especially susceptible to these high voltages. Therefore, except for unique situations, all electrical systems should be grounded per codes/ NEC.

Where this becomes important in control system design is to ground one leg of all control transformers and DC power supplies. For AC control transformers, one conductor should be selected to be grounded. The other conductor is the "hot" leg and should be appropriately fused. For DC power supplies, the zero voltage
A conductor is usually selected to be grounded. One of the advantages of grounding the negative conductors of all DC supplies is that a 0 volt reference is established for the entire system. This can be important in systems with multiple power supplies.

3.6 Power On/Off: One of the first devices that should be installed into the Control Circuit is the main power "On/Off" switch or contact. This "main" control power should not be confused with the "main" power disconnect switch. The Power On/Off switch will usually control all of the 120 VAC "control" power. (Refer to Diagram H below). Many times, systems will be off line for days or longer and it is good practice to de-energize the control portions of systems.

Because there are typically no external indications if a control system is energized or not, it is recommended that a "Power On" light be incorporated. A "Power On" light would be illuminated when the control portion of a system is energized. "Power On" lights are also very helpful for diagnosing system problems. In the case where a system has been commissioned but doesn’t appear to be responding, the Power On light should be checked first. If illuminated, there is a high probability that power is received by the control panel, the main disconnect switch is engaged, the main fuse or CB supplying power to the control transformer is good (however, there is no guarantee that the other phases are functioning properly), the control transformer is functioning properly, the control circuit fuses are operational, and the "On" switch is functioning. While much of this may seem trivial, checking the status of the "Power On" light eliminates a number of potential issues, when troubleshooting a system.

Note: If the power on light is "On", it is a good indication that there is power to the system. If the power on light is "Off", care must be taken that the light is functioning properly. Warning, if the light is defective, the control system may be energized even when the "Power On" light is not illuminated.

Because the Power On Switch usually only controls the control circuit, very little power is removed inside of the control cabinet when the Power Switch is Off and therefore should never be used as a substitute for lockout and tag out procedures.
3.7 Instrumentation Power: Wiring Schematics typically illustrate 120 VAC control power shortly after (ie. below) the Control Transformer. While not being a rule, since the Power On circuit is closely related to the 120 VAC control supply it is shown in the schematic next, followed by the instrumentation and controllers that are powered by 120 VAC.

Some PLC’s are powered by 24 VDC, but many are powered by 120 VAC and are illustrated in this section of wiring. The last devices that require 120 VAC power are usually the DC power supplies.

While 24 VDC is the most common, sometimes a process will require unique sensors and field devices that are powered by other DC voltages. Regardless, it is usually logical to group all DC wiring together in the wiring schematics. PLC input and often times output modules are usually presented in following sections of diagrams.
Diagram H: Example of Control circuit. Note the GFCI and the Isolator to protect the PLC and other 120 VAC instrumentation. The "24VDC" and the ":-" terminals will feed power to all DC field sensors (unless other DC voltages are required).

3.8 Direct Current (DC) Power: The power supplied to the sensors in a system does not have to be 24 VDC, but since this is the voltage that most commonly available sensors, 24 VDC has become a pseudo standard.

As a general rule, any voltage that is 50 volts or more is to be considered "high voltage" and should always be appropriately marked. However, just because 24
VDC control circuits are less than 50 volts, these sections of the wiring should not be treated as "low voltage" circuits. There are a number of codes/NEC requirements that must be met before a circuit can be classified as "low voltage". Since most 24 VDC control circuits used in control systems do not meet all of the code requirements, 24 VDC wiring must meet all applicable codes for "high voltage" wiring.

A particular area that is impacted by the classification of "low" or "high" voltage is the method of installing field wiring. There are generally three types or levels of field wiring. For high voltage wiring, "standard" conduit and components are required. For various hazardous applications, such as where there is the potential of an explosion, "rigid" conduit and components are required. For "low" voltage wiring, no conduit is required.

In an effort to eliminate the cost of conduit, it is tempting to consider all 24 VDC wiring to be low voltage. However, unless 24VDC wiring meets all of the requirements of "low voltage" 24 VDC wiring should be treated as all other high voltage wiring.

Other than for properly classified low voltage wiring, flexible cords should generally not be used. The exception to this rule is where devices need flexibility for position adjustment, which applies to most sensor applications. A good guideline is if a flexible cord is part of a field device as it is supplied from the manufacturer, then the flexible cord is appropriate.

The routing and installation of exposed flexible cords should be such that the cords are mechanically protected and kept reasonably short.

While code does not restrict the length of cords inside of conduits and through cabinets, in the event that a sensor or device fails and needs to be replaced, the use of long cords running throughout the system can become very time consuming if the sensor needs to be replaced. If the manufacturer does not provide an integrated plug and socket into a field device, it is recommended that flexible cords be terminated, preferably with screw terminals within junction boxes, located relatively close to where the field device is mounted. There are a number of exceptions in this area, and therefore all applicable codes/NEC should be reviewed.
3.9 E-Stop Circuit- low voltage: Code may allow for some exceptions but an important requirement of most E-Stop systems is that they "drop out" upon the loss of power, which is different from a simple on-off switch. If power is lost where only an on-off switch is used, the equipment may appear to be safe to be adjusted or maintained. Then if the power is externally restored, very dangerous situations can be created as the equipment may restart un-expectantly. To avoid such problems, E-Stop circuits should incorporate a "Manual Reset". This low voltage "drop out" ability of an E-Stop circuit requires an E-Stop relay or Safety Module.

E-Stop Circuits need to be designed to match the level of the potential risk. Risk Assessments are formal procedures that should be completed for every system. Because of the potential of loss of life and property, Risk Assessments should be determined by appropriately qualified personnel. Below is some general information for the various levels of risk:

3.9.1 The lowest risk level, Category B is applicable where there is a "very low" probability or only where minor injuries may occur. For this level, a simple unrated latching relay may be used. However, it should be noted that many older Control Systems, even with higher risk levels incorporate simple un-rated latching relays for their E-Stop systems.

3.9.2 The second risk level, Category 1 is where there is a "low" risk. A simple latching relay circuit is still acceptable, however the components need to be appropriately rated for safety applications.

3.9.3 The third risk level, Category 2 is where first aid would likely be needed in the event of an accident. This level not only requires all components to be safety rated but the master E-Stop module needs to have self monitoring capabilities to verify continual proper functionality.

3.9.4 The fourth risk level, Categories 3 and 4 include applications where there is a high possibility of serious injury. For this category, the master E-Stop module needs to be appropriately rated. The E-Stop module also needs to be self monitoring and redundant. Self monitoring capabilities allow the E-
Stop system to determine if there is a discrepancy during normal operations. In the event that there is a discrepancy or fault, the E-Stop system will not reset. These types of safety modules usually incorporate a set of status lights which will display fault conditions.

Something to be aware of is that only a single contact needs to be wired for E-Stop circuits in Category B and Category 1 applications. For Category 2 applications and above, redundant contacts are required.

Other than for a few exceptions, non-rated electronic devices, such as PLC’s or software controlled devices should never be used within an E-Stop system. The general rule is that the E-Stop system should not depend upon non-safety rated electronic components or software. Software is particularly vulnerable to unauthorized modifications.

