INST 150 (Digital 3), section 1

Recommended schedule

Day 1

Topics: *Ladder logic and AC motor review*
Questions: *1 through 10*
Lab Exercise: *Motor start/stop relay circuit (question 51)*

Day 2

Topics: *Simple AC motor control circuits and motor protection*
Questions: *11 through 20*
Lab Exercise: *Reversing motor start/stop relay circuit (question 52)*

Day 3

Topics: *Time-delay relays and motor control circuits*
Questions: *21 through 30*
Lab Exercise: *Reversing motor start/stop relay circuit (question 52), continued*

Day 4

Topics: *Introduction to microcontrollers (MCUs)*
Questions: *31 through 40*
Lab Exercise: *MCU light flasher circuit (question 53)*

Day 5

Topics: *Review*
Questions: *41 through 50*
Lab Exercise: *Work on project prototype (progress report: Question 54)*

Day 6

Exam: ("Ladder Logic" exam) *includes motor start/stop relay circuit performance assessment*
Lab Exercise: *Work on project prototype (progress report: Question 55)*

Impending deadlines

Troubleshooting assessment (project prototype) due at end of INST150, Section 2
Question 56: Troubleshooting log
Question 57: Sample troubleshooting assessment grading criteria
Project due at end of INST155, Section 2 (next course)

Skill standards addressed by this course section

EIA *Raising the Standard; Electronics Technician Skills for Today and Tomorrow*, June 1994

F Technical Skills – Digital Circuits

B Basic and Practical Skills – Communicating on the Job

B.01 Use effective written and other communication skills. *Met by group discussion and completion of labwork.*

B.03 Employ appropriate skills for gathering and retaining information. *Met by research and preparation prior to group discussion.*

B.04 Interpret written, graphic, and oral instructions. *Met by completion of labwork.*

B.06 Use language appropriate to the situation. *Met by group discussion and in explaining completed labwork.*

B.07 Participate in meetings in a positive and constructive manner. *Met by group discussion.*

B.08 Use job-related terminology. *Met by group discussion and in explaining completed labwork.*

B.10 Document work projects, procedures, tests, and equipment failures. *Met by project construction and/or troubleshooting assessments.*

C Basic and Practical Skills – Solving Problems and Critical Thinking

C.01 Identify the problem. *Met by research and preparation prior to group discussion.*

C.03 Identify available solutions and their impact including evaluating credibility of information, and locating information. *Met by research and preparation prior to group discussion.*

C.07 Organize personal workloads. *Met by daily labwork, preparatory research, and project management.*

C.08 Participate in brainstorming sessions to generate new ideas and solve problems. *Met by group discussion.*

D Basic and Practical Skills – Reading

D.01 Read and apply various sources of technical information (e.g. manufacturer literature, codes, and regulations). *Met by research and preparation prior to group discussion.*

E Basic and Practical Skills – Proficiency in Mathematics

E.01 Determine if a solution is reasonable.

E.02 Demonstrate ability to use a simple electronic calculator.

E.06 Translate written and/or verbal statements into mathematical expressions.

E.07 Compare, compute, and solve problems involving binary, octal, decimal, and hexadecimal numbering systems.

E.12 Interpret and use tables, charts, maps, and/or graphs.

E.13 Identify patterns, note trends, and/or draw conclusions from tables, charts, maps, and/or graphs.

E.15 Simplify and solve algebraic expressions and formulas.

E.16 Select and use formulas appropriately.

E.18 Use properties of exponents and logarithms.

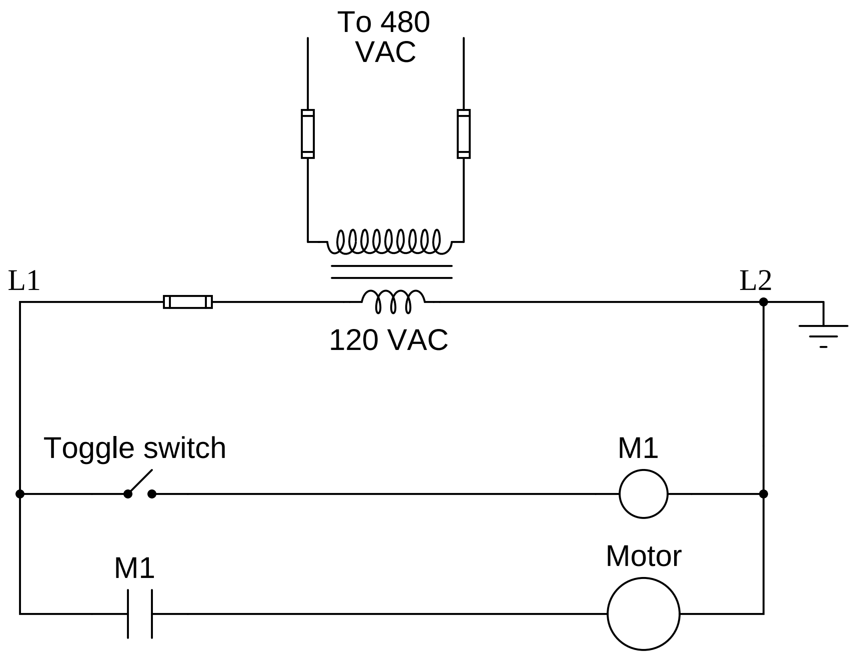
B Additional Skills – Communications

B.08 Automatic controls and robotics. *Partially met – servo motor control only.*

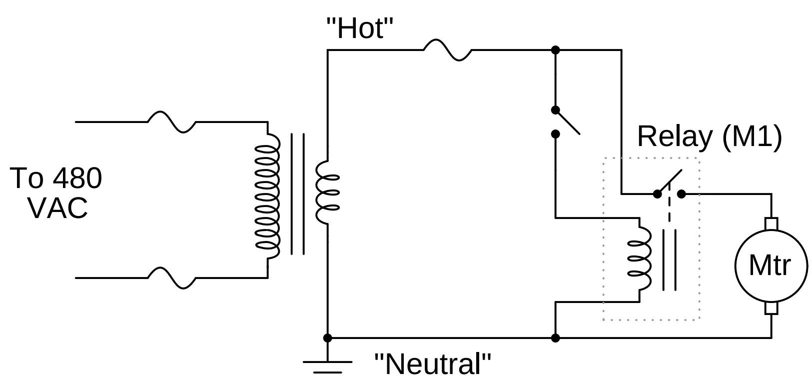
Question 1

Perhaps the most challenging aspect of interpreting ladder diagrams, for people more familiar with electronic schematic diagrams, is how electromechanical relays are represented. Compare these two equivalent diagrams:

First, the ladder diagram:



Next, the schematic diagram:

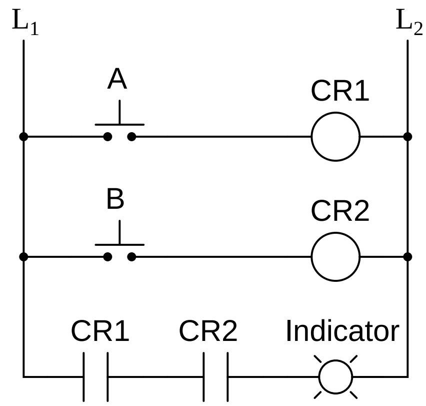


Based on your observations of these two diagrams, explain how electromechanical relays are represented differently between ladder and schematic diagrams.

file 00833

Question 2

In ladder logic symbolism, an electromechanical relay coil is shown as a circle, and the contact(s) actuated by the coil as two parallel lines, almost like a capacitor symbol. Given this knowledge, interpret the following ladder logic diagram:

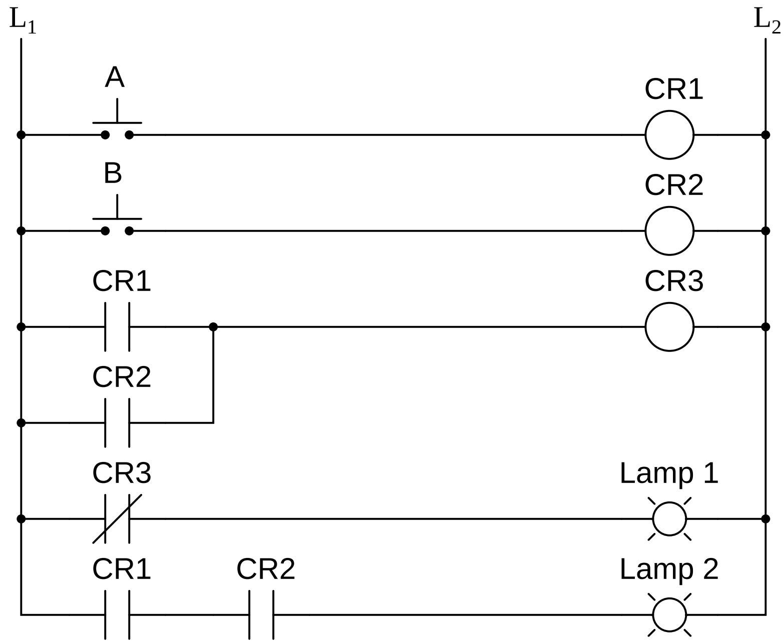


How do we know which relay contact is actuated by which relay coil? How does this convention differ from that of standard electrical/electronic schematic diagrams, where the relay coil is shown as an actual coil of wire (inductor symbol) with the contact "linked" to the coil by a dashed line? Also, what type of logic function behavior (AND, OR, NAND, or NOR) does the above circuit exhibit?

file 02774

Question 3

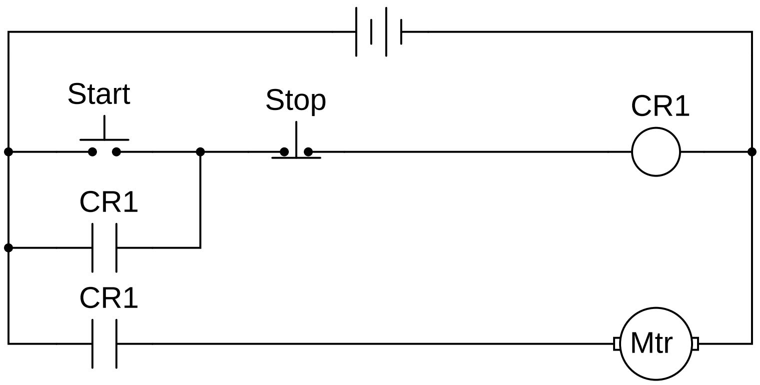
There is a problem somewhere in this relay logic circuit. Lamp 2 operates exactly as it should, but lamp 1 never turns on. Identify all possible failures in the circuit that could cause this problem, and then explain how you would troubleshoot the problem as efficiently as possible (taking the least amount of electrical measurements to identify the specific problem).



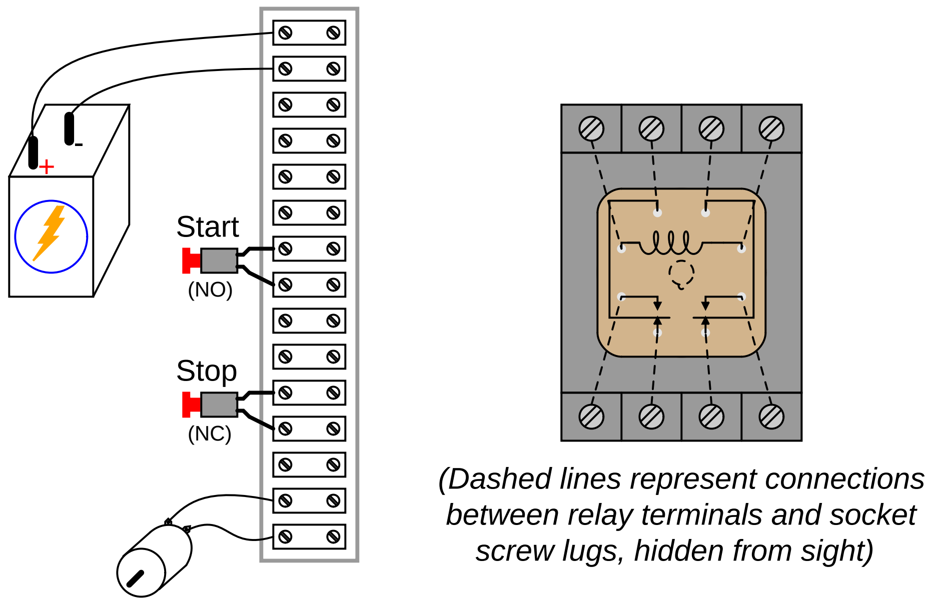
file 01296

Question 4

A *very* common application of electromechanical relay logic is motor control circuitry. Here is a ladder diagram for a simple DC motor control, where a momentary pushbutton switch starts the motor, and another pushbutton switch stops the motor:



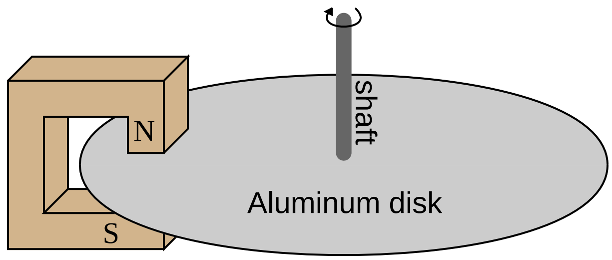
Translate this ladder diagram into point-to-point connections between the following components (shown in the following illustration):



file 01295

Question 5

Electromechanical watt-hour meters use an aluminum disk that is spun by an electric motor. To generate a constant "drag" on the disk necessary to limit its rotational speed, a strong magnet is placed in such a way that its lines of magnetic flux pass perpendicularly through the disk's thickness:



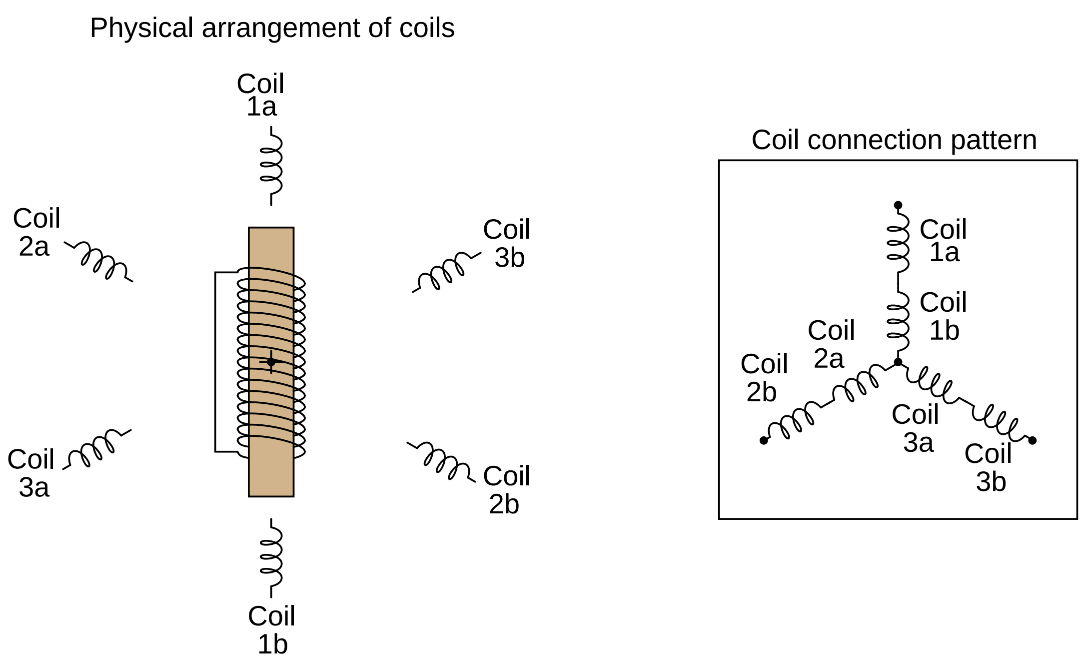
The disk itself need not be made of a ferromagnetic material in order for the magnet to create a "drag" force. It simply needs to be a good conductor of electricity.

Explain the phenomenon accounting for the drag effect, and also explain what would happen if the roles of magnet and disk were reversed: if the magnet were moved in a circle around the periphery of a stationary disk.

file 00745

Question 6

Explain what will happen to the unmagnetized rotor when 3-phase AC power is applied to the stationary electromagnet coils. Note that the rotor is actually a short-circuited electromagnet:



file 00739

Question 7

Explain what *slip speed* is for an AC induction motor, and why there must be such as thing as "slip" in order for an induction motor to generate torque.

file 03216

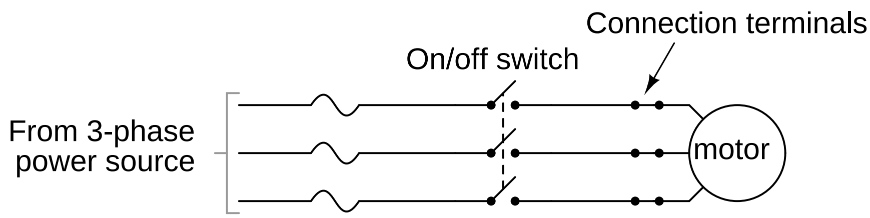
Question 8

A very common design of AC motor is the so-called *squirrel cage* motor. Describe how a "squirrel cage" motor is built, and classify it as either an "induction" motor or a "synchronous" motor.

file 00742

Question 9

What would we have to do in order to reverse the rotation of this three-phase induction motor?

