24 VDC CONTROL – AN EMERGING ALTERNATIVE TO LEGACY 120 VAC CONTROL APPLICATIONS IN NORTH AMERICA

John C. Thompson
Senior Member, IEEE
Project Manager
Cutler-Hammer, Inc.
8850 Stanford Blvd. Ste 3500
Columbia, MD 21045

David B. Durocher
Senior Member, IEEE
Forest Products Industry Director
Cutler-Hammer, Inc.
5000 Meadows Road, Ste 300
Lake Oswego, OR 97035

Abstract – A variety of control voltages are used throughout the world for industrial process control. The most common control voltage in North America is 120 VAC. IEC standards that are widely accepted in other countries including Europe, have used 220 or 240 VAC. Over the past few years, 24 VDC is gaining acceptance. Products based on 24 VDC control are now becoming more available from major manufacturers. This paper will review various issues associated with 24 VDC and 120 VAC control.

I. INTRODUCTION

In the past, control devices have required too much power to make 24 VDC products cost effective or practical. During the past few years, industrial control product manufacturers have placed more emphasis on 24 VDC as the control voltage of choice. Design innovations like increased microprocessor content and separation of control and power circuits have reduced control power requirements. The result has been DC power supplies with improved reliability at reduced costs. Technology advances in power transistor ampere ratings have helped reduce the issues of excessive DC voltage drop over long cable runs. This has led to an increase in the variety of 24 VDC controlled devices along with improvements in quality, robustness, features and size.

Electrical devices that have used 24 VDC for some time include programmable logic controllers (PLC's) and distributed control systems (DCS) central processing units (CPU's), human machine interfaces (HMI's) and input/output (I/O) hardware. Most recently, adjustable frequency drives (AFD's), solid state reduced voltage starters (SSRVS) and servo drives have changed to this control voltage. We are seeing a new generation of contactors, starters, control relays and sensors that will be dedicated to this control philosophy.

Migration to 24 VDC control is being driven by the need for safer operating voltages, simplified compliance with safety standards and more reliable interface with PLC's and DCS.

II. SAFETY CONSIDERATIONS

1) *Evolution from Equipment Protection to Personnel Protection:* Historically, electrical design standards were based on protecting equipment and preventing fires. New industry standards, including those of the National Fire Protection Agency (NFPA) as well as the National Electric Code (NEC) are now beginning to focus on the importance of personnel protection. The prevalent design philosophy today suggests that any time an electrical hazard can be reduced by reducing system voltages to a level that is considered safe, it should be done. Also, any time the available energy level to feed an arc flash can be reduced, it should be considered as a means to enhance safety.

In the past, changes in grounding, ground fault circuit interrupters and double insulation have been adopted for portable tools and equipment. More recently, remote switching and arc-resistant switchgear is being employed to improve personnel safety.

The type of circuit and the contact voltage level have a profound effect upon the resulting injury to people. DC control circuits are not as dangerous to personnel as AC circuits. In general, the sensations produced by DC are greatest when contact is made or broken. Five (5) milliamperes (mA) of DC current produces about the same effect as two (2) milliamperes (mA) of AC current.

2) *Codes and Standards*: Industry codes and standards have changed significantly in an effort to address improved personnel protection from electrical hazards. Article 110.16 of the newly adopted 2002 NEC is a new addition to the code that recognizes recent updates in NFPA 70E-2000 "Electrical Safety Requirements for Employee Workplaces". This new standard addresses the concern of protecting qualified persons who work on energized electrical systems by ensuring they are notified of arc flash hazards and assisting with selection of appropriate Personal Protective Equipment (PPE). Specifically, the new standard states "Switchboards, panelboards, industrial control panels and motor control centers in industrial and commercial occupancies that are likely to require examination, adjustment, servicing or maintenance while energized, must be field marked to warn qualified persons of the danger of electric arc flash. The marking must be clearly visible by qualified persons before they examine, adjust, service or perform maintenance on the equipment." Section 250.2 added to the 2002 NEC includes a new definition of a Ground Fault Current Path. This definition reads as follows: *"Effective Ground Fault Current Path:* An intentionally constructed, low impedance path designed and intended to carry fault current from a line-to-case fault on a wiring system to the grounded (neutral) at the electrical supply source." Both of these new standards demonstrate a clear directive to reduce the potential of exposure to hazardous touch voltages.