Note: Banner Engineering Corp., is one manufacturer that offers a good selection of Master Safety Controllers. Again, supplier’s application support departments are usually very good technical resources for when and how to incorporate their products.
**Diagram I:** Example of category 3 and 4 Safety E-Stop circuit. (Provided for illustrated purposes only).
3.9.5 In addition to the Master Safety Controller, specific attention should be given to all alternative power sources. Examples of alternate power sources are; pneumatic, hydraulic, steam, springs, and gravity, etc. When a system includes an alternate power source, it is very important to install appropriate devices to safely remove or "hold" the energy during E-Stop events.

In most cases, dump valves/devices are a good option which would need to be controlled directly by the E-Stop system. Dump valves/devices should not only isolate the incoming energy, but where appropriate, they should safely exhaust all residual energy within the system. These devices usually provide options to be locked in the safe condition for lockout-tag-out functions.

Something to be aware of is that when E-Stop events are reset, parts of the equipment may begin to move when energy is restored. This is usually not a problem but warnings should be included in manuals and operator training. Sudden movement upon restart should usually be avoided and it may be necessary to modify the program or to incorporate "slow start" devices. In many cases, programs will need to mechanically "reset" the equipment through activating motions to get the machine back to "safe" home positions.

For systems with springs or weights, and any other types of stored internal energy, consideration should be made to incorporate fail safe devices that will automatically restrain motion upon the loss of power.

3.9.6 Probably the most common method of stopping motion is to remove the power to the device. However, when devices (typically motors) are controlled through controllers it is not always recommended to totally de-energize the controller during an E-Stop event.

Below are a few situations where additional care needs to be taken during E-Stop Events:

3.9.7 Manufacturers of motor controllers and Variable Frequency drives (VFD's) usually do not recommend that the supply power be removed from the entire drive for E-Stop purposes. There may be a number of potential problems but one of the most significant issues is that removing supply power
from the motor controller causes the drive to lose control of the motor, often allowing the motor to coast, rather than breaking to a stop. In some applications, the additional time for a motor to coast to a stop may create safety issues. In other situations, safety issues may be created where motors come to an abrupt stop. The design engineer needs to review each potential situation on a case by case basis.

Many motor drive manufacturers provide a dedicated set of terminals through which the E-Stop circuit can be hard wired to stop the motor. Many manufacturers provide the capability to determine the velocity profile for stopping the motor upon E-stop events. Many controllers will dynamically brake the motor. Dynamic braking is the result of "reversing" the torque inside of the motor, causing it to stop within reduced numbers of revolutions.

Note: The normal rule is that electronic circuitry should not be included in E-Stop systems. However, when motor control manufactures determine that their systems are safer with controlled stops, it becomes their responsibility to provide appropriate E-Stop capabilities.

3.9.8 Another example is when a part is held by a gripper. If the energy supply is interrupted as the result of an E-Stop event, the loss of grip and dropping a part can easily create a more dangerous situation than maintaining energy to the gripper. Again, every motion needs to be evaluated to determine if it is more appropriate to maintain the energy or if the energy should be totally removed during E-Stop events. All motion should stop upon an E-Stop event, but all energy may not be removed.

3.9.9 An area that requires careful consideration is when gravity may cause a load to "coast" or "fall" when the E-Stop is activated.

One potential solution is to implement fail safe mechanical brakes which must be activated to allow motion. When the energy is lost or removed, the brake will automatically stop the motion.

Another potential solution is to design a mechanical counterbalance. If a counter balance is applicable then the design may result in the load having very little or no downward weight during an E-Stop event. While counter
balance mechanisms can be mechanically cumbersome, an important side benefit is that smaller motors/ cylinders can be used. Also, the force to raise and the force to lower the load will be roughly the same which will allow the acceleration, deceleration, and speed characteristics to be very similar for when the load is being raised or lowered.

3.10 PLC Wiring Basics: There are a number of PLC manufacturers. Most manufacturers provide several different PLC models. Many offer "families" where basically the "same" PLC is provided but they have different numbers of inputs, outputs, and features, such as the amount of memory.

Note: Another important area is the programming software. For some manufacturers, their software package may be used for all of their models. A number of manufacturers require specific software be purchased for individual series and sometimes even for each model. Because some manufacturers charge a fair amount for their software, software costs should be carefully reviewed when selecting PLC brands and models.

3.10.1 I/O's (inputs and outputs) are generally digital or analog. Digital I/O is commonly referred to as "discrete". Inputs "circuits" may include a single sensor or a number of sensors feeding into a single input. The general practice is to connect single devices into individual I/O, which allows the program to have more specific control of the equipment. Most input circuits are solid state (SS). Output circuits usually energize single "loads" through a solid state device or internal relay contact.

Many PLC designs minimize the number of physical terminals by using a "common" terminal for a group of I/O. Commons are typically internally wired in groups of 1, 2, 4, 8 and 16. When a "group" of I/O is tied to a common, the field devices (sourcing/ sinking) must match the input I/O (sourcing/ sinking). The voltage requirements must also match. As an example, if four Solid Start outputs have a single common terminal then four sinking or four sourcing outputs devices must all share the appropriate common. Sinking and sourcing types of field devices should not be intermixed with the same common.

The PLC documentation should always be referenced to determine the internal
arrangement of I/O's. For some PLC's, output 1 (and sometimes) output 2 are designed for unique or high speeds purposes and are configured with their own commons. Because both of the terminals are available for these special I/Os, in many cases, they can be wired for either sinking or sourcing circuits, and many types for different voltages.

One example where "isolated" outputs are useful is where it is desired for the PLC to control a stepping motor, eliminating the cost of the Stepping Motor Controller. Stepping Motor Drivers commonly require a high speed signal (usually 30K hz or below). It is also common for these signals to only be 5 VDC.

3.10.2 Sinking and Sourcing: Because of the nature of Solid State (SS) devices it is important to understand Sinking and Sourcing inputs and outputs.

Sinking inputs are where voltage is applied to the common and the input is true when the input terminal is grounded. (Diagram J- Left)

Sourcing inputs are where the common is tied to ground and the input is true when the input is supplied with a "sourcing" voltage. (Diagram J- Right).

Sinking outputs are where the common is tied to ground and when the output is activated or true, the output terminal is "sunk" to ground.

Sourcing outputs are where the common is tied to a voltage and when the output is activated or true, the output terminal is "sourced with a voltage.

Sourcing outputs use PNP transistors. Sinking and outputs use NPN transistors. Sometimes outputs are referred to as PNP or NPN respectively.
Diagram J: Sinking/ Sourcing. Transistors "turn on" when the voltage difference between the Base (B) and the Collector (C) is sufficient (usually about 1 volt). When the transistor is "on", current is allowed to flow between the Collector and the Emitter (E), effectively acting as a set of contacts.

Sinking inputs are designed with an internal limiting resister that usually holds the current to about 10ma or less. Such low currents are designed to prevent overheating when field devices "short" (or sink) the input current to ground, even when the short is maintained indefinitely.