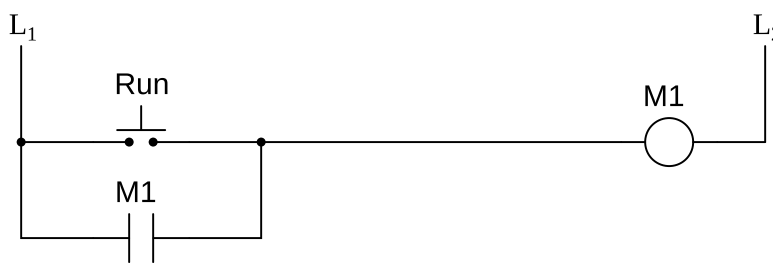


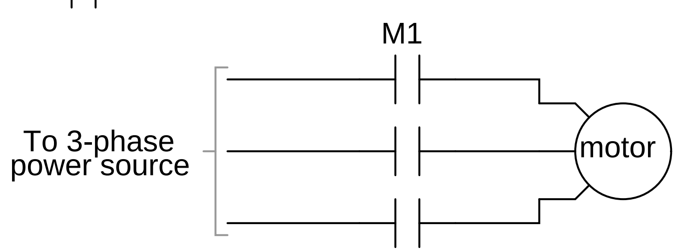
Explain your answer. Describe how the (simple) solution to this problem works.

file 00415

Question 10

Interpret this AC motor control circuit diagram, explaining the meaning of each symbol:





Also, explain the operation of this motor control circuit. What happens when someone actuates the "Run" switch? What happens when they let go of the "Run" switch?

file 00835

Draw the necessary wire connections to build the circuit shown in this ladder diagram:

Ladder diagram:

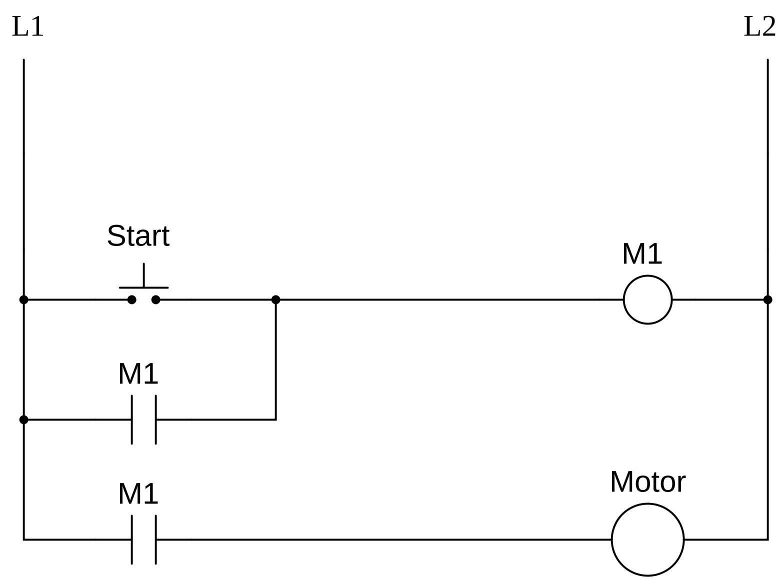
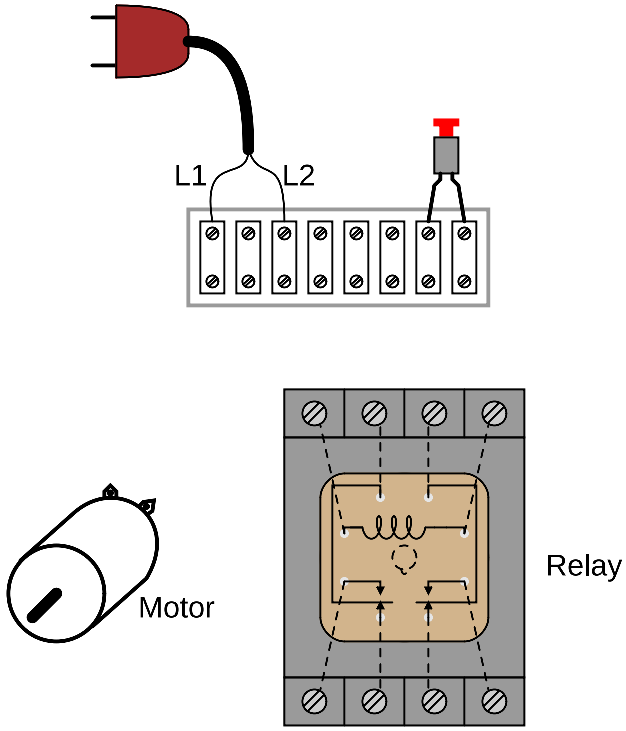


Illustration showing components:



(Dashed lines represent connections between relay terminals and socket screw lugs, hidden from sight)

file 00838

Question 12

The simplest and least expensive style of electric motor control is the so-called *across-the-line* starter. Describe how this motor control circuit functions, and also define the word "starter" in this context.

file 00840

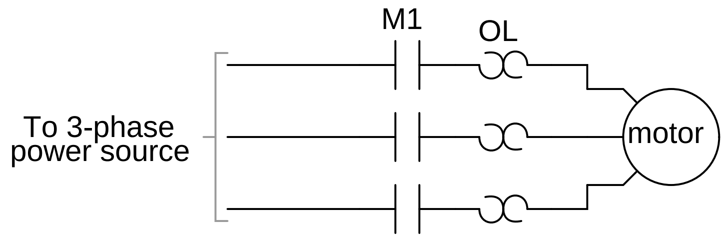
Question 13

Although "across-the-line" motor control circuits are simple and inexpensive, they are not preferred for starting large motors. An alternative to across-the-line motor starting is *reduced voltage* starting. Identify some of the reasons across-the-line starting is undesirable for large electric motors.

file 00841

Question 14

A special type of overcurrent protection device used commonly in motor control circuits is the *overload heater*. These devices are connected in series with the motor conductors, and heat up slightly under normal current conditions:



Although the "heater" elements are connected in series with the motor lines as fuses would be, they are *not* fuses! In other words, it is not the purpose of an overload heater to burn open under an overcurrent fault condition, although it is possible for them to do so.

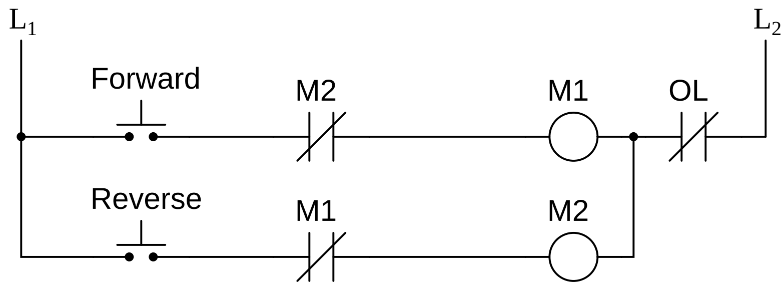
The key to understanding the purpose of an overload heater is found by examining the single-phase (L1 / L2) control circuit, where a normally-closed switch contact by the same name ("OL") is connected in series with the motor relay coil.

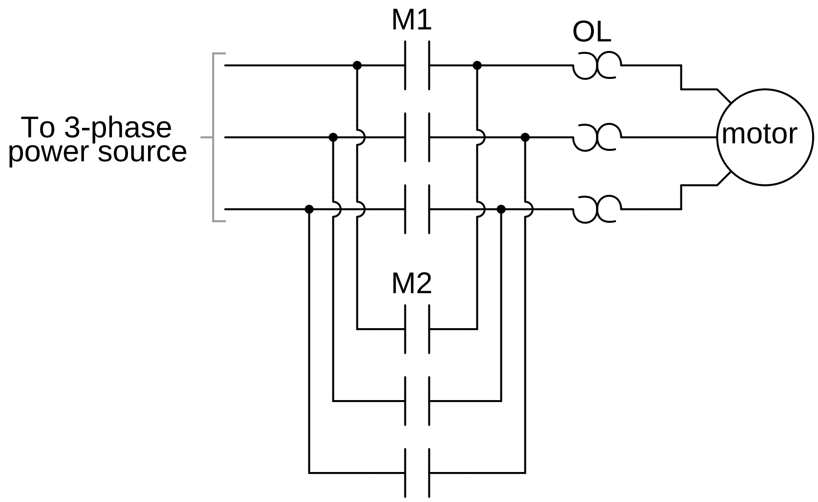
How, exactly, do overload heaters protect an electric motor against "burnout" from overcurrent conditions? How does this purpose differ from that of fuses or circuit breakers? Does the presence of overload heaters in this circuit negate that need for a circuit breaker or regular fuses? Explain your answers.

file 00837

Question 15

The circuit shown here provides two-direction control (forward and reverse) for a three-phase electric motor:



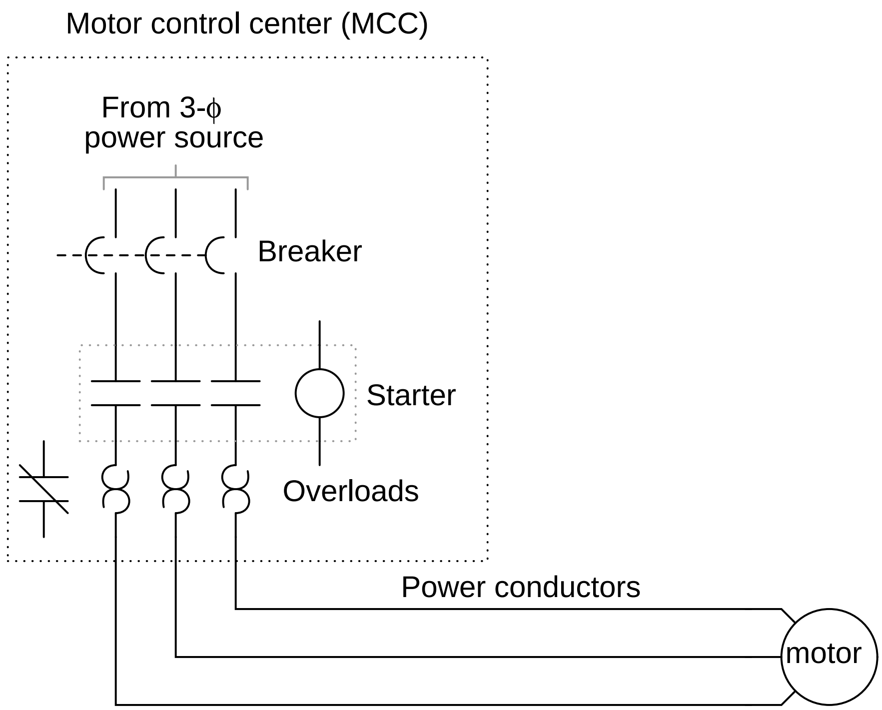


Explain how the reversal of motor direction is accomplished with two different motor starters, M1 and M2. Also, explain why there is only one set of overload heaters instead of two (one for forward and one for reverse). Finally, explain the purpose of the normally-closed contacts in series with each starter coil.

file 03142

Question 16

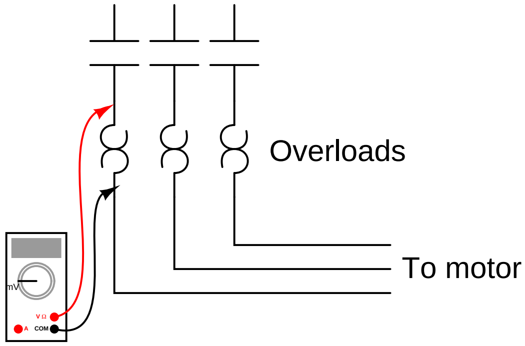
The starter and overload heater assembly for an industrial electric motor is often located quite a distance from the motor itself, inside a room referred to as a *motor control center*, or MCC:



Since it is impossible for a technician to be in two places at once, it is often necessary to perform diagnostic checks on a malfunctioning electric motor from the MCC where the technician has access to all the control circuitry.

One such diagnostic check is line current, to detect the presence of an open motor winding. If a three-phase motor winding fails open, the motor will not run as it should. This is called *single-phasing*. A good way to check for this condition is to use a clamp-on (inductive) ammeter to check line current on all three lines while the starter is energized. This may be done at any location where there is physical access to the motor power conductors.

Suppose, though, you are working on a job site where single-phasing is suspected and you do not have a clamp-on ammeter with you. All you have is a DMM (digital multimeter), which does not have the ability to safely measure the motor's current. You are about to head back to the shop to get a clamp-on ammeter when a more experienced technician suggests an alternate test. He takes your DMM, sets it to the AC *millivolt* range, then connects the test probes to either side of each overload heater element, one heater at a time like this:



Across each overload heater element he measures about 20 mV AC with the starter engaged. From this he determines that the motor is *not* single-phasing, but is drawing approximately equal current on all three phases.

Explain how this diagnostic check works, and why this determination can be made. Also describe what limitations this diagnostic procedure has, and how a clamp-on ammeter really is the best way to measure motor line current.

file 03143

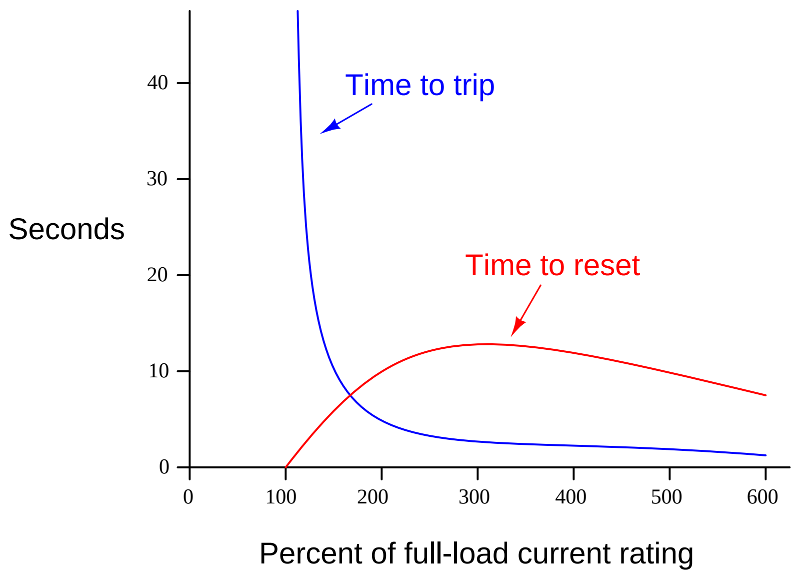
Question 17

A popular strategy for AC induction motor control is the use of *variable frequency drive* units, or VFDs. Explain what varying the frequency of power to an AC induction motor accomplishes, and why this might be advantageous.

file 03145

Question 18

Shown here is a typical set of "curves" for an overload heater, such as is commonly used to provide overcurrent protection for AC electric motors:



Why is there any time required to re-set an overload heater contact after a "trip"? Circuit breakers can be re-closed mere moments after a trip with no problem, and fuses (of course) can be replaced moments after blowing. Is this an intentional design feature of overload heaters, or just an idiosyncrasy?

Also, explain why the reset curve starts to decrease for currents above 300% of the motor's full-load rating. Why doesn't the reset time curve continue to increase with increasing fault current magnitudes?

file 00839

Question 19

Protective relays are special power-sensing devices whose job it is to automatically open or close circuit breakers in large electric power systems. Some protective relays are designed to be used directly with large electric motors to provide sophisticated monitoring, shut-down, and start-up control.

One of the features of these motor-oriented protective relays is *start-up lockout*. What this means is the relay will prevent someone from attempting too many successive re-starts of a large electric motor. If the motor is started and stopped several times over a short period of time, the relay will prevent the person from starting it again until a sufficient "rest" time has passed.