Industrial process users have learned the dangers of poorly grounded systems. The notion that a human body in parallel with solidly grounded electrical control circuit is protected because current will take only the path of least resistance, is a complete fallacy. Unfortunately, there is

always some resistance to ground. Electricity does take low resistance paths, including the one with least resistance, but it also takes every other path available to it. Touch voltage from an energized object is about 75% of the rated voltage. So, even a 120 VAC line-to-case fault from a control power circuit has a touch voltage potential of 90 volts. IEEE Standard 80 uses a value of 1000 ohms for the human body to perform touch voltage calculations. This results in a potential for 90 mA of current to flow through the human body. Death from electrocution can occur from as little as 50 mA in only a few seconds. To reduce potential current flow below 50 mA, industry standards suggest that potential touch voltage conditions never exceed 50 volts AC or DC. With a properly grounded system, standards suggest that potential current flow should be below 5 mA.

The Occupational Safety and Health Administration (OSHA) Standard 29CFR 1910.269 states that operating voltages above 50 volts are considered high risk for qualified persons exposed to live parts while equipment is energized. Current OSHA requirements allow employees to work on energized systems under 50 volts without the use of special protective equipment. This regulation states "Live parts to which an employee may be exposed shall be de-energized before the employee works on or near them. Live parts that operate at less than 50 volts to ground need not be de-energized if there will not be increased exposure to electrical burns or to explosion due to electrical arcs." NFPA Standard 70E defines a dangerous touch voltage as anything over 30 volts.

3) *Shutdown and Lockout Requirements*: Based on the voltage and applicable codes and regulations at a site, maintenance on control equipment may require tag and/or lock out procedures. In the United States, 24 VDC work can be performed hot in unclassified areas, but 120 VAC work must follow a tag/lock out procedure.

For classified (Class 1 Hazardous) locations in Division 1, work on energized circuits is permitted if control circuits are considered intrinsically safe. It is also permitted for controls in Division 2 locations that are nonincendiary.

PLC control and I/O cabinets may have multiple power sources. If only the circuit that is being worked on is locked out, there remains a potential safety hazard to personnel working in the cabinet when the remaining control voltages are 120 VAC. Finger safe terminals and terminal shields over the energized components offer some means of protection from exposure to live parts, but using 24 VDC virtually eliminates potential safety hazards.

4) *Safety Statistics*: Although very few industrial process manufacturers track and record data from incidents of electrical shock, the ones that do have found 120 VAC to be one of the most prevalent voltages. One major chemical company that maintains a database of electrical safety incidents based on type of equipment involved, discovered that a majority of incidents of electrical shock occurred on 120 VAC systems. Using 24 VDC control systems should greatly reduce potential incidence of electrical shock.

III. DEVICE CONSIDERATIONS

1) Operating *Speed*: The ability of the control system to detect and respond quickly to events is often a critical issue.

For discrete switching devices, speed is typically expressed in turn-on (pick up) and turn-off (drop out) times. Some devices such as inductive proximity sensors, include device maximum switching frequency as a part of performance specifications. For solid state output sensors and controller I/O modules, devices designed for 24 VDC control are considerably faster than their 120 VAC counterparts. Electromechanical contactors using AC coils are slightly faster than their DC counterparts. Smaller, general purpose relays have almost equivalent response times while larger relays using DC coils are slower. Fig. 1 shows device operating speed for various components based on DC device speeds relative to AC. The differences in device speeds are only pertinent in control system designs that use hard-wired I/O. In networked I/O, the data transmission speed has the greatest impact on response time.
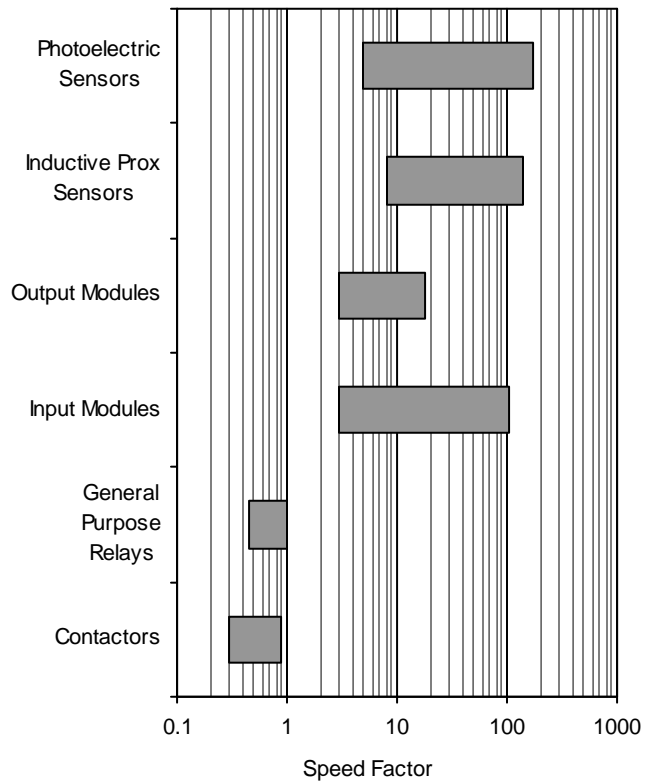