Note: It is very important to know if inputs and devices are sinking or sourcing when making measurements during startup and troubleshooting. The sinking input terminal of a PLC typically measures close to 0 VDC when true. The sourcing input terminal of a PLC typically measures 24 VDC when true. Two opposite voltage results can be measured for "true", depending on if the circuit is sinking or sourcing. Most PLC's display input and output LED's and the input LED's are illuminates when the I/O is true, regardless if the circuit is sinking or sourcing.

Note: Because there is always a small voltage drop across SS devices, about a 1.5 VDC (instead of 0 Volts) can be measured when a Sinking output is "on". When "off" the voltage will usually be 24 VDC.

Some field devices have an additional wire which allows the device to be wired for either NPN or PNP circuits. Devices with mechanical contacts, such as an internal reed switch can also be used in either Sinking or Sourcing circuits because without the solid state Base (B), current is free to flow in either direction.

3.10.3 PLC Inputs/ Outputs: It is fairly common to find smaller numbers of outputs (usually, 4, 8 or 16) to be grouped together to minimize the output current. For inputs, because the current is typically so low it is not uncommon to find one common for 16 inputs.

Many PLC's with SS inputs allow the inputs to be defined as sinking or sourcing, depending upon how the input commons are wired. This means that, all
sensors and input devices need to be either sinking or sourcing, for that system.

Note: There are countless types of sensors/switch devices: Proximity, Pressure, Temperature, Flow, Ph, Level, and many more. Devices that use a mechanical contact usually only have a single pair of output wires. Devices that incorporate solid state technology usually have three or more conductors: power, ground, and return signal. Because of the variety of possibilities, documentation for every sensing device should always be used to verify how devices should be connected to PLC inputs.

A detail worth mentioning is that many sensors can be ordered with and without an indicating LED. It is recommended that devices with LED’s be specified whenever possible. The advantage of the sensor LED is that it is much easier to adjust and verify sensor operation in the field. By observing the LED, sensor adjustments can be made without requiring a second person to report the condition of the Input LED at the PLC.

3.10.4 PLC Outputs: If a PLC output is a mechanical relay contact, then either sinking or sourcing loads can be controlled. Of course, care must be taken to review how the "commons" are connected within the PLC.

Note: because outputs have a limited load capability, the current of all loads should be verified. If the load is too high for the PLC output, the output may be damaged. The solution is to wire an appropriate relay or contactor between the output and the actual load. The PLC documentation will show that most PLC outputs contacts are capable of between .5 and 4 amps of current. This is usually enough to pull in the coils of most relay, contactors and control valves, but not always. The current capabilities of SS outputs are usually lower than relay contacts. If the load capability of an output is inadequate, a contactor or relay can be placed between the output and the load. Such relays are commonly referred to as "interposing" relays (between the PLC output and the load coil).

Interposing relays are also used to interface between differing output and load voltages. As an example, if the control voltage for a group of outputs is 24 VDC, an interposing relay could be used where the contacts could be wired to control a 5 VDC or 120 VAC or some other differing load voltage.
Some PLC outputs are designed to be universal, such as when the output has an internal relay contact. However, care should always be used to verify how the manufacturer intended the inputs and outputs to be used.

The use of organizing groups of contacts together to be compatible with various voltages and sensor types (sourcing or sinking) is often very helpful. An example would be where a group of devices operate on 120 VAC and another group operates on 24 VDC. It is good practice to connect all of the 120 VAC devices to inputs with one common or "bank" while the 24 VDC devices would be wired to a different group.

While contactors will control higher voltage and current loads, the control "coil" voltage of contactors needs to be specified/ordered to match the control voltage of the PLC and control system. As an example, it is fairly common to design output circuits to operate at 24 VDC while contactors may control 480 VAC loads. It is important to not confuse the voltage of the coils of a device from the voltage capabilities of the output contacts of a device. For consistency within a system, it is usually good practice to specify all relays, contactors, control valves, etc. to operate on 24 VDC or some other practical voltage.

3.10.5 Analog Input and Output circuits: Analog input and outputs circuits are very common for PLC's. There are other configurations but most PLC analogue I/O and field devices typically operate on either 0-10 VDC or 4-20ma.

Some analog field devices are only available in either 0-10 VDC or 4-20ma, while many devices can be field selected through jumpers, dip switches or programming.

In some cases a 4-20ma device can be field converted to 0-10 VDC through the use of a 500 ohm precision resistor. As the current flows through the precision resistor, a proportional voltage drop is produced. In these cases a 0-10 VDC input would be connected only across the resistor, detecting/measuring the voltage drop as the field device provides a current between 4-20 ma. However, in a situation where a field device provides a 0-10 VDC signal, an interface device will usually be required to convert a field 0-10 VDC signal into a 4-20ma input.
Note: Analog systems usually need to be calibrated, using the expected maximum and minimum voltage or current to determine the full range of the measurement. Technical support from the manufacturer of Analog devices is usually a very good source for how to setup these calibrations.

Additional study is recommended for Analog technology because it is an extremely broad subject, including instrumentation.

3.10.6 Communication: A large number of components, usually instruments are capable of communicating through a number of digital serial communication protocols. Common "serial" protocols are RS232, RS485, and Ethernet. Serial communications allow for "digital" information to be requested, and sent between various devices.

Through the use of serial communications, a requesting device would send various pre-defined strings of characters. The receiving devices would recognize the string and respond with a pre-defined string/s of characters back with the requested information. Sending devices can usually receive and set parameters in the receiving device. One of the great advantages of serial communications is that the types of information that can be sent and received is potentially unlimited, including measurement values. The documentation for the receiving devices will provide a list of the commands that will be available.

One example could be a temperature controller. The PLC could command a temperature controller to ramp up temperature at a desired rate. The PLC could then periodically request the temperature value until a critical temperature is reached. At the critical point the PLC could be programmed to respond as needed for the process. Serial communications greatly expands the potential capabilities of control systems.

An alternative to serial communications is to use discrete I/O. In place of the communication connection, a number of PLC inputs can be wired directly from the outputs of a field device. An example of this could be for a number of discrete contacts from a field device to "close" when various temperature levels are detected. While discrete I/O are very dependable and straightforward, as the need for information increases so does the number of discrete I/O inputs. At
some point, serial communications becomes more cost effective.

One of the initial problems with RS232 was that an individual communication port and cable was required to communicate with every individual field device. Another significant problem was/is that the maximum length of the communication cables between devices is less than 50 feet. Newer versions of RS232 allow for multiple devices.

RS485 is very similar to RS232 but with a number of improvements. One of the more important features is that the maximum cable length has been increased up to about 4000 feet. RS485 also allows for multiple devices to be connected to a single RS485 port. This is accomplished by assigning a device number (ie. 1, 2, 3 etc.) to each of the devices connected to a RS485 input.

A device number becomes part of the request and return strings so that specific field devices can be identified with various field devices. All of the devices are "listening" but only the appropriate device will respond when it recognizes its own identification number. (Note: The multiple device capability was also later added to many RS232 field devices). The multiple device features requires each of the field devices to be "programmed" to identify its particular device number.

Today, some instruments and field devices can be ordered with either RS232 or RS485 ports. However, many devices are only available with one type of port. Since RS232 and RS485 cannot be directly connected together, incompatibilities can be overcome by incorporating RS232 to RS485 converters.