Explain why a large electric motor would need to "rest" after several successive start-up events. If electric motors are perfectly capable of running continuously at full load for years on end, why would a few start-ups be worthy of automatic lock-out?

file 03131

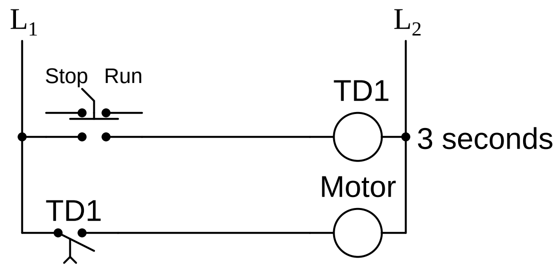
Question 20

Electromechanical relays used to start and stop high-power electric motors (called "contactors" or "starters") must be considered a possible source of *arc flash*. Explain why this is. What is it about the construction or operation of such a relay that invites this dangerous phenomenon?

file 03144

Question 21

A special class of electromechanical relays called *time-delay* relays provide delayed action, either upon power-up or power-down, and are commonly denoted in ladder logic diagrams by "TD" or "TR" designations near the coil symbols and arrows on the contact symbols. Here is an example of a time-delay relay contact used in a motor control circuit:



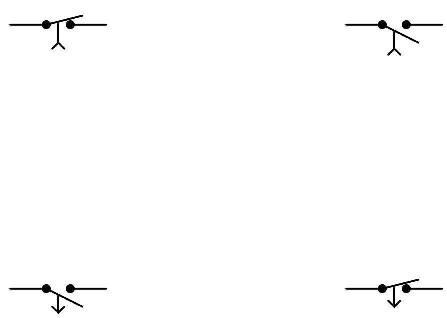
In this circuit, the motor delays start-up until three seconds *after* the switch is thrown to the "Run" position, but will stop immediately when the switch is returned to the "Stop" position. The relay contact is referred to as *normally-open, timed-closed*, or NOTC. It is alternatively referred to as a *normally-open, on-delay* contact.

Explain how the arrow symbol indicates the nature of this contact's delay, that delay occurs during closure but not during opening.

file 03141

Question 22

Match the following time-delay relay contact type symbols and labels:

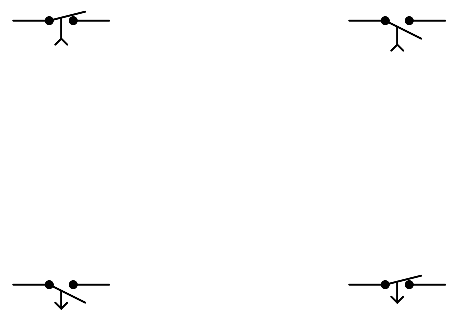


- Normally-open, timed-closed
- Normally-open, timed-open
- Normally-closed, timed-closed
- Normally-closed, timed-open

file 03133

Question 23

Match the following time-delay relay contact type symbols and labels:

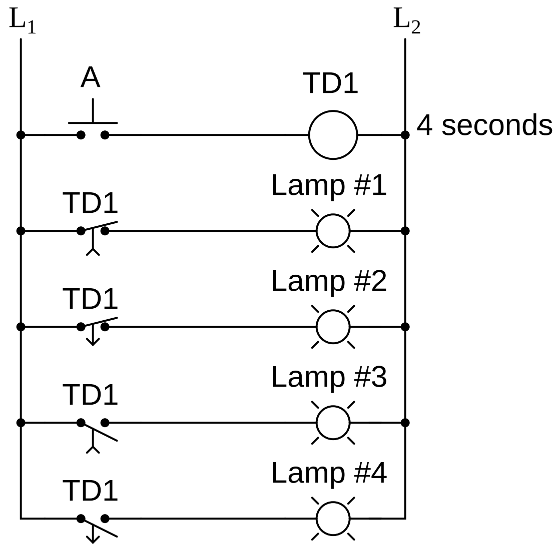


- Normally-open, on-delay
- Normally-open, off-delay
- Normally-closed, on-delay
- Normally-closed, off-delay

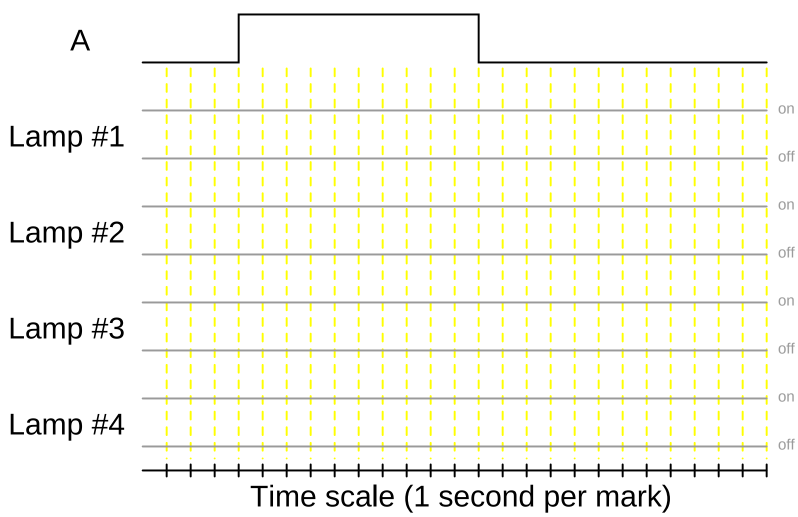
file 03134

Question 24

Time-delay relays are important circuit elements in many applications. Determine what each of the lamps will do in the following circuit when pushbutton "A" is pressed for 10 seconds and then released:



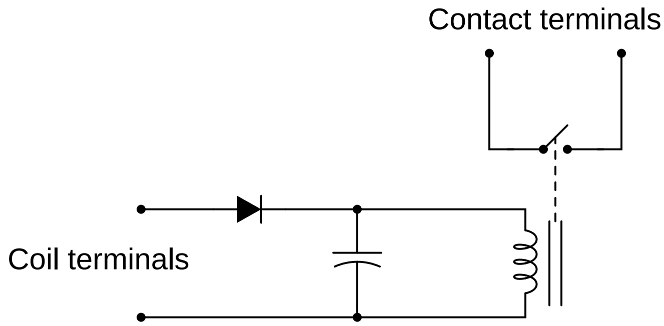
Timing diagram:



file 02381

Question 25

A simple time-delay relay may be constructed by connecting a large capacitor in parallel with the relay coil, like this:

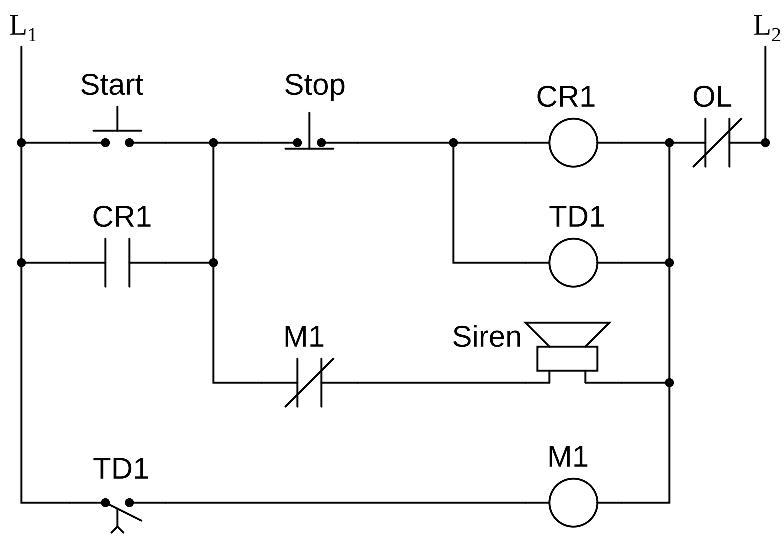


Explain how this circuit works, and also determine what type of time-delay relay function is provided by it (NOTO, NOTC, NCTO, or NCTC).

file 03139

Question 26

An electric motor is used to power a large conveyor belt. Before the motor actually starts, a warning siren activates to alert workers of the conveyor's forthcoming action. The following relay circuit accomplishes both tasks (motor control plus siren alert):

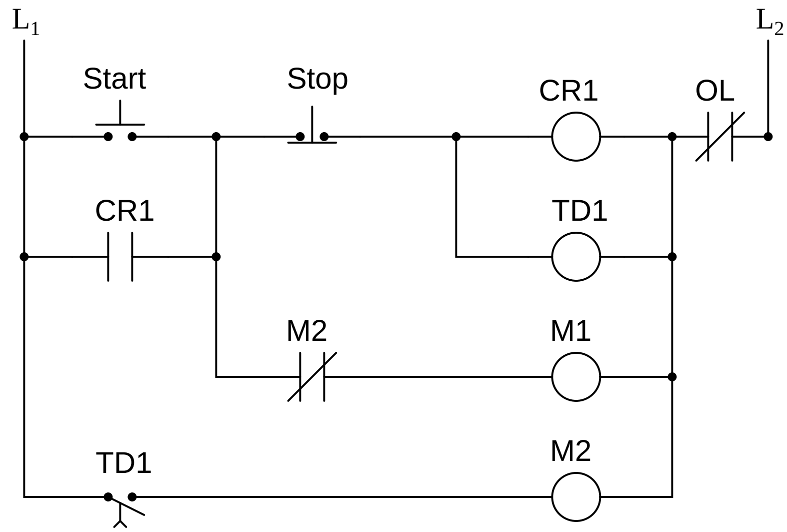


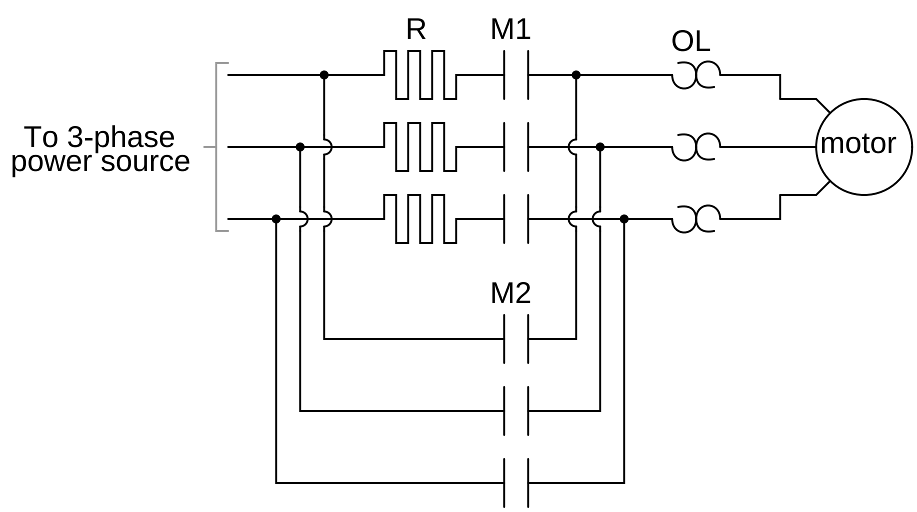
Study this ladder logic diagram, then explain how the system works.

file 03146

Question 27

Large electric motors are often equipped with some form of *soft-start* control, which applies power gradually instead of all at once (as in *"across the line"* starting). Here is an example of a simple "soft start" control system:



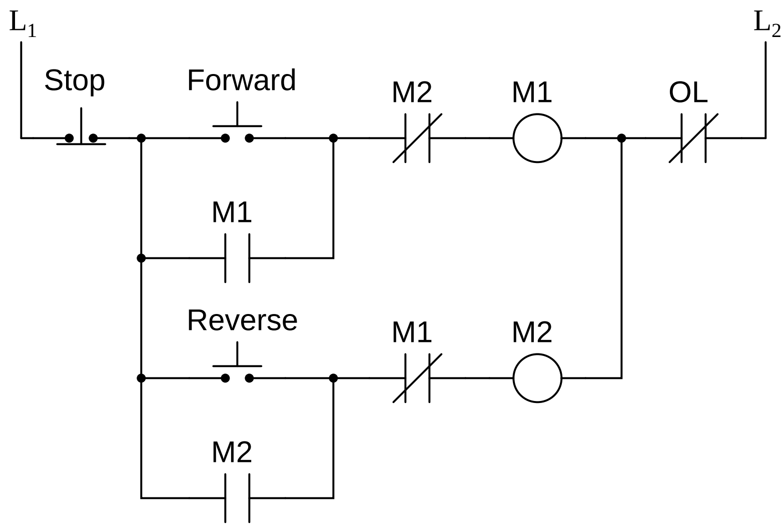


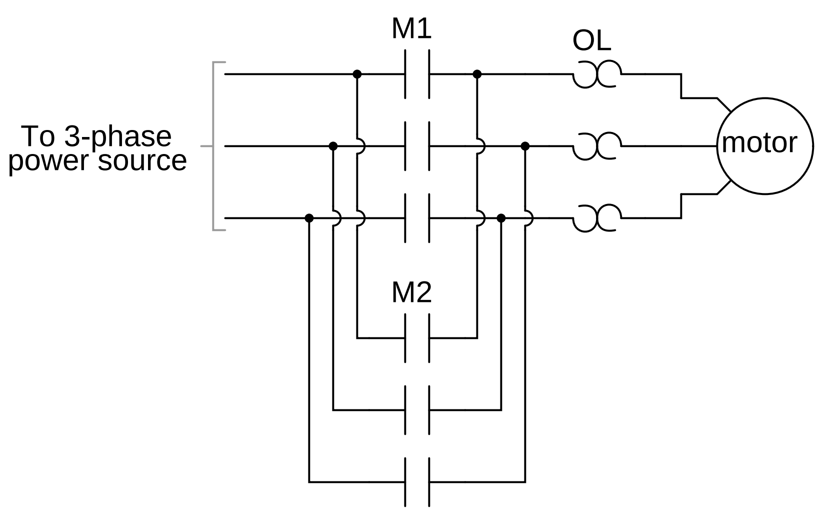
Analyze this ladder logic diagram, and explain how it starts up the electric motor more gently than an "across-the-line" starter would.

file 03149

Question 28

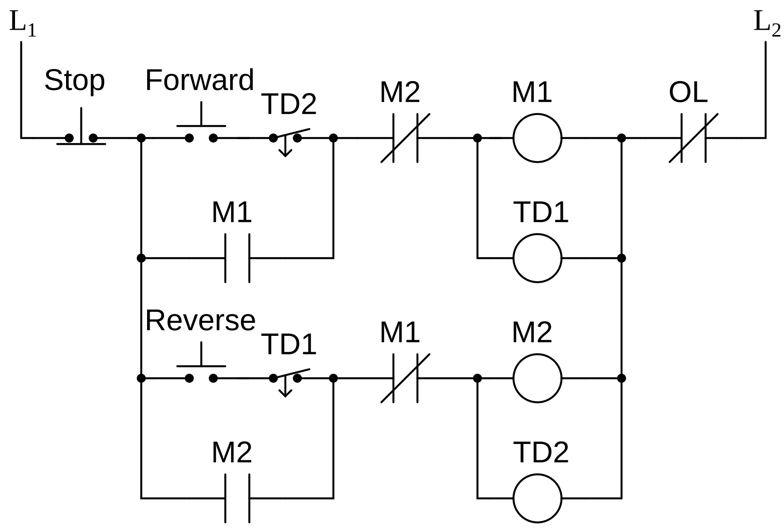
The following ladder logic diagram is for a reversing motor control circuit:





Study this diagram, then explain how motor reversal is accomplished. Also, identify the function of each "M" contact in the control circuit, especially those normally-closed contacts in series with the motor starter coils.