Fig. 1: Relative speed of DC devices compared with AC equivalents.

2) *Size*: The push to reduce cost has led to the minimization of control panel and equipment size. This has led to an increasing demand for smaller and smaller control devices. Sensors are typically offered in a smaller and wider variety of sizes in 24 VDC versions. General purpose relays are typically about the same size. Contactors and starters are smaller. I/O density is significantly higher for 24 VDC controls, up to 64 inputs/module, while the maximum for 120 VAC is normally 16.

3) *Pick Up/Drop Out Voltage Sensitivity*: Minimum pick-up voltages for relays and contactors are essentially equivalent between AC and DC coils. 80% is a typical specification value. However, DC pick-up cycle time is 2 milliseconds

where AC can be 2 to 10 milliseconds. The pick-up time for an AC device is dependent upon the time during the AC cycle that the control command is initiated. Fig. 2 shows that a control command at time t_o results in a pick-up time as long as 10 milliseconds.
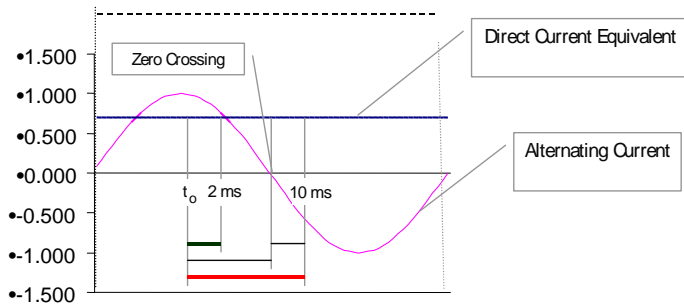

Fig. 2: Comparison of pick-up cycle time for a DC control device versus an AC device.

It is also important to note that the drop out voltage for DC coils is lower than AC coils. Fig. 3 shows test data based on minimum drop out voltage characteristics defined by the Computer & Business Equipment Manufacturers Association (CBEMA) curve. This plots percent voltage retention versus a defined duration of disturbance for various devices tested at a 1.0 ampere load. The test data shows that drop out voltages can be 15 to 40% lower for DC coils. This may significantly improve the reliability of a control system that is subject to voltage dips.
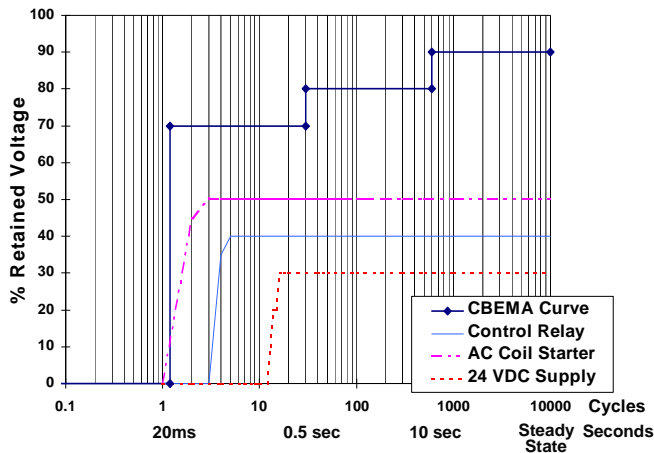
CBEMA Curve Test Results

Fig. 3: CBEMA plot of percent voltage retention versus disturbance duration in cycles and seconds for tested devices at 1.0A load.