The recent trend has been for various "forms" of Ethernet ports to be incorporated into PLC's and field devices. There are a number of proprietary "Ethernet" types of protocols, including classic Ethernet itself. Care must be taken to ensure that all of the devices will communicate with the same protocol. Because of greater speeds, intranet and internet capabilities, Ethernet communications offer a tremendous improvement over RS232 and RS485 communication protocols. Another great advantage is that wiring is accomplished with standard CAT5 cables and connectors.

Note: If a system is designed to use a standard Ethernet system, it usually
becomes very easy to remotely communicate and program PLC's and other Ethernet devices. However, because process Intranet systems may be accessed from the Internet, it is very important to address potential security issues.

Note: All communication ports included in a process should be illustrated on the Process I/O diagram.

3.10.7 Touch Screen Operator Interface: Probably the most powerful device that is connected to the PLC through communications cables are Touch Screen Operator Interfaces. These devices are basically embedded computers with display panels that can be programmed to display virtually anything that any computer monitor can display.

Different screens can be programmed to display "virtual" lights and buttons. Virtual lights can be programmed to mirror the on-off status of PLC inputs and outputs in real time. Because of the "touch" screen capabilities, "virtual" buttons can simulate physical buttons. Text boxes can display data registers within the PLC and process parameters can be loaded from number input boxes on screens into PLC registers.

Data from PLC registers, such as from an analog input can be displayed and even graphed in real time. A tremendous capability of most operator interface devices is that a fair amount of data can be stored within the device. A very useful example of data storage is to "log" error messages. Error messages can include, a description of the event, the time and the date. This information can be invaluable to align cause and events for process troubleshooting.

While operator interfaces provide the possibility of tremendous power and control, their incorporation into control systems should be carefully evaluated. Operator Interfaces carry a fair amount of additional hardware and programming costs. What is more significant is that for many control systems, especially smaller projects, good designs should be so robust and intuitive to operators that Operator Interfaces may add little or no value.

3.10.8 Expansion modules: There are generally two physical configurations for PLC's. The first configuration is PLC's with a fixed number of
inputs and outputs. These configurations of PLC's are often referred to as "shoe boxes". The second configuration uses various "rack" systems where a large range of types of input and output modules can be mixed and matched. As an example, while it is good practice to maintain consistency within a system, both Sinking and Sourcing modules could be mixed together to allow for any type of field devices. Regardless of if a shoe box or a rack systems is specified, there is a finite number of input and outputs modules that can physically be attached to the PLC. For bigger systems, one solution that most PLC manufacturers offer is the addition of "expansion" racks or modules.

Expansion racks/ modules usually communicate through a parallel cable, which restricts the distance between the main PLC unit and the expansion racks.

3.10.9 Another solution to expanding the number of I/O is "distributed" architecture. Distributed systems are similar to expansion modules, except, instead of using expansion cables, Ethernet or similar types of proprietary communications are used to network various PLC's, and "remote" I/O racks together. When connections are made to expansion or distributed racks the main PLC usually automatically detects the new I/O. Therefore no additional program setup is usually required. However, some manufactures, especially with older systems require the programmer to "map" or specifically define each of the extended I/O's.

For some applications, distributed systems offer a number of advantages. Not the least of which is that the number of inputs and outputs is greatly expanded. A major disadvantage of non-distributed control systems that extend over larger distances is that the total length of wires between all of the field devices and the PLC can become extremely large. Distributed systems can greatly reduce the amount of wire by allowing a group of field devices to be connected to field "hubs". The "hubs" then only need individual communications cables back to the main PLC.

Distributed systems are typically designed so that if a distributed module or even the main PLC fails, the rest of the system will continue to operate.

A situation where distributed systems can be helpful is when a machine is too large to ship in one physical piece. The common problem is that when the
machine is physically separated into shippable size sections, there may be hundreds/thousands of wires that will need to disconnected and then reconnected onsite. One solution is to incorporate a series of plugs and receptacles. However, plugs and receptacles increase the number of connections that can reduce the reliability of the control system. Even though a machine may be physically smaller, because communications cables are simpler than massive bundles of wires, distributed systems may be appropriate, even on "smaller" projects.

3.10.10 Modular vs. Integrated Systems: As PLC's became more powerful, and as more types of I/O became available, it became possible to integrate a tremendous amount of the control system into a single PLC, including much of the instrumentation. In addition to the typical discrete I/O, highly integrated systems usually also have a fair amount of analog Inputs and Outputs. Many models of PLC's also offer specialized modules, such as thermocouple and Resistance Temperature Detectors (RTD's). With analog and specialized modules a variety of sensors can be wired directly into the PLC, math and control loops can then be programmed to control a variety of types of outputs through Proportional-Integral-Differential (PID) program blocks, creating PID control loops.

While "integrated" systems appear to be "cleaner" and compact (ie. less external instrumentation) these systems have some disadvantages. The biggest issue is that troubleshooting requires very in-depth knowledge of these systems, including the use of Software development tools. This can be especially problematic if the original PLC programmer is no longer available.

A very effective troubleshooting techniques is to swap instruments or components to isolate the source of problems. This technique is fast and guarantees that factory calibrated instrumentation has been put into service. However, if "instrumentation" is integrated into the PLC, these types of troubleshooting techniques are usually lost.

Integrated temperature control system example: Instead of a dedicated Temperature Controller, an integrated system would receive temperature signals through a thermocouple or RTD input module. The set point and other information would be entered into the PLC. This would be a good application for
an operator interface screen. The output signal could possibly be sent out to the heater control (usually a solid-state device) through an analog output. If there is a failure of any one of these devices, because of the integration, it could be difficult to track down the problem, whereas, a dedicated temperature controller could easily be replaced.

Note: Other advantages of most off-the-shelf control modules are that they are often the result of extensive product development and testing. For integrated system, all additional features need to be programmed/ added into the design.

There are certainly situations where both approaches are appropriate. The advantages and disadvantages should be evaluated when designing system architectures.

3.10.11 Control Valve wiring. One of the major categories of outputs or "loads" is control valves. Control valves usually control pneumatic or hydraulic actuators. Hydraulic and pneumatic systems are extensive subjects that are not covered here. However, wiring to these systems deserves some discussion.

For many situations it is best to mount individual valves away from the control panel. For other applications it is best to implement manifold valve systems which are close to the control cabinet. The basic question to determine which approach is best is if it is more appropriate to route the control wiring out to field devices or if the valves should be centralized, requiring more tubing/ piping to be routed back to the control panel.

If control manifolds are more appropriate, the next question is where the manifold should be mounted in respect to the control panel. The first choice that many new control designers often specify is to mount the manifold inside of the control cabinet. The problem with this is that code does not allow for piping and tubing to be inside of the electrical control cabinet. There may be exceptions if appropriate physical barriers and other requirements are met, but generally, "plumbing" inside of electrical control cabinets is more trouble than it is worth and should be avoided.

One of the reasons for wanting to mount manifolds inside of the control cabinet is to help prevent unauthorized adjustments. If security is an issue, a much
better alternative for code and other practical issues is to incorporate a dedicated Valve Control Cabinet. If needed, such cabinets can provide security by incorporating locks and keys.