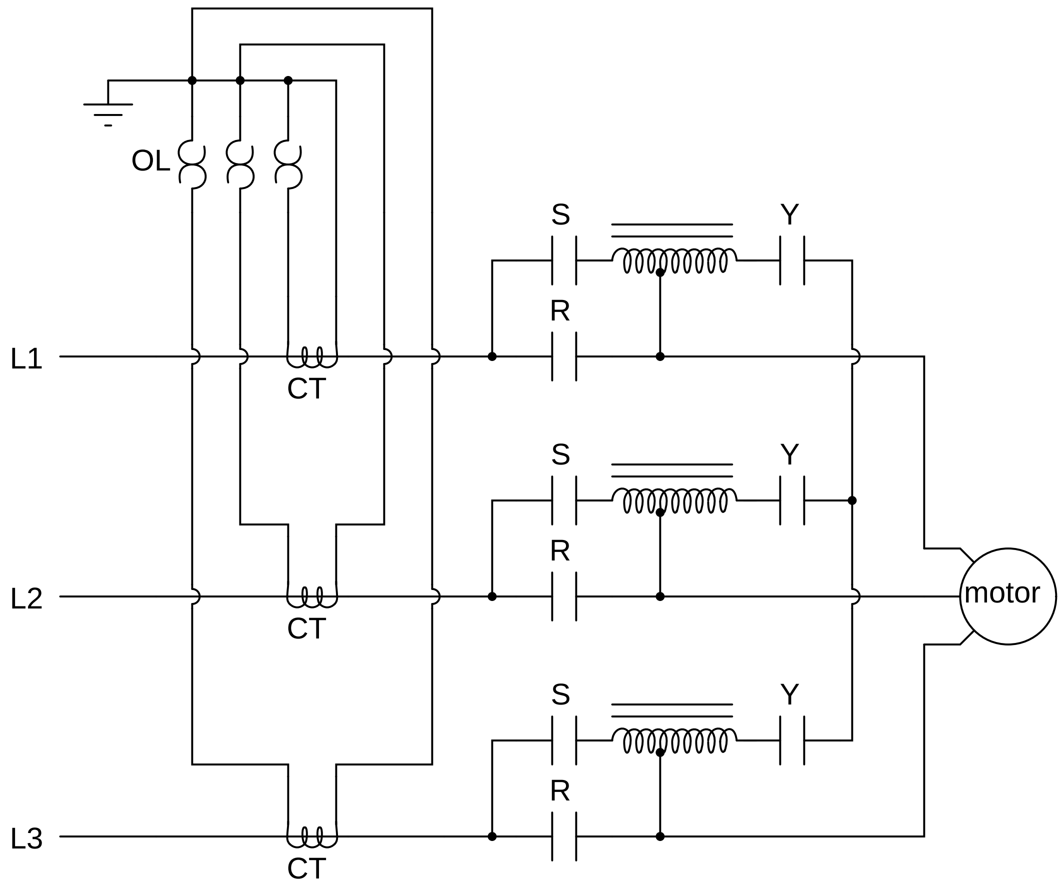
Now consider the following modification made to the reversing motor control circuit (motor and power contacts not shown here):



What extra functionality do the time-delay relays contribute to this motor control circuit?
file 03148

Question 29

There are several different methods of providing *reduced-voltage starting* for electric motors. One of them is the *autotransformer* method. Here is a diagram showing how this works:



"L1," "L2," and "L3" represent the three phase power supply conductors. Three sets of contacts (R, S, and Y) serve to connect power to the motor at different times. The starting sequence for the motor is as follows:

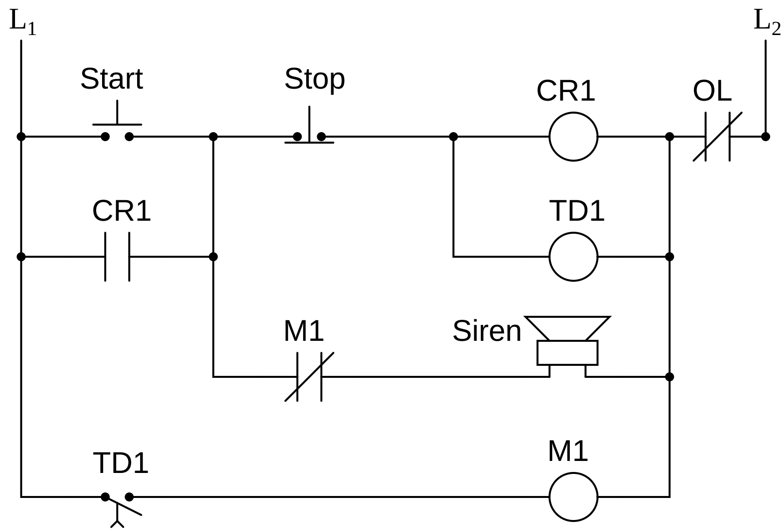
1. Motor off (R open, S open, Y open)
2. Start button pressed (S and Y contacts all close)
3. Time delay (depending on the size of the motor)
4. Y contacts open
5. Time delay (depending on the size of the motor)
6. R contacts close, S contacts open

Explain the operation of this system. How do the autotransformers serve to reduce voltage to the electric motor during start-up?

file 00843

Question 30

An electric motor is used to power a large conveyor belt. Before the motor actually starts, a warning siren activates to alert workers of the conveyor's forthcoming action. The following relay circuit is supposed to accomplish both tasks (motor control plus siren alert):



Unfortunately, there is a problem somewhere in this circuit. Instead of activating the siren before starting the motor, there is silence. The motor's start is still delayed by the correct amount of time, but the siren never makes a sound. Identify some possible causes of this problem. Also, identify portions of the circuit you know to be functioning properly.

file 03147

Question 31

Read the following quotation, and then research the term **microcontroller** to see what relevance it has to the quote:

I went to my first computer conference at the New York Hilton about 20 years ago. When somebody there predicted the market for microprocessors would eventually be in the millions, someone else said, "Where are they all going to go? It's not like you need a computer in every doorknob!"

Years later, I went back to the same hotel. I noticed the room keys had been replaced by electronic cards you slide into slots in the doors.

There was a computer in every doorknob.

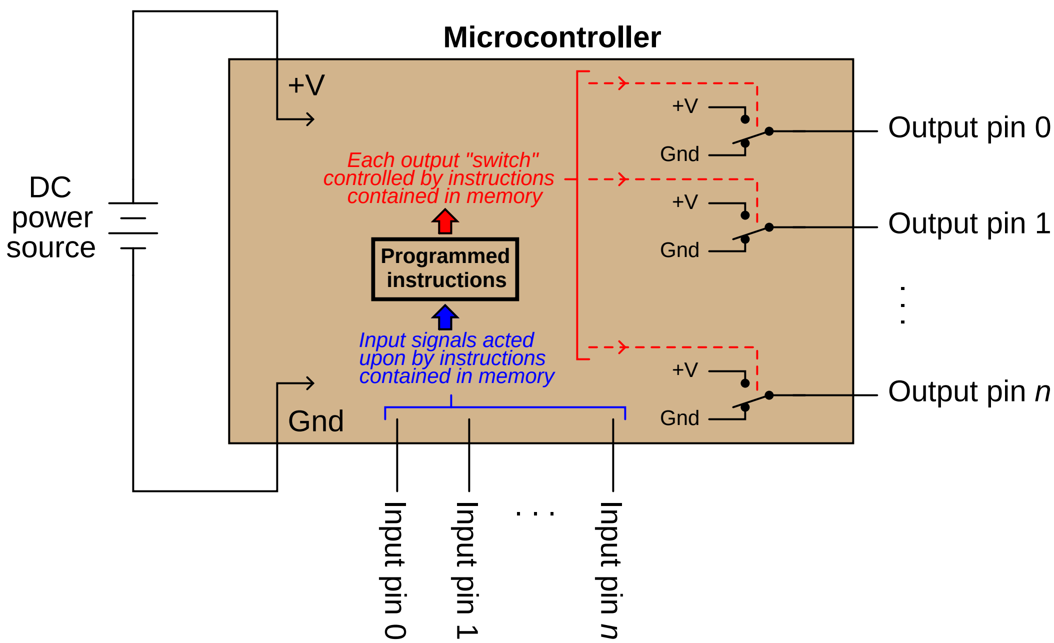
– Danny Hillis

file 02581

Question 32

A *microcontroller unit*, or *MCU*, is a specialized type of digital computer used to provide automatic sequencing or control of a system. Microcontrollers differ from ordinary digital computers in being very small (typically a single integrated circuit chip), with several dedicated pins for input and/or output of digital signals, and limited memory. Instructions programmed into the microcontroller's memory tell it how to react to input conditions, and what types of signals to send to the outputs.

The simplest type of signal "understood" by a microcontroller is a discrete voltage level: either "high" (approximately +V) or "low" (approximately ground potential) measured at a specified pin on the chip. Transistors internal to the microcontroller produce these "high" and "low" signals at the output pins, their actions being modeled by SPDT switches for simplicity's sake:



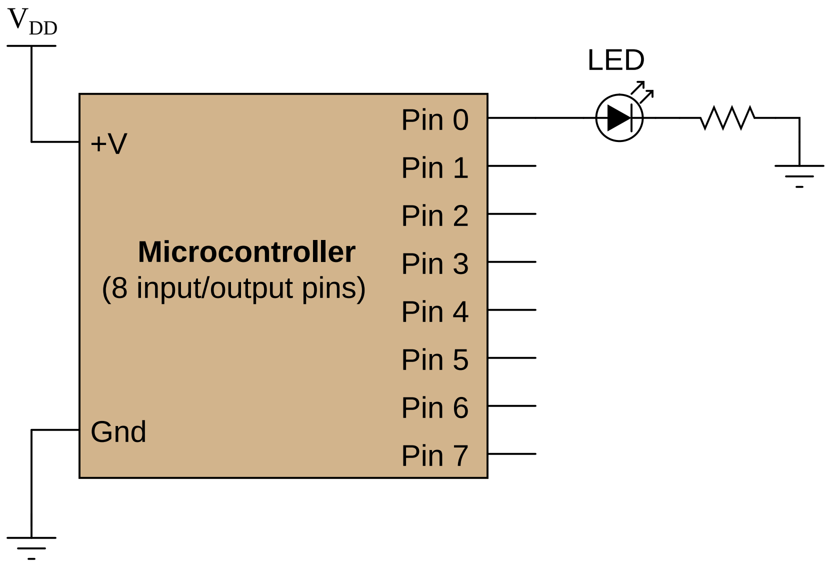
Microcontrollers may be programmed to emulate the functions of digital logic gates (AND, OR, NAND, NOR, etc.) in addition to a wide variety of combinational and multivibrator functions. The only real limits to what a microcontroller can do are memory (how large of a program may be stored) and input/output pins on the MCU chip.

However, microcontrollers are themselves made up of many thousands (or millions!) of logic gate circuits. Why would it make sense to use a microcontroller to perform a logic function that a small fraction of its constituent gates could accomplish directly? In other words, why would anyone bother to program a microcontroller to perform a digital function when they could build the logic network they needed out of fewer gate circuits?

file 02596

Question 33

A student decides to build a light-flasher circuit using a microcontroller instead of a 555 timer or some other hard-wired astable circuit. Unfortunately, there is a problem somewhere. When first powered up, the LED lights on for 1 second, then turns off and never turns back on. The only way the LED ever comes back on is if the MCU is reset or its power is cycled off and on:



Pseudocode listing

```
Declare Pin0 as an output
BEGIN
  Set Pin0 HIGH
  Pause for 1 second
  Set Pin0 LOW
END
```

A fellow student, when asked for help, modifies the program listing and re-sends it from the personal computer where it is being edited to the microcontroller, through a programming cable. The program listing now reads as such:

Pseudocode listing

```
Declare Pin0 as an output
LOOP
  Set Pin0 HIGH
  Pause for 1 second
  Set Pin0 LOW
ENDLOOP
```

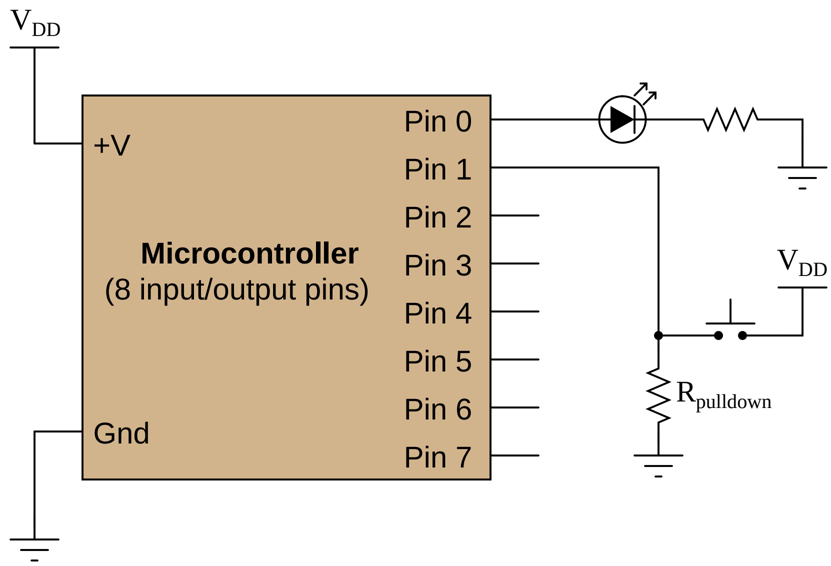
When the MCU is reset with the new program, the LED starts blinking on and off . . . sort of. The LED is "on" most of the time, but once every second it turns off and then immediately comes back on. In fact, the "off" period is so brief it is barely noticeable.

What the student wanted was a 50% duty cycle: "on" for 1 second, then "off" for 1 second, repeating that cycle indefinitely. First, explain the significance of the classmate's program modification, and then modify the program listing again so that the LED does what the student wants it to.

file 02597

Question 34

A student decides to build a light-flasher circuit using a microcontroller. The LED is supposed to blink on and off only when the pushbutton switch is depressed. It is supposed to turn off when the switch is released:



Pseudocode listing

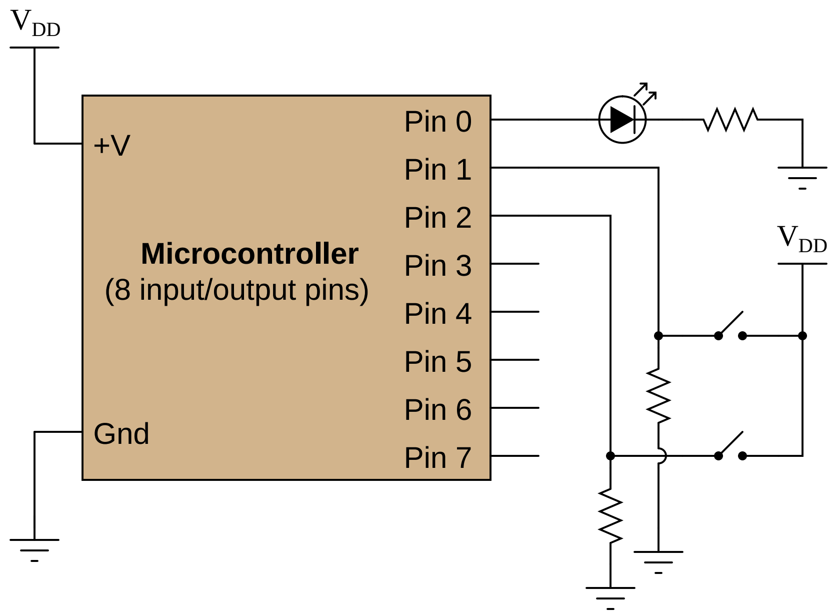
```
Declare Pin0 as an output
Declare Pin1 as an input
WHILE Pin1 is HIGH
  Set Pin0 HIGH
  Pause for 0.5 seconds
  Set Pin0 LOW
  Pause for 0.5 seconds
ENDWHILE
```

The LED blinks on and off just fine as long as the pushbutton switch is held when the MCU is powered up or reset. As soon as the switch is released, the LED turns off and never comes back on. If the switch was never pressed during start-up, the LED never comes on! Explain what is happening, and modify the program as necessary to fix this problem.

file 02598

Question 35

Examine the following schematic diagram and program listing (written in "pseudocode" rather than a formal programming language) to determine what type of basic logic function is being implemented in this microcontroller unit:



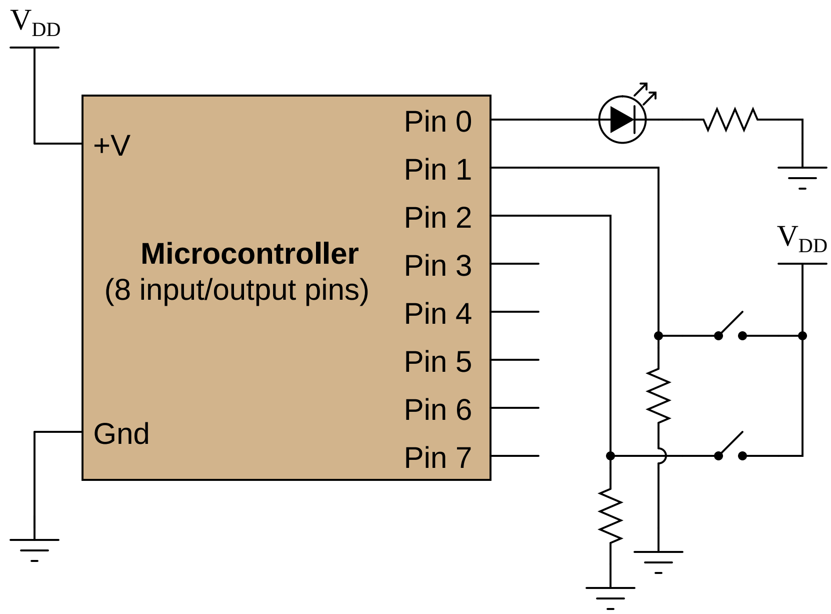
<u>**Pseudocode listing**</u>

```
Declare Pin0 as an output
Declare Pin1 and Pin2 as inputs
LOOP
  IF Pin1 is HIGH, set Pin0 HIGH
  ELSEIF Pin2 is HIGH, set Pin0 HIGH
  ELSE set Pin0 LOW
  ENDIF
ENDLOOP
```

file 02582

Question 36

Examine the following schematic diagram and program listing (written in "pseudocode" rather than a formal programming language) to determine what type of basic logic function is being implemented in this microcontroller unit:



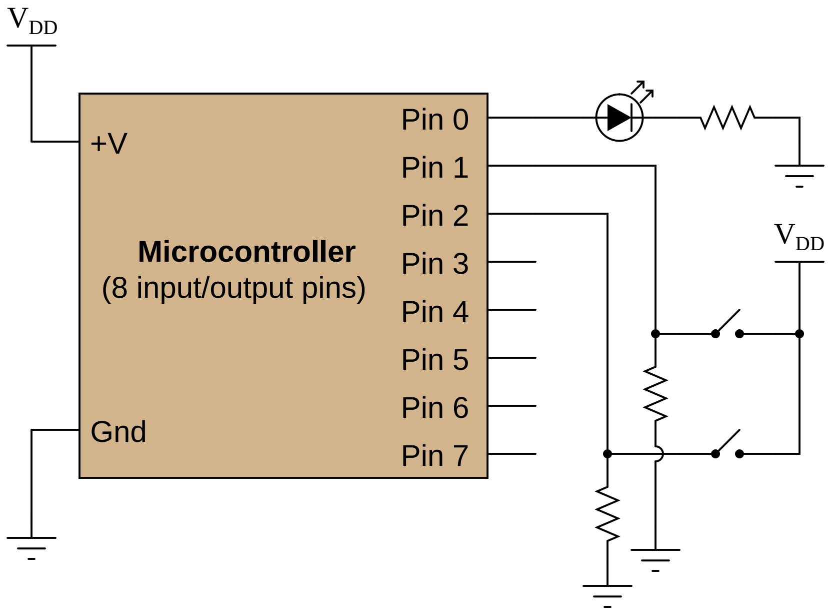
Pseudocode listing

```
Declare Pin0 as an output
Declare Pin1 and Pin2 as inputs
LOOP
  IF Pin1 is LOW, set Pin0 LOW
  ELSEIF Pin2 is LOW, set Pin0 LOW
  ELSE set Pin0 HIGH
  ENDIF
ENDLOOP
```

file 02583

Question 37

Examine the following schematic diagram and program listing (written in "pseudocode" rather than a formal programming language) to determine what type of basic logic function is being implemented in this microcontroller unit:



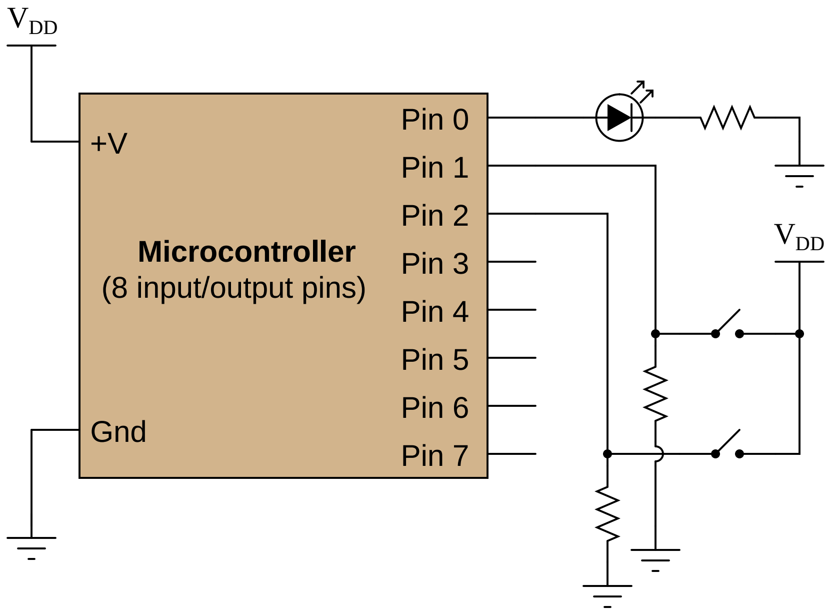
Pseudocode listing

```
Declare Pin0 as an output
Declare Pin1 and Pin2 as inputs
LOOP
  IF Pin1 is LOW, set Pin0 HIGH
  ELSEIF Pin2 is LOW, set Pin0 HIGH
  ELSE set Pin0 LOW
  ENDIF
ENDLOOP
```

file 02584

Question 38

Examine the following schematic diagram and program listing (written in "pseudocode" rather than a formal programming language) to determine what type of basic logic function is being implemented in this microcontroller unit:



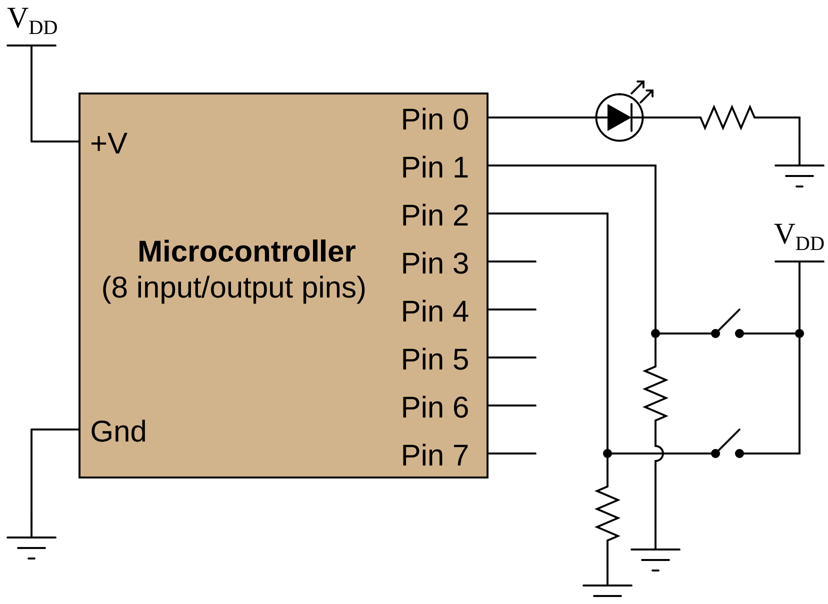
Pseudocode listing

```
Declare Pin0 as an output
Declare Pin1 and Pin2 as inputs
LOOP
  IF Pin1 is HIGH, set Pin0 LOW
  ELSEIF Pin2 is HIGH, set Pin0 LOW
  ELSE set Pin0 HIGH
  ENDIF
ENDLOOP
```

file 02585

Question 39

Examine the following schematic diagram and program listing (written in "pseudocode" rather than a formal programming language) to determine what type of basic logic function is being implemented in this microcontroller unit:



Pseudocode listing

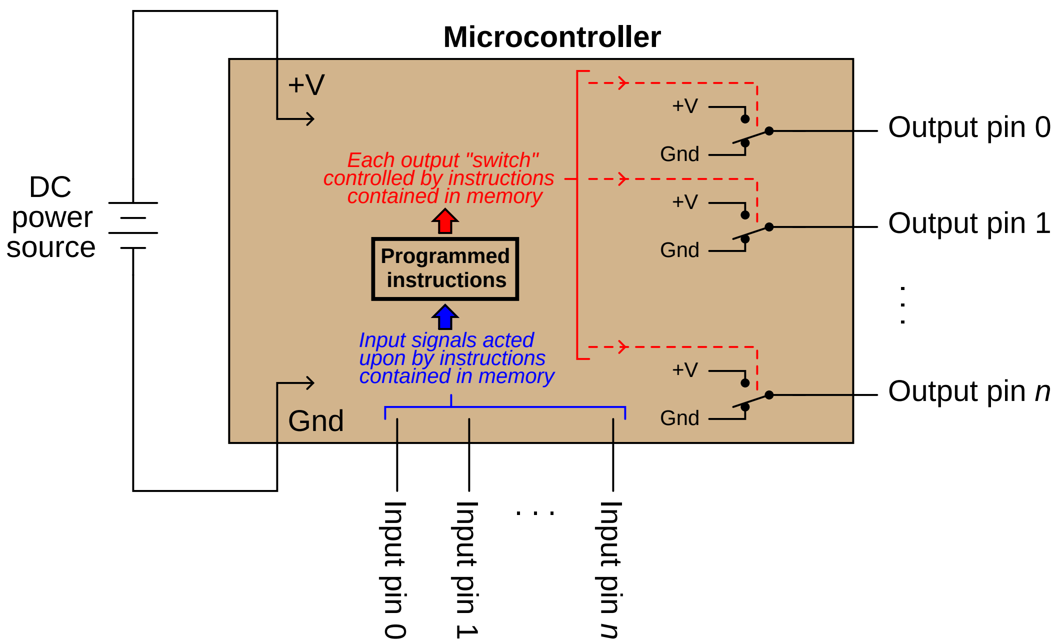
```
Declare Pin0 as an output
Declare Pin1 and Pin2 as inputs
LOOP
  IF Pin1 is same as Pin2, set Pin0 LOW
  ELSE set Pin0 HIGH
  ENDIF
ENDLOOP
```

file 02586

Question 40

A *microcontroller* is a specialized type of digital computer used to provide automatic sequencing or control of a system. Microcontrollers differ from ordinary digital computers in being very small (typically a single integrated circuit chip), with several dedicated pins for input and/or output of digital signals, and limited memory. Instructions programmed into the microcontroller's memory tell it how to react to input conditions, and what types of signals to send to the outputs.

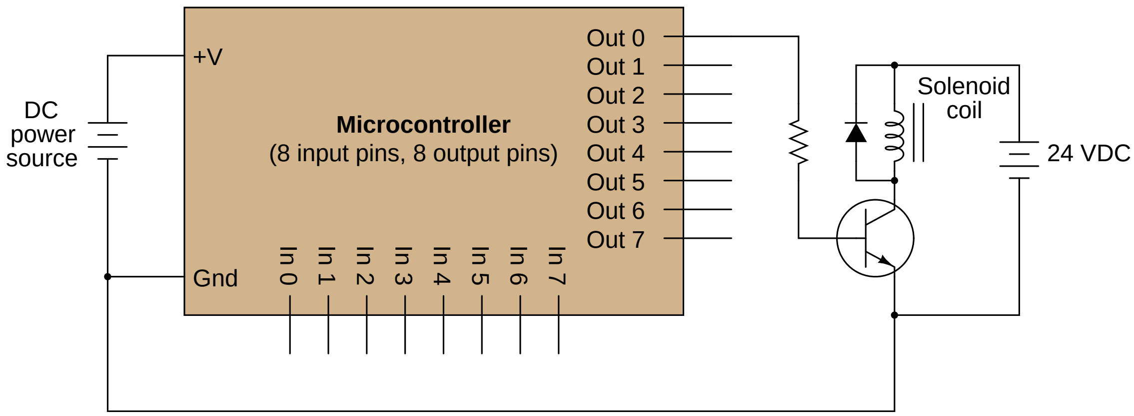
The simplest type of signal "understood" by a microcontroller is a discrete voltage level: either "high" (approximately +V) or "low" (approximately ground potential) measured at a specified pin on the chip. Transistors internal to the microcontroller produce these "high" and "low" signals at the output pins, their actions being modeled by SPDT switches for simplicity's sake:



It does not require much imagination to visualize how microcontrollers may be used in practical systems: turning external devices on and off according to input pin and/or time conditions. Examples include appliance control (oven timers, temperature controllers), automotive engine control (fuel injectors, ignition timing, self-diagnostic systems), and robotics (servo actuation, sensory processing, navigation logic). In fact, if you live in an industrialized nation, you probably own several dozen microcontrollers (embedded in various devices) and don't even realize it!

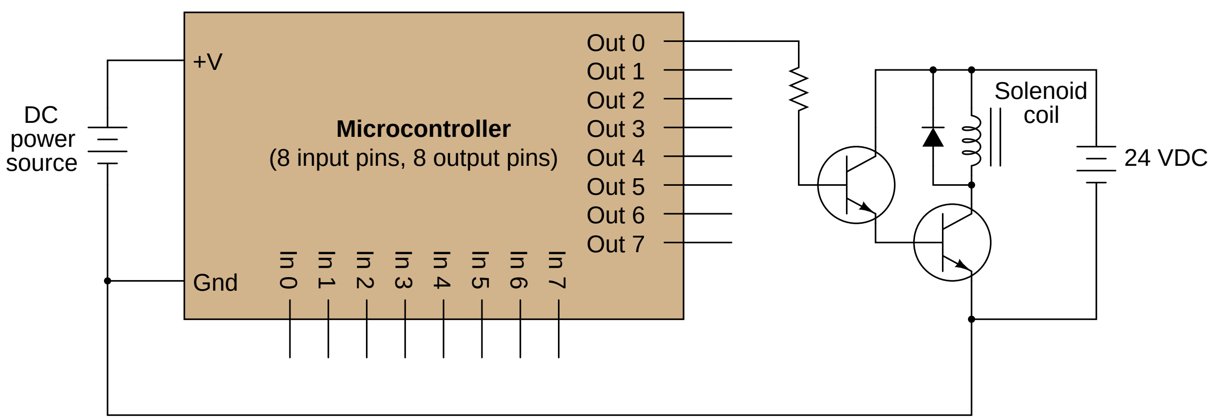
One of the practical limitations of microcontrollers, though, is their low output drive current limit: typically less than 50 mA. The miniaturization of the microcontroller's internal circuitry prohibits the inclusion of output transistors having any significant power rating, and so we must connect transistors to the output pins in order to drive any significant load(s).

Suppose we wished to have a microcontroller drive a DC-actuated solenoid valve requiring 2 amps of current at 24 volts. A simple solution would be to use an NPN transistor as an "interposing" device between the microcontroller and the solenoid valve like this:

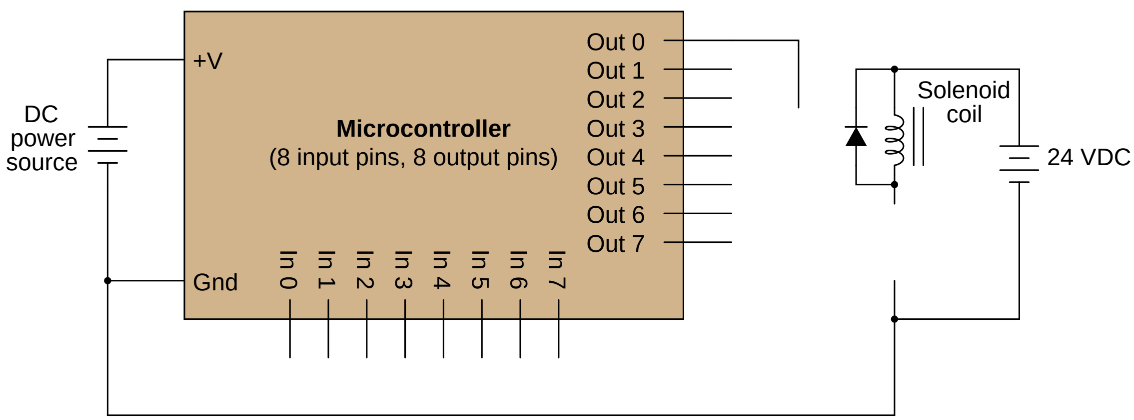


Unfortunately, a single BJT does not provide enough current gain to actuate the solenoid. With 20 mA of output current from the microcontroller pin and a β of only 25 (typical for a power transistor), this only provides about 500 mA to the solenoid coil.

A solution to this problem involves two bipolar transistors in a *Darlington pair* arrangement:



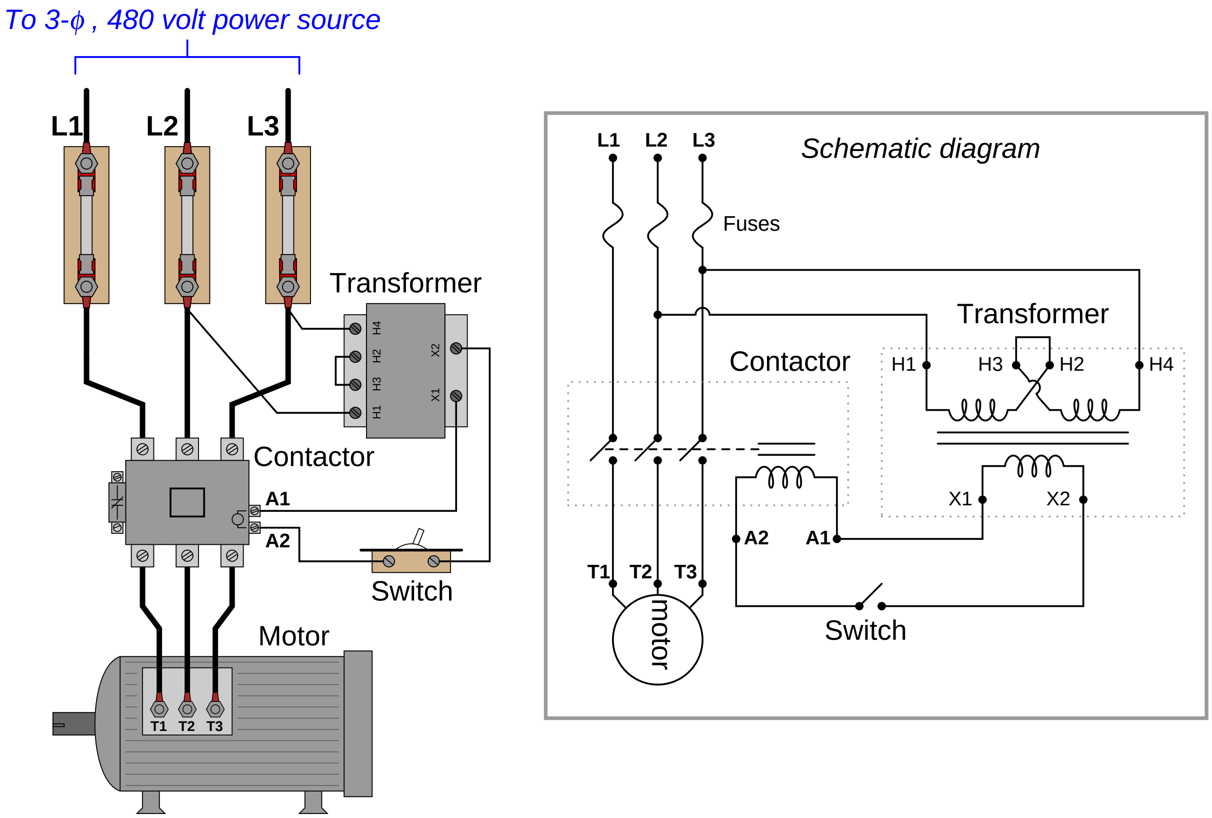
However, there is another solution yet – replace the single BJT with a single MOSFET, which requires no drive current at all. Show how this may be done:



file 02422

Question 41

Identify at least three independent faults that could cause this motor not to start:

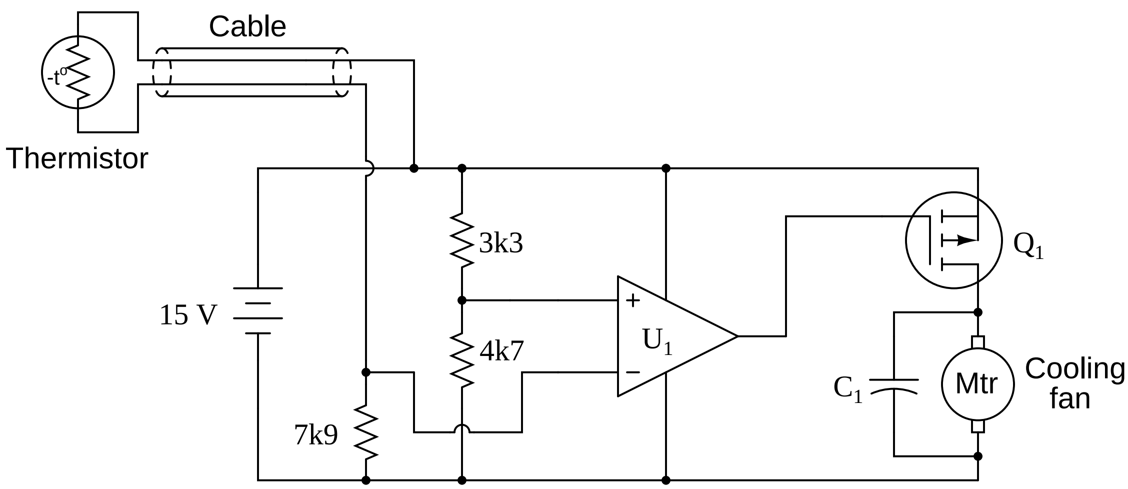


For each of the proposed faults, explain *why* they would prevent the motor from starting.

file 03829

Question 42

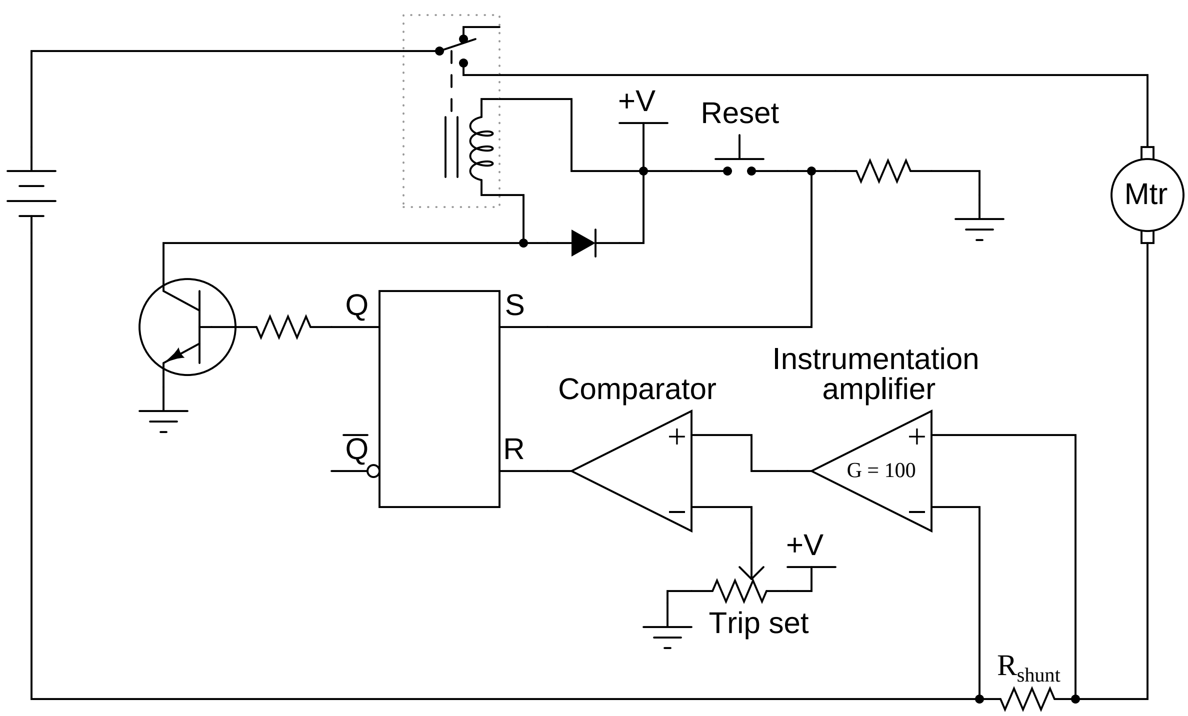
Calculate the amount of resistance that the thermistor much reach in order to turn the cooling fan *on*:



file 04021

Question 43

Explain how this motor overcurrent protection circuit works:



file 04022

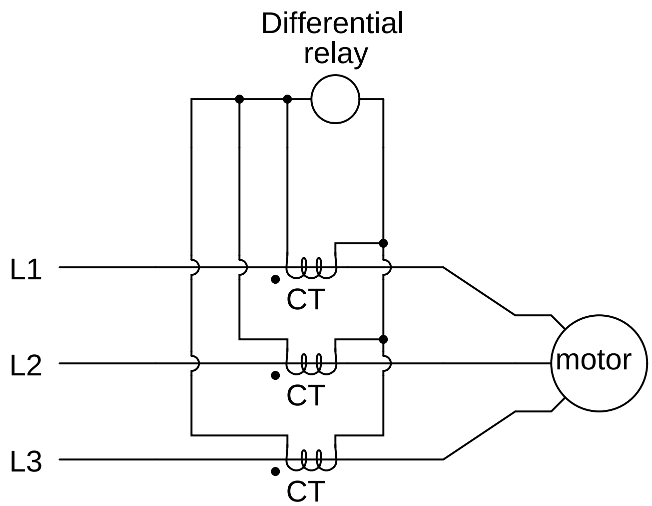
Question 44

A *differential* relay is a common type of protective relay used in power systems. One of the more common forms is the differential current relay. A very common example of a differential current relay – so common, in fact, that nearly every house is equipped with at least one – is the *GFCI*, or *Ground Fault Current Interrupter*. Explain what a GFCI is, and then in a larger context, explain what a differential relay protects against.

file 04023

Question 45

Explain what sort of electrical fault this differential current relay protects against:

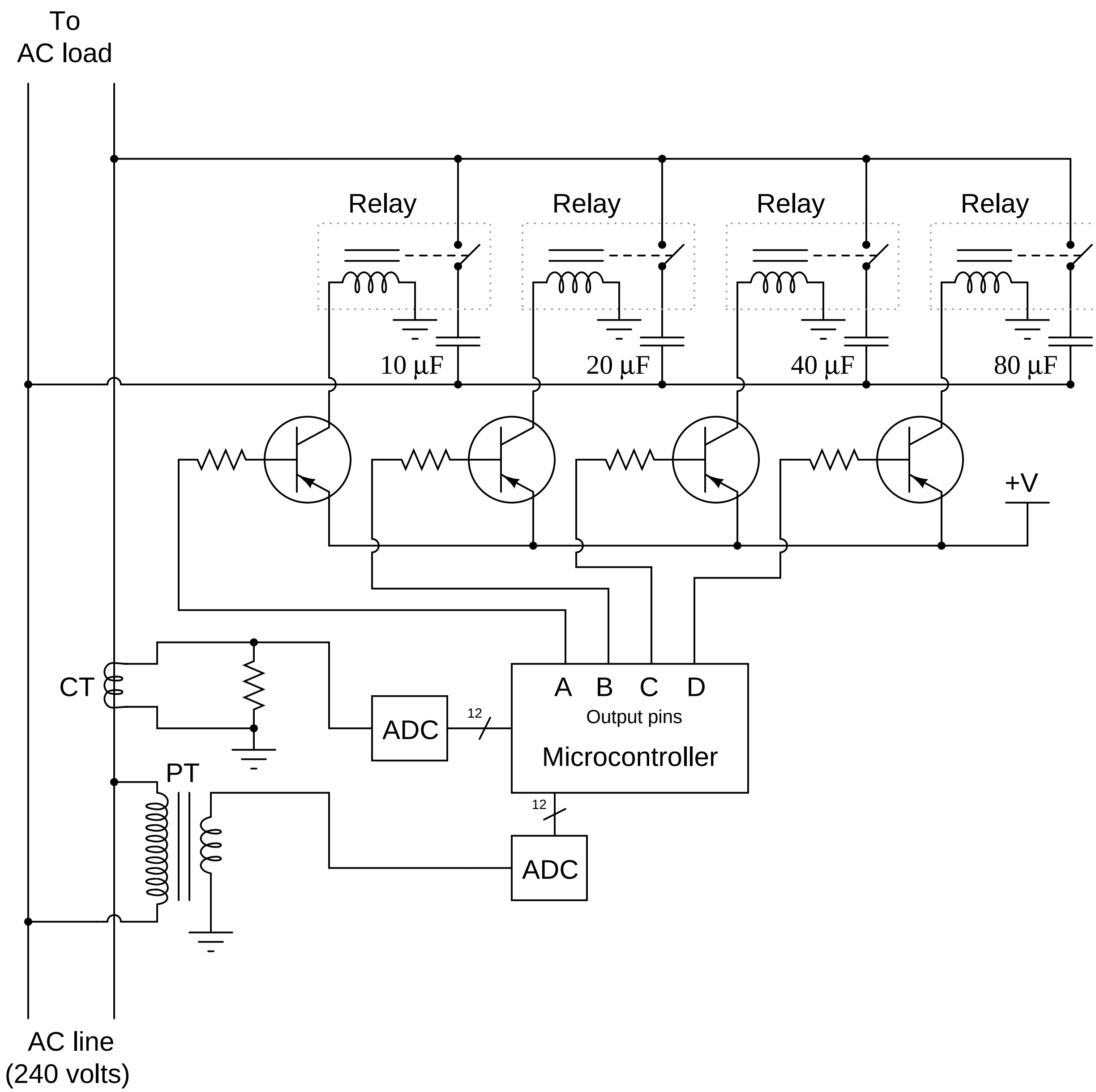


Also, explain what this relay will do to protect the circuit if it detects this kind of fault.

file 04024

Question 46

A microcontroller is used to provide automatic power factor correction for an AC load:



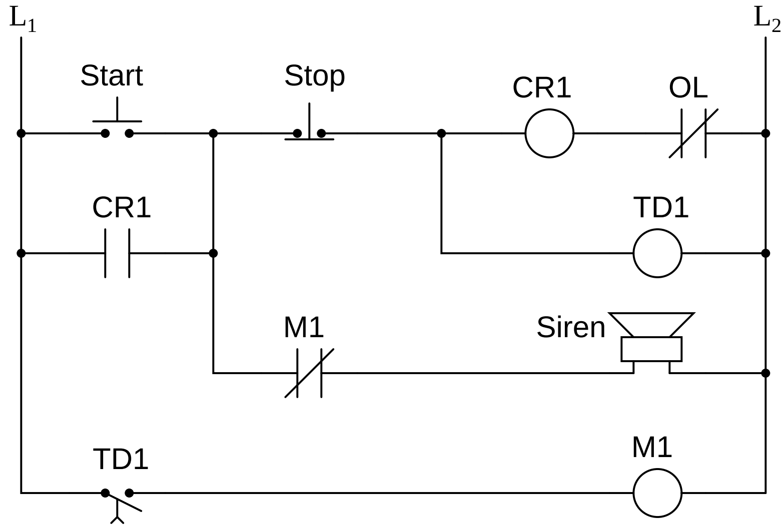
Examine this schematic diagram, then answer the following questions:

- How can the microcontroller sense the power factor of the AC load?
- How many discrete steps of power factor correction can the microcontroller engage through its four output pins?
- What would the MCU's output be to correct for a load drawing 15 amps with a lagging power factor of 0.77? Assume a line frequency of 60 Hz, and a correction algorithm that adjusts for the best *lagging* power factor (i.e. it will never over-correct and produce a leading power factor).
- What is the corrected (total) power factor with those capacitors engaged?

file 04025

Question 47

An electric motor is used to power a large conveyor belt. Before the motor actually starts, a warning siren activates to alert workers of the conveyor's forthcoming action. The following relay circuit accomplishes both tasks (motor control plus siren alert):

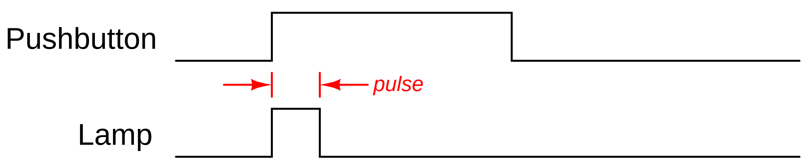


However, this circuit is poorly designed. Although it works just fine under normal conditions, it may not do what it should in the event of an overload heater trip (if the normally-closed "OL" contact opens). Explain what is wrong with this circuit.

file 04028

Question 48

Suppose you needed to build a circuit that pulsed a lamp on and off (once) when a pushbutton is pressed and held. In other words, you wanted the lamp to do this:

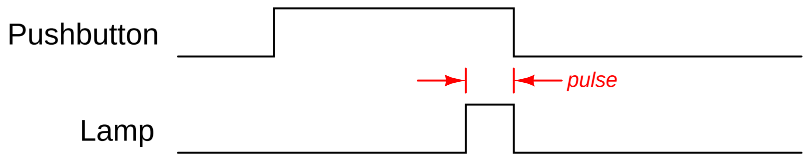


Draw a ladder logic diagram for a circuit that would fulfill this function, using at least one time-delay relay.

file 03136

Question 49

Suppose an engineer draws the following timing diagram for a time-delay relay circuit and then hands the diagram to a technician to figure out how to build it:

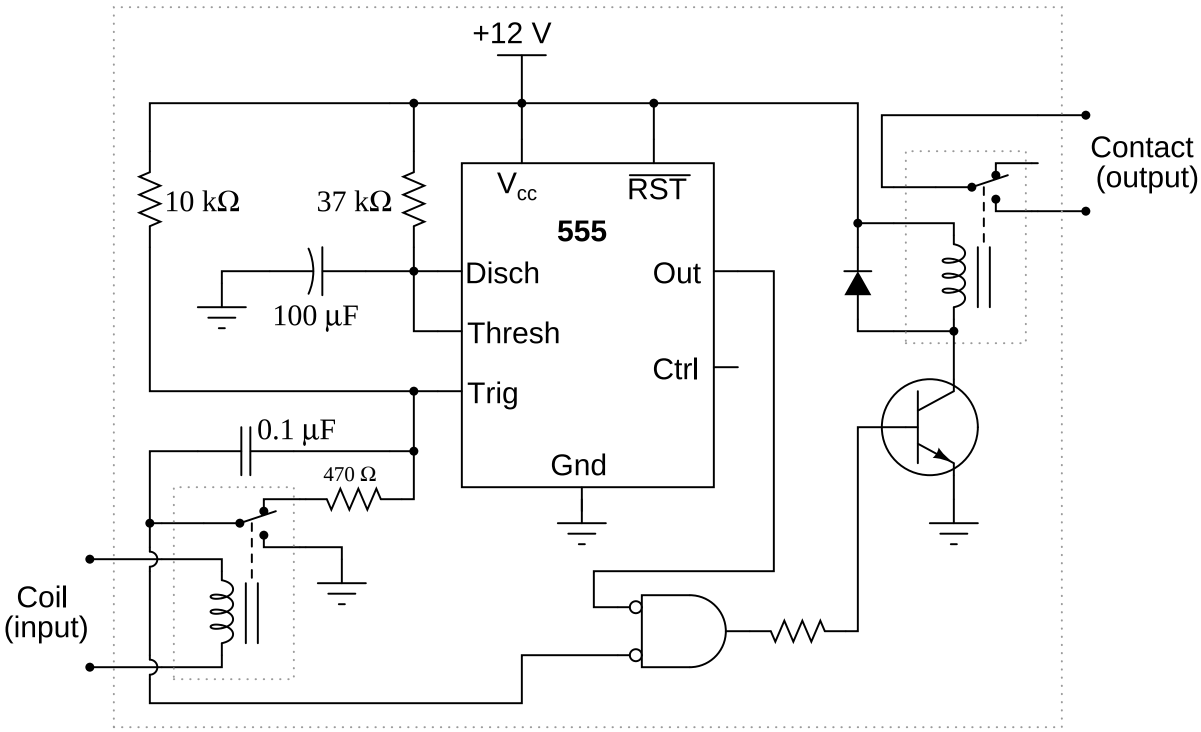


The technician, being well educated in the ways of time-delay relays, takes one look at this timing diagram and begins to laugh. Explain why this diagram is funny.

file 03138

Question 50

Determine what sort of time-delay relay this circuit is:



Also, calculate the amount of delay, in seconds. Hint: the 555's timing capacitor will charge from 0 volts to $\frac{2}{3}$ supply voltage during the charging cycle.