4) *Leakage and Latching Current*: Off state leakage current and minimum required latching currents are important electrical characteristic of all semiconductor based switching devices. Failure to consider these issues can lead to control problems including devices not turning on, or worse, not turning off on a control command. Most sensors and output cards designed for 24 VDC exhibit very low leakage currents. Typical values are less than 1 mA. Many 120 VAC devices (such as a PLC triac output) exhibit higher levels of leakage

current, 3 mA being common. Since AC devices exhibit higher leakage current than their DC counterparts, problems with dimly lit indicator lights or general purpose relays that won't drop out can occur. In these applications, a parallel connected load resistor is needed.

5) *On-board versus Out-board Component Design:* Although 24 VDC control logic devices such as sensors, pilot devices, PLC I/O and DCS controls are readily available today, power devices such as contactors and motor starters using 24VDC control have had limited availability. Traditionally, designs of these products have included a DC control coil to magnetize a moving armature to close power contacts. However, the control interface has typically remained a 120 VAC control power source used in conjunction with an on-board rectifier, usually built within the contactor coil. This allowed the use of a DC coil with the associated advantages of low drop out voltages and higher contact pressure, but with the convenience of 120 VAC control. Today, manufactures offer out-board DC power supplies separate from the starter that convert a range of input voltages from 200 to 575 VAC 3-phase or single phase to 24 VDC. These devices can be designed based on criteria different from DC power supplies used to power sophisticated electronic circuits. There is not a need for high voltage regulation, low ripple currents, or inrush current limitation. As a result, an application specific device designed for DC coil control power can be smaller and is available at a lower cost. Functionally, this device replaces the control power transformer typically used in a motor control center (MCC) starter unit assembly.

IV. CONTROL SYSTEM DESIGN ISSUES

1) *Surge Suppression*: Surge suppression devices are normally used when switching inductive loads. With hard contacts, they are needed to suppress transient Electro-magnetic interference (EMI). When solid state outputs are used, surge suppression is required to protect the output circuitry. For AC control systems, a resistor/capacitor snubber or metal oxide varistor (MOV) is typically used. In DC control systems, diode suppressors are normally used.

2) *Control Cable Length*: There are two effects of long cable length to be considered:

- Line resistance and inductance can create excessive voltage drop, resulting in a device failing to pick up.
- Line coupled capacitance can potentially cause a load to not drop out.

Effect of Resistance and Inductance: NEMA standards require magnetic devices to operate at 85% of rated voltage. Current drawn through long control wire runs causes a voltage drop so if the cable is too long the coil will not be picked up and seal in. For AC systems the series impedance of the control wires is the only factor considered when inrush current is present. For example, a typical Size 1 starter's inrush is 210 VA with a holding load of 18 VA. Control wire size should be based on 210 VA. To allow for voltage sags of 10%, the voltage drop in the control wires should be limited to 5% of the rated coil voltage.

For 24 VDC systems there is no substantial difference in the device inrush load when compared to 120 VAC. But the holding load can be up to five times greater. The impact of line impedance varies inversely with the magnitude of the control voltage. So, the effect of line impedance is increased at lower voltages. For 24 VDC systems, voltage drop can potentially be a significant issue. Voltage drop for both 120 VAC and 24 VDC circuits can be compared by the calculations below:

$$\text{Voltage Drop} = \text{Wire Length X Wire Resistance X Current}$$

$$\% \text{ Voltage Drop} = \frac{\text{Voltage Drop}}{\text{Nominal Voltage}}$$

To compare the impact of voltage drop for 24 VDC versus 120 VAC circuits, assume for this example an application with the same power draw, wire size and efficiency. Since 24 volts is $1/5^{th}$ 120 volts:

$$24 \text{ VDC Current} = 5 \text{ X } 120 \text{ VAC Current}$$

Substituting the Voltage Drop formula above, yields:

$$24 \text{ VDC } \% \text{ Voltage Drop} = \frac{5 \text{ X Resistance X Length}}{1/5 \text{ X } 120 \text{ VAC}}$$
$$= 25 \text{ X } 120 \text{ VAC } \% \text{ Voltage Drop}$$

Thus, total percent voltage drop for a 24 VDC control circuit can be a concern for longer cable lengths. This adverse condition can be minimized through the use of a larger wire size (from #16 AWG to #14 AWG as an example) as this reduces the line impedance impact of voltage drop.