For many systems (especially smaller systems) a very good location for mounting manifolds and related fluid equipment is to the outside of the electrical control cabinet. This allows for the valves to be fully wired into the cabinet, minimizing the field wiring when the panel is later mounted to the equipment.

[Image of pneumatic control on the back of a control panel]

Picture of Pneumatic Control on the back of a Control Panel. Bank of valves to the left. Main air solenoid valve, center top. Air regulator and lockable shut off valve, upper right. Air pressure monitoring sensors, lower right.

Older and smaller valve designs usually require a single control cord per valve.
Many manufacturers design electrical raceways and electrical plugs inside of their valve manifolds. This allows for valves to be changed or replaced simply by unplugging and plugging new valves onto the manifold without having to deal with the solenoid wiring.

Some newer manifold designs eliminate most of the wiring by controlling the valves through a proprietary communication cables, essentially a mini-distributed approach. For these products, the location of the manifolds is much more flexible because there is only a single communication cable that needs to be connected between the manifold stack and the control cabinet.

3.11 Terminal Strips: Terminals and terminal strips are very valuable for generally making dependable connections but more importantly to divide "field" wiring from "panel" wiring. There are some situations where the field wires should be connected directly to inside of the control panel, such a large wires for bigger motors, but whenever possible all field wires should "land" at a terminal strip.

Terminal strips allow the control panel manufacturer to not have any dangling wires inside of the control panel. Thus panel builder are able to test and verify that all wiring inside of the control panels is accurate and complete, up to the terminal strip.

Because field wiring is usually performed by different personnel than the panel builder, it is much better to have all field wiring "landed" at the terminal strip. Terminal strips allow field personnel to not need to "understand" or to identify electrical components inside of the control cabinet. All that they need for installation is to know what the wire numbers are for each field device. Note: This is another area where the Process I/O diagram can be very valuable.

Also, because terminal strips divide the wiring, startup and troubleshooting is also simplified. If there is a wiring issue, the problem is either inside or outside of the control cabinet. Once the location of a problem is isolated, it is much easier to identify where and who should correct the problem.

3.12 Wire numbers: While troubleshooting systems, it can be extremely time
Consuming to trace wires through wired bundles. Therefore it is very important to specify and adopt effective wire numbering standards. Some of the rules that have proven to work well are as follows:

Wire Number Rule 1: All wires and terminals that are connected directly together should have the same number. Conversely, all wires and terminals with the same number should be properly connected.

Wire Number Rule 2: Both ends of each wire should be labeled with the same number.

Wire Number Rule 3: Every time that a circuit (ie. a wire) is interrupted by a device, other than a terminal, the wire number needs to be changed. Fundamentally, any unique number can be used per wire. However, since it is often necessary to "trace" a field device back to a particular PLC input or output, it is highly recommended that the wire numbers and the PLC I/O be related. As an example if a wire is numbered "X1" (input 1 on the PLC) and is connected to one side of a switch, the wire exiting the other side of the switch could be labeled "X1A" (but never "X1" again).

In the example above, two switches are connected in series into input #1 of a PLC. The first wire would be connected to the PLC input and could be labeled, "I1" or "X1" (or some other consistent labeling scheme). The other end of this wire would be connected to one side of the first switch (the switch could be labeled "S1"). For this example this first wire will be labeled "X1". Following the path of the circuit, the wire exiting S1 could be labeled "X1A" and would also be connected to the first side of the second switch (S1A). If there were other devices to be connected to S1A, the exit wire could be labeled X1B, then "X1C", etc. as the wires "jump" from device to device. The significance of the wire and the component numbers in this example is that "1" is included in all of the
designations, which are related to PLC input number. Different suffixes and prefixes should be added so that the individual wires remain separated from each other. The advantage of this numbering scheme (all designations including the "1") is that all field devices, all of the wiring, and the PLC I/O will be easily identified, which is very helpful for initial installation and troubleshooting purposes. The device numbers should be consistent with the Process I/O diagram.

Note: In the example above, it should be noted that the last wire number in this circuit will not be designated with a "X1B". This is because the circuit will either need a source or a sink signal voltage, depending how the PLC inputs are configured and will therefore be "-" or "+" or "24VDC", etc.

Note: Some PLC software packages use "I" for inputs and "O" for outputs. Others use various schemes such as "X" for inputs and "Y" for outputs. This is important so that input 1, "I1" does not get confused with output 1, "O1". Some manufacturers don't use any prefix-designation but separate the inputs from the outputs by the use of number rangers. One example of this is where inputs are from 0 to 256 while outputs start at 500 to 756. Regardless of the if "I" or "X" or any other designation is used, it is helpful that the labeling scheme on the Process I/O diagram match what the PLC manufacturer used because this allows consistency between the internal program elements of the software to match the Process I/O diagram and the rest of the documentation.

4 Component Selection:

After the Wiring Schematic is completed, specifying all of the major electrical components is simply a matter of systematically selecting a device for every major item on the electrical schematic that meets the electrical requirements and codes.

All components should be appropriately rated for the application. Other characteristics that may be important are, cost, availability, and if similar or the same devices has been previously used, especially if there are spare parts stocked.
5 Panel Design:

The first task of designing any control panel is to determine the physical size of the panel. The easiest method to accomplish this is to draw a scaled representation for every component in the Electrical Schematic that will need to be mounted inside of the control panel. These graphical components can be as simple as a square or a rectangle but they must all be represented at the same scale. It is also helpful to add the device designations to each "component", such as R1, R2, etc.

Most control panels are available with a "back" panel. Back panels allow for a considerable amount of the wiring to be performed on a flat surface, which saves time before being placed inside of the control panel enclosure. The size of the back panel should also be drawn to scale. As different sizes of panels are selected and all of the components have appropriate space, the size of the control panel can be determined. CAD systems are very helpful for these activities.

Adequate space for fingers and "open" space for future additions should always be considered. It is highly recommended that wire ways be specified and included in most designs. Many devices allow/require for wires to exit from the "top" and the "bottom" (when facing the device in the panel) so wire ways should usually be mounted above and below rows of devices. (See Picture Below).
Once all of the components are graphically arranged on the back panel, similar representations should be developed for all of the operator switches, lights and panel instruments. The layout should be fairly close to what was defined during the design of the Process I/O diagram (as shown below).

The depth of the larger components should be reviewed to verify that the components mounted to the back panel have enough clearance with the components mounted to the front door of the control panel. Most control panel designs can be specified with different depths. While unique depths can be custom fabricated, standard depths are usually less expensive. Common available depths are 6", 8", 10", 12", 18" and 24" but the majority of individual machine control cabinets, used for smaller projects is 8" or 10" or 12" deep.

When the assembly drawings illustrate all of the major electrical components, both inside and outside of the control cabinet/s, a Bill of Material (BOM) should be developed. As a minimum, all BOM items should describe the type of each item, such as a "switch" or a "light", an accurate part number, and the brand.

When completed, the Panel Assembly drawings with BOM's and the wiring schematic can be sent out to obtain competitive quotes from qualified panel shops.