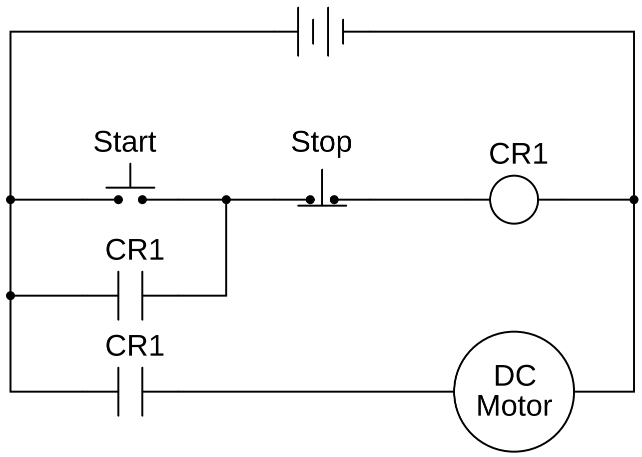
file 04029

Competency: **Relay start/stop motor control circuit** Version:

Description

Build a start/stop motor control circuit using
an electromechanical relay and two pushbutton switches

Schematic



Truth table

Predicted

Start	Stop	Motor
0	0	
0	1	
1	0	
1	1	

Actual

Start	Stop	Motor
0	0	
0	1	
1	0	
1	1	

Fault analysis

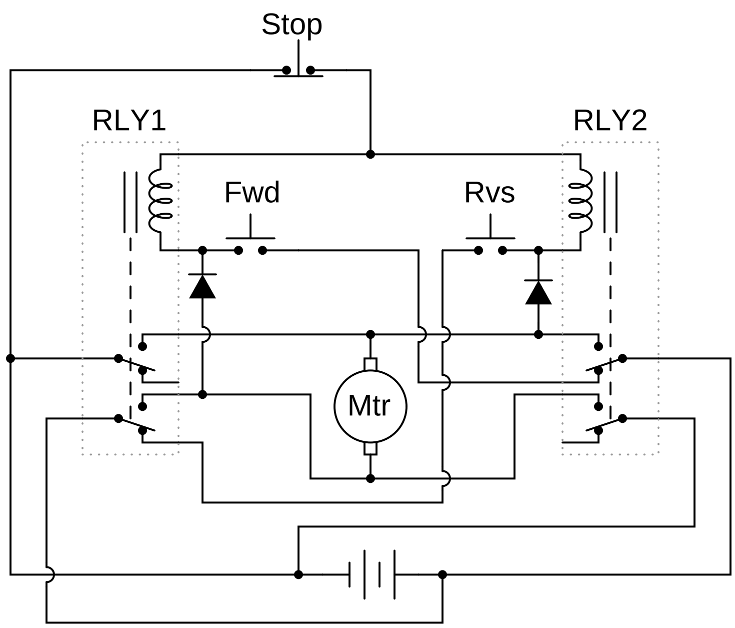
Suppose component ☐ fails ☐ open ☐ other ______ ☐ shorted

What will happen in the circuit?

file 02362

Competency: **Reversing start/stop motor control circuit** Version:

Schematic



Parameters

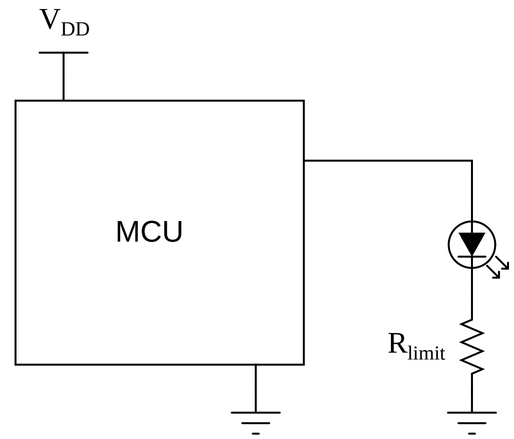
Motor starts and latches in "Forward" ☐

Motor starts and latches in "Reverse" ☐

file 03151

Competency: **Light flasher using MCU** Version:

Schematic



Given conditions

t_{on} = t_{off} =

Program

file 03152

Project progress report (1 day)
Date:
Description of progress made on this day

file 03995

Project progress report (1 day)
Date:
Description of progress made on this day

file 03995

Troubleshooting log

Actions / Measurements / Observations (i.e. *What I did and/or noticed . . .*)	**Conclusions** (i.e. *What this tells me . . .*)

file 03933

Question 57

NAME: ________________ **Troubleshooting Grading Criteria**

You will receive the highest score for which *all* criteria are met.

100 % *(Must meet or exceed all criteria listed)*
A. Absolutely flawless procedure
B. No unnecessary actions or measurements taken

90 % *(Must meet or exceed these criteria in addition to all criteria for 85% and below)*
A. No reversals in procedure (i.e. changing mind without sufficient evidence)
B. Every single action, measurement, and relevant observation properly documented

80 % *(Must meet or exceed these criteria in addition to all criteria for 75% and below)*
A. No more than one unnecessary action or measurement
B. No false conclusions or conceptual errors
C. No missing conclusions (i.e. at least one documented conclusion for action / measurement / observation)

70 % *(Must meet or exceed these criteria in addition to all criteria for 65%)*
A. No more than one false conclusion or conceptual error
B. No more than one conclusion missing (i.e. an action, measurement, or relevant observation without a corresponding conclusion)

65 % *(Must meet or exceed these criteria in addition to all criteria for 60%)*
A. No more than two false conclusions or conceptual errors
B. No more than two unnecessary actions or measurements
C. No more than one undocumented action, measurement, or relevant observation
D. Proper use of all test equipment

60 % *(Must meet or exceed these criteria)*
A. Fault accurately identified
B. Safe procedures used at all times

50 % *(Only applicable where students performed significant development/design work – i.e. not a proven circuit provided with all component values)*
A. Working prototype circuit built and demonstrated

0 % *(If any of the following conditions are true)*
A. Unsafe procedure(s) used at any point

file 03932

Answer 1

One of the most significant differences is that in ladder diagrams, relay coils and relay contacts (the normally-open contact in this diagram shown as a capacitor-like symbol) need not be drawn near each other.

Follow-up question: what do the two labels "L1" and "L2" represent?

Answer 2

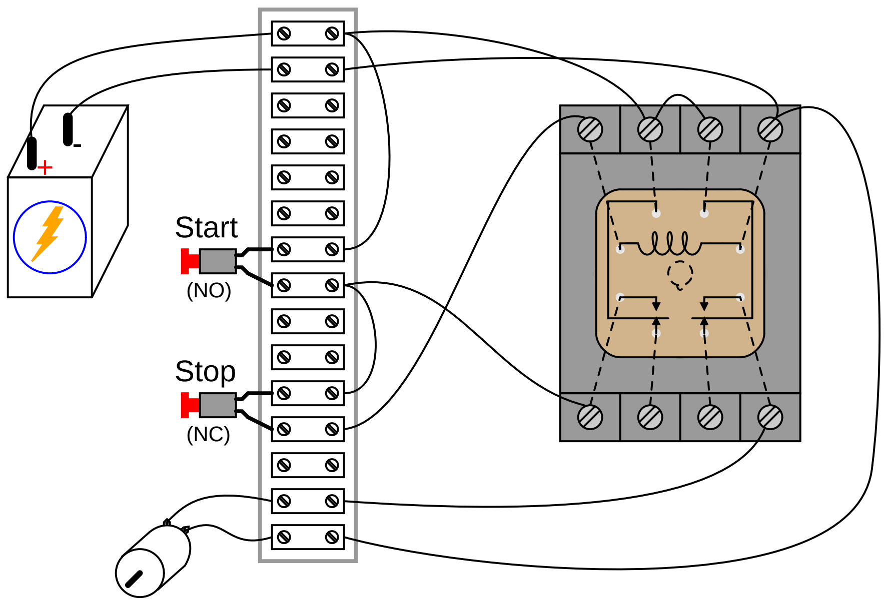
In ladder logic diagrams, relay coils are associated with their respective contacts by *name* rather than by proximity. In this particular circuit, the logic function represented is the AND function.

Answer 3

This is a problem worthy of a good in-class discussion with your peers! Of course, several things could be wrong in this circuit to cause lamp 1 to never energize. When you explain what measurements you would take in isolating the problem, be sure to describe whether or not you are actuating either of the pushbutton switches when you take those measurements.

Answer 4

The wiring sequence shown here is not the only valid solution to this problem!



Answer 5

This is an example of *Lenz' Law*. A rotating magnet would cause a torque to be generated in the disk.

Answer 6

The rotor will rotate due to the action of Lenz's Law.

Follow-up question: what would happen if the rotor's coil were to become open-circuited?

Answer 7

The difference between the speed of the rotating magnetic field (fixed by line power frequency) and the speed of the rotor is called "slip speed". Some amount of slip is necessary to generate torque because without it there would be no change in magnetic flux ($\frac{d\phi}{dt}$) seen by the rotor, and thus no induced currents in the rotor.

Answer 8

There is a lot of information on "squirrel cage" electric motors. I will leave it to you to do the research.

Answer 9

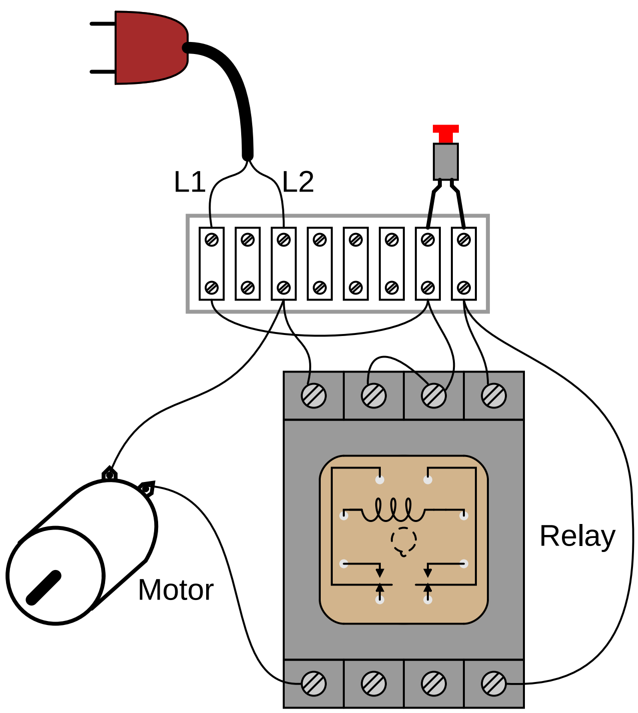
Reverse any two lines. This will reverse the phase sequence (from ABC to CBA).

Answer 10

In this circuit, the motor will start once the "Run" switch is actuated. When the "Run" switch is released, the motor continues to run.

Follow-up question: this circuit has no "stop" switch! What would have to be modified in the ladder logic circuit to provide "stop" control?

Answer 11



Answer 12

A "starter" is another name for the large power relay used to conduct current to the motor lines. Starters are also known as *contactors*, and are usually labeled with the letter "M" in ladder diagrams.

Answer 13

I'll let you research the answers to this question!

Answer 14

When the overload "heaters" become excessively warm from overcurrent, they trigger the opening of the "OL" contact, thus stopping the motor. The heaters do not take the place of regular overcurrent protection devices (circuit breakers, fuses), but serve a different purpose entirely. It is the task of the overload heaters to protect the *motor* against overcurrent by mimicking the thermal characteristics of the motor itself. Circuit breakers and fuses, on the other hand, protect an entirely different part of the circuit!

Answer 15

Motor reversal is accomplished by reversing the phase sequence of the three-phase power going to the motor (from ABC to ACB). The existence of only one set (three) heaters may be adequately explained if you consider a scenario where the motor overheats after being run in the "Forward" direction, then an immediate attempt is made to run it in "Reverse." Finally, the NC contacts (typically called *interlock* contacts) prevent lots of sparks from flying if both pushbuttons are simultaneously pressed!

Answer 16

Each overload heater element possesses a small amount of electrical resistance, which is the key to this diagnostic procedure. Of course, the measurement obtained is strictly qualitative, not quantitative as a clamp-on ammeter would give.

Follow-up question #1: what sort of result might occur with this diagnostic check if the motor were indeed single-phasing due to one of the overload heaters failing open?

Follow-up question #2: what other causes could there be for a three-phase motor "single-phasing" other than a motor winding failed open?

Answer 17

Variable frequency drives allow for the precise and efficient control of induction motor speed, which is not possible by other means.

Answer 18

The reset time for an overcurrent heater is an intentional design feature. If the heater is too hot to re-set, then the motor is too hot to re-start.

Answer 19

I won't give you a direct answer here, but I will provide a big hint: *inrush current*.

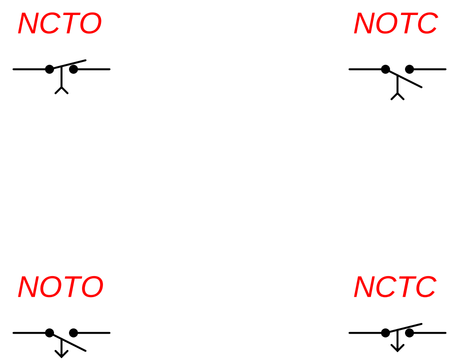
Answer 20

Electromechanical relays interrupt circuit current by drawing pairs of metal contacts apart, separating them with an air gap. Because this contact motion is not instantaneous, it is possible to generate an arc across the air gaps of such magnitude that it becomes an arc flash.

Answer 21

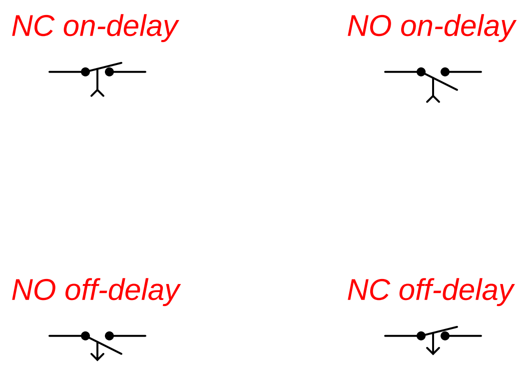
Note that the "arrow" is pointing in the up direction, toward the direction of contact closure.

Answer 22



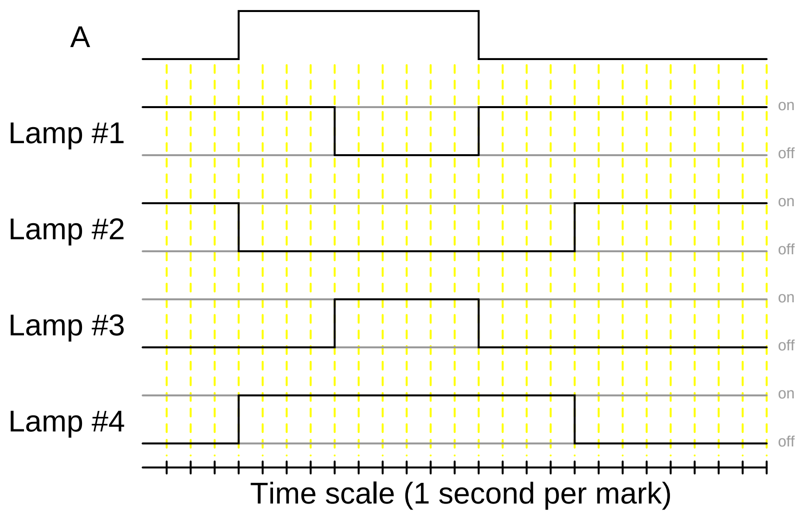
Follow-up question: how do you make sense of the arrow in each contact symbol, with regard to whether the contact is timed-open or timed-closed?

Answer 23



Follow-up question: how do you make sense of the arrow in each contact symbol, with regard to whether the contact is an "on-delay" or an "off-delay"?

Answer 24



Follow-up question: identify each relay contact by name:

- Normally-closed, timed-open
- Normally-open, timed-open
- Normally-closed, timed-close
- Normally-open, timed-close

Answer 25

Normally-open, timed-open (NOTO).

Follow-up question: what purpose does the diode serve in this circuit?

Answer 26

This is an exercise for you and your classmates to analyze!

Answer 27

In this system, resistors limit the motor's line current during the initial start-up period, and then are bypassed after the time delay relay times out.