Effect of Line Coupled Capacitance: In AC control systems, the effects of line capacitance in control wiring must be taken into consideration. Line capacitance can present a problem in AC control circuits, especially when control devices (such as a stop pushbutton) are in the circuit, remote from the controlled device. Fig. 4 shows an example of coupled capacitance in a typical AC control circuit. The effective line capacitance is the total capacitance between control wires as well as cable to conduit. Factors that determine line capacitance include conductor diameter, the distance between adjacent conductors and distances to the conduit, length of the run and even humidity and water filled conduits. If cable runs are too long, this capacitance will prevent coils from dropping out. The impact of coupled capacitance increases approximately with the square of the control voltage. At 120 VAC, capacitance is generally not an application concern for cable runs under 2 miles. At 480 VAC, cable runs should be limited to under 800 feet. For DC control circuits, the effect of capacitance is not present since capacitance will only conduct an AC current. Selecting DC is one good solution to eliminate the effects of capacitance coupling.

3) *Wiring Practices*: In 120 VAC systems, internal panel and field device wiring can often be grouped with power wiring. This can reduce wiring costs versus 24 VDC systems, where field devices (like sensors) generally require separate routing of conductors.
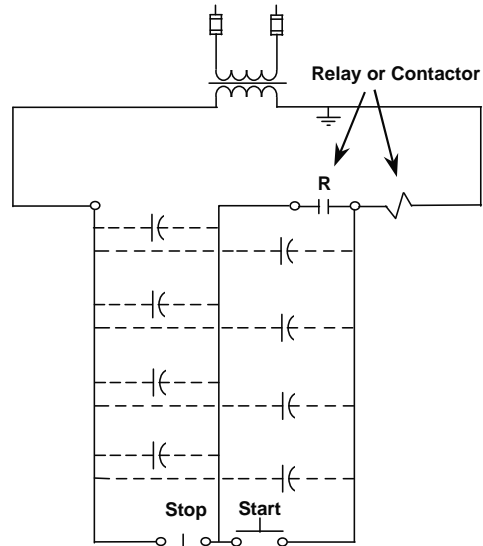

Fig. 4: The effects of capacitance in a 120 VAC control circuit.

4) *Protection Against Drop-out Due to Momentary voltage dips*: Voltage dips are common in industrial process facilities, typically caused by large motors starting on weak or heavily loaded supply systems. Typically, motor contactors drop out at 65% of rated voltage. AC control systems without special protection are far more susceptible to voltage dips than DC control systems because DC power supplies have capacitors in their filters that store energy. Since most dips are less than ten cycles in duration, DC coils have much better ride through capability.

5) *Interfaces With Process Control Systems*: Most programmable logic and distributed control systems use 24 VDC for their interfaces and data highway signals. Careful design can reduce the need for interposing relays and multiple power sources. Introduction of a second power source over 50 V into a cabinet or other control unit should be avoided wherever possible. Special warnings should be posted if this safety hazard exists.

V. RELIABILITY

1) *Control Power Supply Reliability*: Reliability requirements for control power supplies are dependent on the process. If it can be restarted easily, power supply reliability is not important unless safety is a concern. But if restart is very expensive and/or safety is an issue, a reliable power supply is needed.

Typically for AC control systems a UPS is used. Where very high reliability is important, two independent UPS' are used. These typically are fed through an automatic transfer switch with an open transition. One must consider using a very short transfer time to coordinate with the downstream control relays to keep them from dropping out during transition. In most cases, general purpose relays cannot be coordinated with a high-speed open-transition transfer switch but heavy duty machine tool relays can.

DC control systems, on the other hand, can be paralleled and fed from different sources without the need of a transfer switch. This eliminates the concern for downstream relays

from dropping out. Fig. 5 shows a typical connection for both and AC and a DC control system.
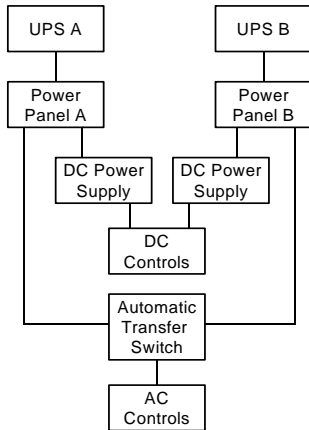