Note: A similar set of drawings can be developed for obtaining quotes for the field wiring. Depending upon what other drawings are available, sometimes a duplicate of the Process I/O diagram can be used by adding an appropriate BOM, balloons.
and notes.

Note: Appropriate "Notes" are very important to include in drawing packages. Every company usually develops a standard set of notes (sometimes referred to as "boiler plate" notes). The exact wording may be different but all notes should specify that applicable codes and standards be followed. "Notes" is an advanced topic and it is recommended that further study be made in this area.

5.1 NEMA rated Panels: Code requires that control cabinets and panels be NEMA rated. Depending upon the expected environment the appropriate NEMA rating can be determined. Below are some general guidelines:

<table>
<thead>
<tr>
<th>Nema Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>General purpose. Not recommended for Industrial applications.</td>
</tr>
<tr>
<td>3 Series</td>
<td>Weather Resistant</td>
</tr>
<tr>
<td>4 Series</td>
<td>Water and harsher environments</td>
</tr>
<tr>
<td>7,8,9</td>
<td>Hazardous Locations</td>
</tr>
<tr>
<td>12</td>
<td>General Industrial Applications, <em>(Most commonly used)</em></td>
</tr>
</tbody>
</table>

The categories above are fairly obvious. The majority of industrial applications are installed in Nema 12 cabinets. In addition to the control cabinet classifications, the field wiring also falls into three general categories: Standard Conduit, Rigid Conduit, and Mechanically unprotected. Standard conduit is roughly equivalent to Nema 12.

Note: Where chemicals are present that could result in an explosion or fire, code requires Class 1 wiring. Class 1 wiring is either in rigid conduit or wired through "intrinsically safe" modules. The concept behind rigid conduit is that it is strong enough to contain any *internal* explosion. The approach behind intrinsically safe wiring is that the interface modules limit the electrical energy to prevent sparks. Since the energy that is allowed by intrinsically safe wiring is so small, only standard field wiring requirements need to be applied. As the internal areas of a device increases the resulting pressure from an explosion increases. As the physical size of enclosures increases the construction needs to be much heavier,
so the costs for Class 1 equipment become quite high. Because of the physical
size of control panels, explosive rated control cabinets are usually very
expensive. An alternative is to mount standard cabinets outside of the
hazardous area with either rigid or intrinsically safe wiring to the field devices.
Class 1 application is an advanced topic, which requires additional study.

5.2 Good wiring practices and EMI issues: "Power" conductors feeding power
to loads such as motors or heaters. "Control" conductors convey signals from
the field into the control system. "Power" and "control" wiring should not be
mixed in the same conduit or wire way. When current flows through a conductor,
a magnetic field is generated which can generate Electro-Magnetic-Interference
(EMI). If two conductors are physically located close enough to each other, the
current in one conductor can generate a voltage in the second conductor. This
phenomenon is similar to how a transformer functions. If the magnitude of a
power conductor is large enough to generate a voltage spike in a control
conductor a "false" signal may be generated in the control wiring. Because of the
typical high current surges in motor circuits, most motors and loads are not
affected by EMI.

False spikes generated in the control wiring can be quite disruptive for control
system logic. To complicate these issues, these types of false signals tend to be
random which make them extremely hard to track down and correct.

It is possible for power conductors and signal wiring to be in close proximity to
each other and not create any problems. A significant factor is the length of
"contact" between the two types of conductors. One situation where power and
control conductors may come into "brief" contact with each other is inside of
control cabinets. These short contact lengths are usually not a problem.
However, a good control cabinet design will arrange components inside the
control cabinets to minimize such "contact". Whenever possible PLC input wiring
should be ran in different wire ways than from output wiring.

Instrumentation signal wiring is typically very sensitive to EMI. The solution for
most instrumentation wiring is to use shielded twisted pair cabling.

Note: While shielding can be very effective in guarding against EMI, if cable
shielding is connected at both ends (one at the field device and one end at the
instrument) a "ground loop" will be formed. This is an advanced topic but in general the best method to avoid ground loops is to specify that only one end of instrumentation cable shielding be grounded, usually at the instrument input connections.

5.2.1 Another source of EMI is if control wiring is exposed to high energy radio waves (such as an RF welder). In these environments, every unshielded conductor can become a small antenna that can potentially produce false spikes/signals. The best solution is to "shield" all wiring. Another solution is to install Ferrite Beads on the ends of the signal wires.

Note: There is an advantage for using sinking inputs where EMI is an issue. This is because spikes are usually positive. The false state of a sinking input is already at some elevated voltage; therefore, a higher voltage spike usually has little or no effect on the logic of the input. However, a positive spike into a sourcing input is much more likely to be detected as a false signal.

5.3 Interlocks: Many control cabinet are designed with a mechanical interlock between the door/s and the Main Disconnect Switch for safety purposes. (See Picture Below). There are also electrically controlled interlocks which can be used for auxiliary or remote panel doors.
Some troubleshooting functions must be performed while a control system is energized. Therefore main interlock devices usually incorporate an "over ride" option which allows doors to be opened without interrupting the power. It should be remembered that just because a control Cabinet Door is open, this doesn't mean that it is safe to work within the control cabinet.

Furthermore, in many instances, if a "tool" is required to open an access door or panel, code does not always require interlocks. The potential danger here is that any tool, including something as simple as a screwdriver or a quarter allows non-qualified personnel to be able to open electrical access doors while systems may be energized. Just because a door can be opened, it doesn't mean that it is safe to enter into or work inside of the control cabinet or a machine. High voltage labels should also be placed on appropriate doors and observed.

The master disconnect switch, usually located in an upper corner of the cabinet should have the incoming power being fed down through from the top. This results in a "zone" towards the top of most cabinets that should be avoided.

It is important to know that even when the main disconnect interrupts the power, there is still power in and around the main disconnect switch. While it will be safe to work in most of the interior space of the control cabinet,
caution should always be used because there is still some power present inside of the control panel.

To completely remove power from the cabinet, the Circuit Breaker supplying power to the cabinet and through the feeder lines needs to interrupt the power. This would definitely be necessary for any work on the feeder lines or the main Disconnect Switch and is a situation where proper Lockout and Tag out procedures should be followed.

An additional precaution is to have "finger" safe guards covering the connections inside of the control panel. It is important to be aware that many older panels may not have finger safe guards. Also, finger safe guards may not prevent tools and chips (when drilling holes) from coming in contact with the power terminal.

While requiring a "tool" to open a panel may meet code, in many cases the design engineer must evaluate if more protection may be prudent. In such cases, electrically controlled interlocks can be used for auxiliary or remote panel doors. For these applications a key operated override switch can be installed. However, only qualified personnel should have access to such keys and they should understand that they are responsible when a panel is opened with live voltage.

5.4 Control Panel Accessories: Besides a variety of mechanical and electrical door locks, there are a number of accessories that can be included in control panel designs.

For larger, especially deeper cabinets, internal lights are available that make it much easier to work inside of the control panels.