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   ┌─────────┐          ┌─────────┐
   │  UPS A  │          │  UPS B  │
   └────┬────┘          └────┬────┘
   ┌────┴────┐          ┌────┴────┐
   │  Power  │          │  Power  │
   │ Panel A │          │ Panel B │
   └────┬────┘          └────┬────┘
      ┌─┴──────┐    ┌──────┴─┐
      │DC Power│    │DC Power│
      │ Supply │    │ Supply │
      └───┬────┘    └────┬───┘
          │   ┌──────┐   │
          └───┤  DC  ├───┘
              │Controls│
              └───┬──┘
          ┌───────┴────────┐
          │   Automatic    │
          │    Transfer    │
          │     Switch     │
          └───────┬────────┘
              ┌───┴───┐
              │  AC   │
              │Controls│
              └───────┘
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Fig 5: Dual DC/AC Power Source Configurations

2) *Operational Life*: Devices that incorporate electromechanical switching of hard contacts tend to have a shorter life than their solid state counterparts. This is due to contact wear and mechanical failure. Most manufacturers offer only 24 VDC control for solid state devices, suggesting that 24 VDC must be more dependable.

In low power applications for 24 VDC control, contact continuity is an issue that should be addressed. In most cases, oxidation of the contacts slowly increases contact resistance until continuity is lost. The rate and degree of oxidation is due to a number of conditions including contact design, operating current, switching frequency and operating environment. Proper selection of the switching device will reduce or eliminate occurrences of this problem.

Contact material must be reviewed to determine if it's suitable for the application needs. Gold plated contacts typically provide the lowest contact and highest oxidation resistance but have the lowest current carrying capability and mechanical durability. Other alloys can offer better performance but also require higher minimum currents to operate reliably. Mechanical contact design itself can have a significant impact on contact continuity. Bifurcated and pentafurcated contact designs can significantly reduce continuity application issues. Hermetically sealed contacts are available for applications in extreme environment applications operating at very low power levels.

Indicator pilot lamps have a very poor life expectancy compared to other control devices. Published estimated operating hours for 24 VDC and 120 VAC incandescent lamps are approximately equal. 24 VDC LED lamps provide the longest life expectancy.

VI. COSTS

While good design, reliability and safety are key ingredients to a successful controls system, cost is always an important criteria in determining if a particular solution is acceptable. The costs of a control scheme encompasses a variety of items including engineering, startup, operation and maintenance. All of these must be considered when determining the total lifetime costs.

1) *Engineering*: It is difficult to determine the difference in engineering costs, however familiarity and reuse of previous designs is usually a key factor in reducing development time and effort.

2) *Hardware*: The most common and often the only factor considered when designing a control scheme is the purchase cost of the components. In general the 24 VDC versions of the smaller, lower power, devices such as sensors and pilot devices cost less while the larger, electromechanical devices such as starters cost more. Fig. 6 shows relative cost of 24 VDC devices versus their 120 VAC counterparts.
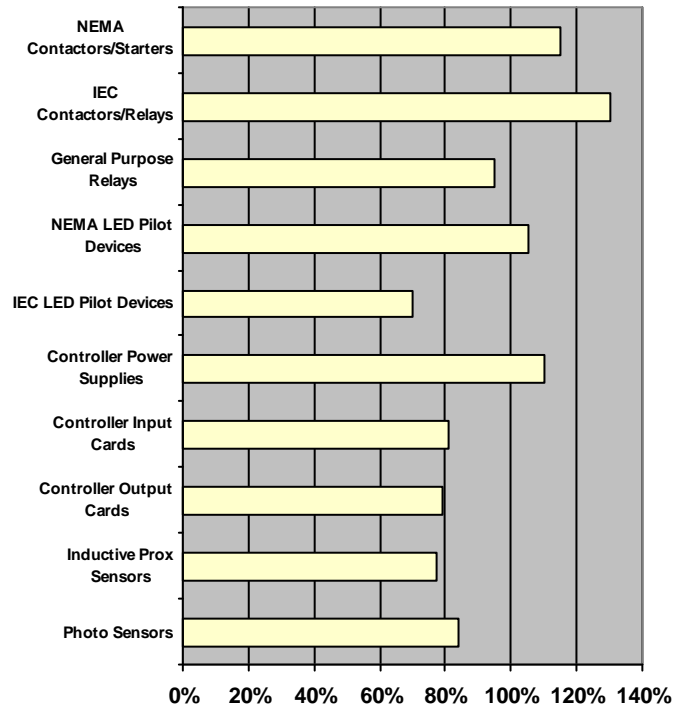

Fig. 6: Costs of 24 VDC devices as a percent of 120 VAC devices.

Historically, 120 VAC control power transformers cost less than 24 VDC power supplies. DC power supplies provide better voltage regulation and isolation than simple control transformers. Today, 24 VDC power supplies designed for use with standard control components such as contactors, relays and pilot devices are available that offer the alternative of reduced functionality at a lower cost. Loosening restrictions on voltage regulation to +/- 10% has enabled newer designs of 24 VDC power supplies to close the gap in cost versus 120 VAC transformers. Fig. 7 shows both a traditional 120 VAC control power transformer with a top mounted secondary fuse clip and a reduced functionality 24 VDC power supply. Since the power supply is a functional equivalent of the control power transformer, it can be used with a 24 VDC starter coil in a MCC unit in place of the transformer. 24 VDC power supplies generally offer inherent current limiting, shutting down when sensing a shorted output, and recovering after the fault has cleared. Compared to 120 VAC control systems, this eliminates the need to replace blown secondary fuses, offering a higher degree of control system reliability.

Fig. 7: Traditional 120 VAC control power transformer and 24 VDC power supply counterpart.

Another technology that reduces hardware costs for 24 VDC controls involves coil control circuitry for NEMA rated starters. These devices have traditionally been more costly than their AC counterparts due to the size and cost of the DC coil. Although the contact holding force is much greater for DC designs, holding load currents for DC coils are also higher. This contributes to higher control power requirements and potentially a voltage drop problem for longer cable runs. To address this issue, coil control electronics have been added that apply full voltage when the device is energized but then via pulse modulation techniques, reduced coil voltage after the contactor closes. This maintains higher contact force (about 20% above a traditional 120 VAC contactor) while reducing holding VA requirements to levels well below inrush VA. Although coil control electronics may seem sophisticated and costly for a standard NEMA starter, most new starter designs already include electronic overload protection, so the required circuit board is already a component of the starter design.

3) *Installation*: Wire gauge size in DC systems is typically smaller (#18-22 AWG) than AC systems (#14-16 AWG). Smaller gauge wire is less expensive and allows the use of high density terminations. This allows the enclosure and raceway size to be reduced. However, without proper training and tools, this may increase termination time during commissioning by plant electricians.

The new NEC rules governing open wiring and cable support can significantly impact installation costs. Where in the past everything was installed in enclosed raceway systems, the new guidelines now permit installation without the use of raceways. This has a significant impact on installation man-hours, reducing a project's bottom line.

4) *Startup, Operation and Maintenance*: The ability to detect incorrect wiring and operation of devices are factors that contribute to the startup and operation costs of a control system. For most systems, the downtime costs of equipment generally outweigh the cost of the devices. Devices providing capabilities for diagnosing problems such as open inputs,

shorted outputs, etc. tend to be more available in 24 VDC versions. Control systems designed to monitor and report their status and health will be easier to troubleshoot and less costly to maintain. Also, repair and replacement of devices in low voltage systems can be accomplished with power applied, reducing overall downtime. This could be a critical factor in process industries or applications where downtime comes at a premium.

VII. SUMMARY

Selecting a system control voltage should be made based on careful consideration of several factors. The two common voltages being utilized in North American process control applications include 120 VAC and 24 VDC.

The use of 120 VAC control is currently more common in industrial applications in North America. As a result, engineers are more familiar with 120 VAC design, installation and troubleshooting practices. Using test power from a common receptacle has made this choice convenient for qualified personnel troubleshooting control systems. There are fewer design issues with field wiring regarding voltage drop and noise. Extreme care should be taken to assure safety from potential electrical shock. Although this potential is presumed a low risk by most electricians that routinely work on equipment at much higher voltages, the fact remains that exposure to a live and poorly grounded 120 VAC circuit is a relatively frequent occurrence that can be fatal.

The use of 24 VDC control is growing, particularly in process control applications. It is inherently safe and is aligned with the new codes and standards established for enhanced safety. It allows for a reduction in the times where lockout/tagout must be performed and often times control panels can be serviced while still energized. The devices are becoming extremely reliable, are often less expensive and have better response times. 24 VDC power supplies provide signal isolation and protection against shorted outputs and power quality issues. 24 VDC allows direct interfacing with process control equipment, reducing the need for interposing relays.

Renewed emphasis on personal safety and improved performance gives a strong edge to 24 VDC control for new applications. As new product designs become available, and costs continue to decrease, 24 VDC will inevitably become the control system voltage of choice for industrial applications.

VIII. RERERENCES

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