A major issue that needs to be considered when designing most control systems is the amount of heat that can be generated inside of a control panel. Transformers and large power supplies are usually the largest sources of heat. If the internal heat load is small in comparison of the physical size of the control cabinet, the operating temperature of the cabinet will remain within reasonable limits. However, if the heat load is too large, cooling fans may need to be installed.
The challenge with cooling fans is that for hot air to go out, cooler air must be allowed to be let in. Many control cabinet manufacturers provide louver and fan kits. However, the louver kits usually allow a tremendous amount of dirt to enter into the control cabinet. One solution is to specify better filters. A practice that has been very effective has been to use a series of car air filters (shown below). And yes, the design engineer will probably take some "ripping" for their use of an automotive product. However, these filters are high quality, readily available and inexpensive.

For some applications, where there are harsh chemicals, "conductive" dust, etc. it is not appropriate to cycle enough filtered air through the control cabinet. A solution for these types of situations is that cabinet manufacturers provide air condition units where heat is removed without any air entering or exiting the control cabinet.

For control panels mounted in cold conditions, temperature controlled heaters may need to be specified.

Other types of accessories are available but one that is commonly needed is a unit that controls the humidity inside of control cabinets.

Manufacturer application engineering departments are good source for how and when to use the available control panel options.

6 Software Development

PLC programming is an extensive topic. Therefore the following description is only
meant as a brief introduction.

6.1 Ladder Logic: PLC's were introduced in the early 1980's. Before that time, most of the logic components used for control systems were limited to relays, timers and cam timers. The standard practice for wiring schematics was to have vertical power rails where the power usually flowed from the left, controlled by various logic elements (ie switches and sensors) where loads would be positioned next to the "right", 0 volt or neural rail. This general arrangement simulated a "ladder", and thus was given the term, "ladder logic".

![Diagram K: Two vertical Rails, with power flowing from left to right. Control Elements (usually diagramed on the left) allow power to energize outputs and loads (usually diagramed on the right).](image-url)
Diagram L, Ladder diagram structure using PLC: The essential "ladder" is still commonly used to describe PLC's inputs and outputs (I/O). Essentially, power flows from the left, through the control elements (ie. switches, pushbuttons and sensors) into the PLC inputs. These inputs allow the programmed logic to control the outputs. The power continues to flow from left to right, from the outputs to the loads and control elements (ie. contactors, lights, solenoid valves, and relays). It should be noted that the inputs and outputs of most PLC's (but not all) can be configured for sinking or sourcing. If C1 (Common 1) above is tied to 0 volts then the PLC inputs will be Sourcing (ie. when voltage is detected, the input will be "on"). If C1 is tied to 24 volts (or another appropriate voltage) then the inputs will be Sinking (ie. when the switches or elements "short" the inputs down to zero voltage the input will be "on"). A similar approach is available for the outputs. In this example, please note Commons 3-7, (Com3, 4, 5, 6, 7). Since the outputs of this PLC are mechanical contacts, both Sinking and Sourcing output loads can be driven.
Because ladder logic was widely understood in industry, PLC manufacturers "emulated" ladder logic in their programming. Instead of actual wiring, virtual wiring was entered into the PLC programs. "Real" wires connect sensors, switches, coils etc. to the I/O terminals of the PLC, but once connected, the internal wiring is "virtual". The advantage of virtual wiring is that it is considerably easier to modify than physical wiring.

6.2 Special Control Modules: Because PLC relay logic is not "physical", whole new virtual devices have been developed for PLC's. Examples of special functions are; stepping motor functions, keypad input functions, PID loop functions, and many others. Special function blocks are usually represented as a "box" in most PLC software so that the necessary "software" inputs and outputs can be "connected". These blocks usually contain critical variables, with important data being stored within designated registers. PLC's can be extremely powerful because register values can be programmatically modifying according to various conditions. As an example, there will usually be a designated register for the distance, the maximum speed, the acceleration and the deceleration of a stepping motor function. Therefore conditions can be programmed to dynamically control the distance and speed as needed, allowing for tremendous creativity and flexibility.

The documentation of PLC's is the best source of what custom logic blocks are available, and what parameters can be controlled by the program. Technical support may also be helpful.

6.3 General Programming: The general programming approach is to develop a series of logical events to control each of the motions or functions. The Process I/O diagram is extremely useful to accomplish these tasks. Once each of the functions has been programmed, they can then be logically arranged together. Miscellaneous I/O and the operator interfaces noted on the Process I/O diagram can then be addressed. Essentially, the Process I/O diagram is a "road map" for what needs to be implemented in the program. By using the Process I/O diagram, mental cartoons of the functions can be visualized. At such a point the programmer only needs to convert the sequence of operations into PLC code. A very effective approach is to program a series of logical steps, each responding to feedback from various sensors, timers, etc. to initiate the next step.

6.4 Math: Before PLC's, it was fairly difficult for control systems to implement math. However, the math capabilities of PLC's have opened whole new areas of
applications. The general approach for math calculations for many PLC's is based around the use of the "accumulator". The typical sequence for math functions is: 1) A value is transferred from a memory register into the accumulator. 2) A math operation (such as +,-,*,/) is called along with a second memory register. 3) The value in the accumulator is replaced with the result of the defined math function. 4) The value in the accumulator is usually then transferred back to a desired memory register (such as the maximum speed of a motor function). Again, the PLC documentation is usually very helpful to determine what parameters can be altered and exactly which memory location needs to be accessed.

This four step math process is relatively cumbersome; however, with a little creativity, by calculating values and loading them into the various special function block registers, the overall results can be very effective and powerful.

6.5 E-Stop Events: As parts of a machine/ process are cycling through their various sequences, E-Stop events can easily create significant "confusion". Sometimes, it is necessary to design logical recovery sequences that provide for orderly recover of the process after an E-Stop reset. For the PLC to recognize an E-Stop event, a contact from the E-Stop system should usually be feed into a PLC input. E-Stop input should not be used to affect E-Stop functions but they are valuable to "halt" the program and to allow for orderly re-start of the process when the E-Stop is reset.

Another type of event that should be considered is how to recover from a power loss. The consequences of power loss and what will be needed to recover for any step in the process needs to be carefully considered. For many systems, power loss is equivalent to an E-Stop event. However, if parts can be dropped as a result of power loss, or if there are time sensitive steps (such as glue drying) it may be necessary to have all of the "parts" removed from the system before a restart can be initiated. The unique features of every system need to be addressed, but most systems should be evaluated for both E-Stop and power loss events.

6.6 Reset Buttons: A Program Reset button is usually very helpful for initially starting a process, recovering from power loss events and sometimes for E-Stop resets. When Program Reset buttons are initiated, the PLC can be programmed to clear appropriate PLC registers, restart timers, and set counters back to their appropriate conditions. In more complex situations, the Program Reset Button may
be need to be used to initiate sequences that will automatically return movements safely back to their "home" positions.

6.7 Stop Buttons: It is poor practice to use E-Stop buttons to stop a process; therefore a Stop Button should be incorporated to allow the operator control of the process. A primary difference between the Stop Button and the E-Stop Buttons is that the E-Stop should stop all motion immediately, whereas the Stop Button should usually signal the PLC to come to an orderly stop at the completion of the current set of sequences. In many systems, it doesn't matter if the process is stopped in mid-cycle. However, Stop Buttons are necessary for systems where it is very important to only stop at appropriate "stages" or steps of the process. Thus the program can be designed to properly respond when the Stop command is detected.

7 Installation and Startup

7.1 Electrical Shock Safety: There are very few situations where controls cabinets should not be "locked" electrically or mechanically when energized. However, troubleshooting activities, may require measurements to be taken or adjustments to be made which may dictate some potential exposure to high voltage and possibly various other kinds of energy. Therefore, safety must always be the highest priority when working around control systems. Only qualified personnel, wearing appropriate Personal Protection Equipment (PPE), should perform potentially dangerous tasks.

While all applicable codes and standards should always be followed, it should never be assumed that a system is safe, just because the main disconnect switch is in the "off" position. Wiring errors, improperly modified systems, and a number of other reasons may allow high voltage to exist, even when the power is expected to have been removed. Therefore, properly trained personnel should always verify that all power has been removed and that a system is safe, before proceeding to work on and around a control system.

7.2 Multiple Power Sources: The main disconnect switch may remove one voltage source but Code does allow for situations where more than one power source can be fed into a control cabinet. Whenever possible, multiple power sources should be avoided. In the event that multiple power sources are unavoidable, all applicable codes and appropriate warning labels should be applied.
Therefore, all employees working around control systems should have appropriate training and especially be alert to all safety labels.

7.3 Arc Flash Safety: Arc Flash is the result of a direct short which produces a high energy shock wave. In addition to the "blast" produced from an arc flash, an additional danger is the high velocity micro-bullets of molten metal that can be expelled. Blast radii can be lethal from relatively short distances up to many feet.

A direct short can be the result of a short circuit but human error (such as dropping a tool) is probably the most common cause. Since such blasts occur while personnel are usually working close to energized systems, arc flash incidents can easily become quite serious.

There are formulas for determining the magnitude of Arc Flash Blasts. Such determinations involve a thorough understanding of the science and therefore it is highly recommended that only qualified personnel determine the extent of the Arc Flash danger.

Note: Arc Flash potentials greatly dependent upon the available power source, so it is extremely difficult for equipment manufacturers or control designers to anticipate the appropriately level of Arc Flash Hazard. Therefore, properly qualified resources should evaluate and label systems for Arc Flash hazards as part of the installation and commissioning process.

Note: Many older control systems do not have proper Arc Flash Labels. Therefore, the arc flash potentials of both new and existing systems should be "surveyed" by appropriate consultants or personnel.

Again, the blast from an Arc Flash may be relatively small but molten "micro-bullets" could easily cause serious eye injury. Therefore, **appropriate eye protection should always be used.** In more extreme cases, the Arc Flash potential will require complete protective suits. The Arc Flash analysis and the appropriate protective equipment should always be available during the installation and startup phase of projects.

7.4 Lockout and Tag-out Procedures: Lockout and Tag-out procedures are not covered in detail in this discussion but they deserve mention. Standards exist
that should be used to develop appropriate Lockout and Tag-out procedures for every piece of equipment in a facility. The basic goal of these procedures is to ensure that all power sources and energy is removed before work is performed, and to ensure that all personnel are clear before re-energizing.

E-Stops should guarantee that all motion is stopped, but it does not guarantee that all energy has been removed. Therefore, E-Stops should never be considered as an acceptable substitute for work that should only be performed with appropriate Lockout and Tag-out procedures.

Some of the most gruesome industrial accidents could have been prevented if proper Lockout and Tag-out procedures had been followed. It is very important for appropriate procedures to be developed, and reviewed by appropriately qualified resources. It is also important that management take steps that these procedures are strictly followed.

8 Documentation

The value of good documentation should never be underestimated. If the Process I/O diagram has been properly developed, it will be a good foundation for writing the "maintenance" manuals.

Sometimes maintenance manuals and operator manuals are confused. In most industrial environments "operator manuals" are probably best described as "work instruction". While a work instruction will take some information from maintenance manuals, the majority of the information will be how the operator is to perform various tasks. Some of the tasks will involve interface through the control system but many tasks, such as safety practices, inspection, material/ part handling and others should be included in work instructions.

8.1 Maintenance Manual Basics: A title page is helpful and should have the name of the process or machine with the appropriate equipment number (if applicable). There should also be a "version" date in the event that there may be changes or updates. Sometimes a picture of the equipment is helpful.

An Index is important for a quick reference to the various sections of the manual.

An introduction page should start with a brief description of what the equipment is designed to do. The maximum production rate and other important variables
should be noted. It is often helpful to describe what is produced and if appropriate, the part numbers.

8.2 Safety Warnings Page: A "Safety Warnings" section should include all of the appropriate safety warnings. Additional warnings should be added for general operation, maintenance activities, and for any operations that may cause damage to the equipment or parts.

8.3 Facilities Requirements: An itemized list of the facilities requirements, including the required power, air, water, exhaust, special footings, etc. This information should be duplicated on the Machine Name Plate.

8.4 Equipment Set-up: Pictures are very helpful and should be included where appropriate in this section.

All critical weight and lifting requirements should be designated, and if appropriate a lifting point diagram.

All critical height, alignments and leveling requirements should be specified. This information will be needed by the mechanical installers. If appropriate, any anchoring that may be needed.

The location of all "facility" connections should be identified. Examples are: pneumatic, water, drain, exhaust air, steam, piping, etc.

The Process I/O diagram can be used to develop brief descriptions of the sequence of operations.

The direction of all motors should be defined so that they can be verified. A check list should be added when appropriate and should include the full operating current of all major loads.

A check list for all communication and other non-power wiring cables that should be verified before attempting operating the equipment/ process.

A list of how all adjustments (mechanical, sensors, etc.) should be described. Each item should include the equipment needed to make the measurements, how
the adjustments should be made, and the target set-point. Pictures are usually very helpful for this portion of manuals. The list should be presented in a systematic order, especially when some adjustment may affect other. Any specific warnings or procedures that may occur while adjustments are being made should be noted.

Note: It is recommended that the Process I/O diagrams be updated per any "red line" changes. It is also helpful to document various settings and ranges of settings that may have been discovered/determined through the startup process.

A brief description of all of the operator interface lights, buttons, switches, etc. should be described with an explanation of the expected results.

8.5 Equipment Operation: By systematically using the Process I/O diagram the "theory" of operation can be described.

An itemized list of the parts, fixtures and/or materials that will ultimately be used for production should be included. If appropriate, the loading and unloading of process materials should be described.

8.6 Documents: At lease the following documents should be included.

1. The Process I/O diagram.
2. All electrical and pneumatic/hydraulic schematics.
3. All assembly drawings including BOM's.
4. A printout of the software with comments.
5. A catalogue "cut sheet" for all major components.
6. Operator manuals for all instrumentation, major electrical and mechanical components.

Closing Comments:

The 8 step process that has been described to develop Control systems is based around the development of the Process I/O diagrams. This diagram becomes a roadmap for developing the Wiring Schematics. Wiring Schematics then become a roadmap for selecting the components and the layout of the control panel.
numbers, then the wiring, startup, programming, troubleshooting, and documentation will all be more efficient.

The Process I/O diagram is also helpful for writing and troubleshooting the software as each "function" is included into the program/s.

The final step is to accumulate all of the information and to develop maintenance manual/s.