Answer 28

The normally-open and normally-closed "M" contacts provide seal-in and interlock functions, respectively. The time-delay relays prevent the motor from being *immediately* reversed.

Follow-up question: figure out how to simplify the time-delay relay circuit. Hint: integrate the time-delay and interlocking functions into a single contact (per rung).

Answer 29

When the "S" and "Y" contacts are all closed, the autotransformers form a three-phase "Y" connection, with line voltage (L1, L2, and L3) applied to the "tips" of the "Y," and a reduced motor voltage tapped off a portion of each autotransformer winding.

When the "Y" contacts open, the three autotransformers now function merely as series-connected inductors, limiting current with their inductive reactance.

When the "R" contacts close, the motor receives direct power from L1, L2, and L3.

Follow-up question: how do the overload heaters function in this circuit? They aren't connected in series with the motor conductors as is typical with smaller motors!

Answer 30

Note that the following lists are not comprehensive.

Possible faults:

- Siren failed open
- M1 contact (normally-closed) failed open

Things known to work:

- Control relay CR1
- Motor starter
- Motor

Answer 31

I'll let you do your homework on this question!

Answer 32

Ease of configuration and flexibility!

Answer 33

A "loop" is necessary for the MCU to repeat the on/pause/off sequence. What is needed now is another time delay within the loop:

<u>Pseudocode listing</u>

```
Declare Pin0 as an output
LOOP
  Set Pin0 HIGH
  Pause for 1 second
  Set Pin0 LOW
  Pause for 1 second (new line of code)
ENDLOOP
```

Answer 34

The conditional "WHILE" loop needs to be placed inside an unconditional loop:

Pseudocode listing

```
Declare Pin0 as an output
Declare Pin1 as an input
LOOP
  WHILE Pin1 is HIGH
    Set Pin0 HIGH
    Pause for 0.5 seconds
    Set Pin0 LOW
    Pause for 0.5 seconds
  ENDWHILE
ENDLOOP
```

Follow-up question: what purpose does the resistor $R_{pulldown}$ serve in the pushbutton circuit?

Answer 35

This microcontroller implements the logical OR function.

Answer 36

This microcontroller implements the logical AND function.

Answer 37

This microcontroller implements the logical NAND function.

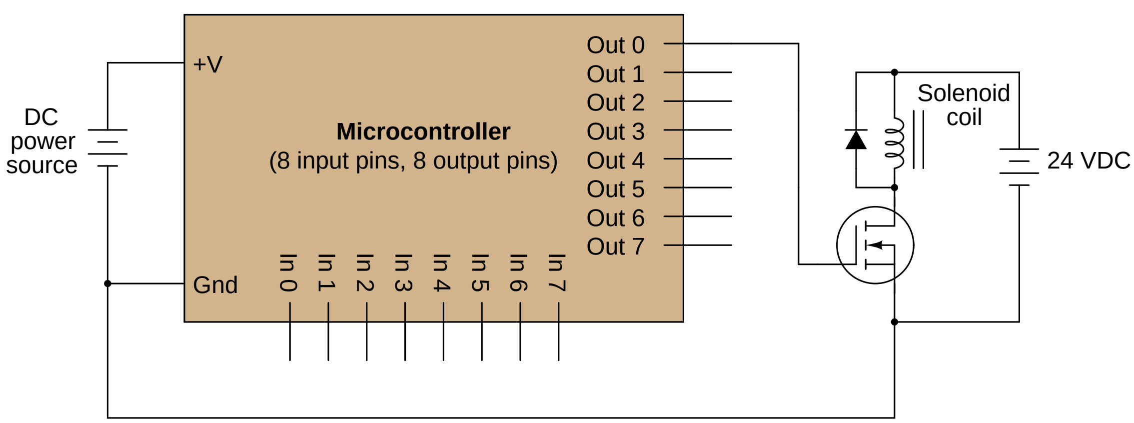
Answer 38

This microcontroller implements the logical NOR function.

Answer 39

This microcontroller implements the logical Exclusive-OR function.

Answer 40



Answer 41

Here are some possible faults (not an exhaustive list by any means!):

- Any fuse blown
- Contactor coil failed open
- Any transformer winding failed open
- Broken jumper between H3 and H2 on the transformer
- Corroded wire connection at terminal A1 or A2
- Motor winding failed shorted

Follow-up question: there will be a difference in operation between the L1 fuse blowing and either the L2 or L3 fuse blowing. Explain what this difference is, and why it might serve as a clue to what was wrong.

Answer 42

Thermistor resistance = 5.547 kΩ

Answer 43

I'll let you and your classmates figure out this circuit! It is fairly straightforward to analyze.

Answer 44

The function of a GFCI is very easy to research, so I'll leave that to you. In a more general sense, a *differential relay* protects against conditions where two or more electrical quantities (usually current) are not in phasor balance. That is, a differential relay will trip when two or more electrical quantities do not precisely balance one another when they should.

Answer 45

The differential relay shown protects against *ground faults* inside the motor. Although not shown in the diagram, the protective relay will actuate a contact that will tell the motor's control circuitry to cut power to the motor in the event of a ground fault.

Answer 46

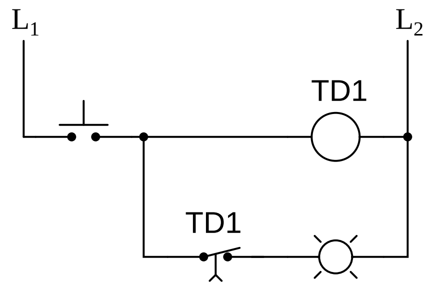
I'll let you and your classmates discuss how the MCU might detect power factor. There is more than one valid solution for doing so!

The 20 μF and 80 μF capacitors would both be engaged: MCU output DCBA would be `0101` (note that the outputs must go *low* to energize their respective relays!). With this output, the corrected power factor would be 0.99939 rather than the original 0.77.

Answer 47

I'll give you a hint: suppose someone pushes *and holds* the start button long enough that time delay relay TD1 completes its timing cycle?

Answer 48



Answer 49

Time-delay relays can do a lot of neat things, but they cannot predict the future!

Answer 50

This is a *normally-open, timed-closed* (also known as a *normally-open, on-delay*) relay, with a time delay of 4.065 seconds.

Answer 51

The real circuit you build will validate your circuit design.

Answer 52

The real circuit you build will validate your circuit design.

Answer 53

Use circuit simulation software to verify your predicted and actual truth tables.

Answer 54

Be sure to note *everything* accomplished for each day, so your instructor has a complete record of your progress.

Answer 55

Be sure to note *everything* accomplished for each day, so your instructor has a complete record of your progress.

Answer 56

I do not provide a grading rubric here, but elsewhere.

Answer 57

Be sure to document all steps taken and conclusions made in your troubleshooting!

Notes 1

Discuss these diagrams with your students, noting any significant advantages and disadvantages of each convention.

In reference to the challenge question, the symbols "L1" and "L2" are very common designations for AC power conductors. Be sure your students have researched this and know what these labels mean!

Notes 2

Many students find it confusing that relay contacts and coils need not be drawn next to one another in a ladder logic diagram, because it is so different from the schematic diagrams they are accustomed to. The non-necessity of proximity in a ladder logic diagram does have its advantages, though! It is simply a matter of getting used to a new way of drawing things.

Notes 3

Be sure to leave plenty of classroom time for a discussion on troubleshooting this circuit. Electrical troubleshooting is a difficult-to-develop skill, and it takes lots of time for some people to acquire. Being one of the most valuable skills a technical person can possess, it is well worth the time invested!

The challenge question is very practical. Too many times I have seen students take meter measurements when their other senses provide enough data to render that step unnecessary. While there is nothing wrong with using your meter to confirm a suspicion, the best troubleshooters use all their senses (safely, of course) in the isolation of system faults.

Notes 4

This circuit provides students with an opportunity to analyze a simple *latch*: a system that "remembers" prior switch actuations by holding a "state" (either set or reset; latched or unlatched). A simple motor start/stop circuit such as this is about as simple as latch circuits get.

Students should be able to immediately comprehend the benefit of using nice, neat, structured ladder diagrams when they see the tangled mess of wires in a real motor control circuit. And this is not even a complex motor control circuit! It takes very little imagination to think of something even uglier than this, and what a task it would be to troubleshoot such a circuit without the benefit of a ladder diagram for guidance.

Notes 5

Mechanical speedometer assemblies used on many automobiles use this very principle: a magnet assembly is rotated by a cable connected to the vehicle's driveshaft. This magnet rotates in close proximity to a metal disk, which gets "dragged" in the same direction that the magnet spins. The disk's torque acts against the resistance of a spring, deflecting a pointer along a scale, indicating the speed of the vehicle. The faster the magnet spins, the more torque is felt by the disk.

Notes 6

Here, we see a practical 3-phase *induction* motor. Be sure to thoroughly discuss what is necessary to increase or decrease rotor speed, and compare this with what is necessary to increase or decrease speed in a DC motor.

Notes 7

It is easy enough for students to research "slip speed" in any motor reference book and present a definition. It is quite another for them to explain *why* slip is necessary. Be sure to allow ample time in class to discuss this concept, because it is at the heart of induction motor operation.

Notes 8

Although it is easy enough for students to find information on squirrel cage motors classifying them as either induction or synchronous, you should challenge your students to *explain* why it is one type or the other. The goal here, as always, is *comprehension* over *memorization*.

Notes 9

One of the reasons three-phase motors are preferred in industry is the simplicity of rotation reversal. However, this is also a problem because when you connect a three-phase motor to its power source during maintenance or installation procedures, you often do not know which way it will rotate until you turn the power on!

Discuss with your students how an electrician might go about his or her job when installing a three-phase motor. What would be the proper lock-out/tag-out sequence, and steps to take when connecting a motor to its power source? What would have to be done if it is found the motor rotates in the wrong direction?

Notes 10

This circuit is known as a *latching* circuit, because it "latches" in the "on" state after a momentary action. The contact in parallel with the "Run" switch is often referred to as a *seal-in contact*, because it "seals" the momentary condition of the Run switch closure after that switch is de-actuated.

The follow-up question of how we may make the motor stop running is a very important one. Spend time with your students discussing this practical design problem, and implement a solution.

Notes 11

This question helps students build their spatial-relations skills, as they relate a neat, clean diagram to a relatively "messy" real-world circuit. As usual, the circuit shown here is not the only way it could have been built, but it is one solution.

Notes 12

Ask your students to identify any motor control circuit diagrams they've already seen as being "across-the-line." If there are no convenient motor control circuit diagrams available for illustration, you may want to ask a student to draw an "across-the-line" starter circuit on the whiteboard for everyone to see.

Notes 13

The reasons for using reduced-voltage starting instead of across-the-line starting go beyond electrical! Discuss this with your students.

Notes 14

Ask your students to describe the information they found on overload heaters through their research. There are different styles and variations of overload heaters, but they all perform the same function. Also, be sure to review with your students the purpose of fuses and circuit breakers. These devices are not intended to protect the load (motor), but rather another important component of an electrical system!

An interesting way to explain the function of overload heaters is to refer to them as *analog models* of the motor windings. They are designed such that at any given current level, they will take as long to heat up and reach their trip point as the real motor itself will take to heat up to a point of impending damage. Likewise, they also cool off at the same rate as the real motor cools off when no power is applied. Overload heaters are like small motor-models with a thermostat mechanism attached, to trip the overload contact at the appropriate time. It is an elegant concept, and quite practical in real motor control applications.

Notes 15

Ask your students to explain exactly *why* "sparks [would fly]" if both pushbuttons were pressed at the same time. The name commonly given to the NC contacts is *interlock*, because each one "locks out" the other starter from being energized.

Notes 16

I have used this diagnostic check more than once to troubleshooting a single-phasing electric motor. It is amazing what sorts of diagnostic checks you can do with a high-quality DMM and a sound understanding of electrical theory!

Notes 17

Central to the answer of this question is the principle of a *rotating magnetic field* and how rotor speed is primarily a function of line frequency. While the internal details of a VFD are quite complex, the basic operating principle (and rationale) is not.

Notes 18

Remind your students that the purpose of an overload heater is to provide a thermal analogue of the electric motor itself. Ideally, the heater heats up and cools down at the exact same rate as the motor. This explains why there is a necessary reset time after an overload heater causes the motor control circuit to "trip."

Ask your students to share the common design features of an overload heater, from their research. How do these devices actually function? If your students understand this, they should have no difficulty understanding why overload heater contacts require time to reset after a trip.

The reason for the reset time curve decreasing after about 300% full-load current is a bit more complex to answer. This, as well, is not an idiosyncrasy, but rather a design feature of the overload heater. Since greater levels of current will trip the heater in a shorter time, they actually heat up the motor less during that brief "on" time than a sustained overcurrent of lesser magnitude. Therefore the motor does not need to cool down as long prior to the next re-start.

Notes 19

Inrush current is a factor with *every* motor type, AC or DC. It is easy to forget just how substantially larger a typical motor's inrush current is compared to its normal full-load current. When students consider the magnitude of the currents involved, and also the fact that most electric motors are fan-cooled and therefore lacking in cooling during the initial moments of a start-up, the reason for automatic lock-out after several successive start-up events becomes obvious.

Notes 20

Arc flash is just as hazardous to electrical technicians as electric shock, yet I have seen (and worked with) people who pay no attention to the dangers! It must be understood that motor starters are by their very nature arc-generating devices, and that under certain unusual conditions may generate lethal arc flashes. You might want to ask your students what sorts of unusual conditions could lead to a contactor producing an actual arc flash (rather than merely a few small sparks).

Notes 21

The arrow symbol is not difficult to figure out, but it is essential to know when working with time-delay relay circuits. Ask your students to describe their understanding of the arrow symbol as they answer this question.

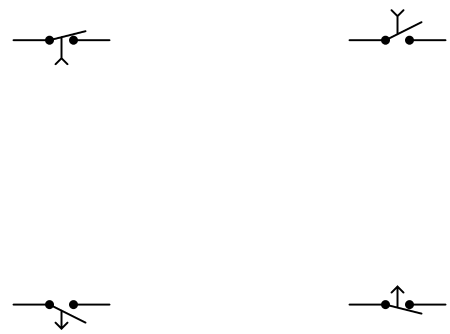
Notes 22

Ask your students to present their personal explanations of how to make sense of the arrow directions, in relation to whether the relay is "timed-open" or "timed-closed." The correlation is really not that complex, but it is a good thing to clearly elaborate on it for the benefit of the whole class. You may want to re-phrase the question like this: "Does the arrow represent the direction of timed motion or the direction of instantaneous motion?"

Notes 23

Ask your students to present their personal explanations of how to make sense of the arrow directions, in relation to whether the relay is an ”on-delay” or an ”off-delay.” The correlation is really not that complex, but it is a good thing to clearly elaborate on it for the benefit of the whole class. You may want to re-phrase the question like this: ”Is it possible to determine whether each contact is on- or off-delay merely by looking at the arrow, or must one also consider the ”normal” status?”

If some students believe this may be determined by arrow direction alone, show them these symbols:



Notes 24

Time-delay relays are not the easiest for some students to understand. The purpose of this question is to introduce students to the four basic types of time-delay relay contacts and their respective behaviors. Discuss with your students how the contact symbols make sense (arrows on the switch actuators describing direction of delay).

Note to your students how it is possible to have different types of time-delay contacts actuated by the same relay coil.

Notes 25

For substantial time delays (many seconds) on large relays (high-current coils), the capacitor must be *huge*, making this a somewhat impractical circuit for all but miniature relays.

Notes 26

This circuit provides students an opportunity to analyze the workings of a delayed-start motor control circuit, where some other action (a siren in this case) takes place during the motor's delay. Have your students present both their analyses and the methods behind the analyses as you work through this question with them.

Notes 27

After being accustomed to seeing resistors drawn as zig-zag symbols, it may take some students a few moments to realize the ”square wave” components in the motor power diagram are actually resistors. Confusing? Yes, but this is the standard symbolism for ladder-logic diagrams!

Notes 28

This circuit provides students an opportunity to analyze the workings of a delayed-start, reversing motor control circuit. Have your students present both their analyses and the methods behind the analyses as you work through this question with them.

Notes 29

For each step of the start-up sequence, it is possible to re-draw the circuit feeding power to the motor, in order to make its function more apparent. Do not create these re-drawings yourself, but have your students draw an equivalent circuit for each step in the start-up sequence.

The follow-up question is a good review of current transformers (CT), as well as an introduction to the use of overload heaters in high-current electrical systems.

Notes 30

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Notes 31

Not only is the quotation funny, but it is startling as well, especially to those of us who were born without any computers in our homes at all, much less multiple personal computers.

A point I wish to make in having students research the term "microcontroller" is to see that most of the computers in existence are not of the variety one ordinarily thinks of by the label "computer." Those doorknob computers – as well as engine control computers in automobiles, kitchen appliances, cellular telephones, biomedical implants, talking birthday cards, and other small devices – are much smaller and much more specialized than the "general purpose" computers people use at their desks to write documents or surf the internet. They are the silent, unseen side of the modern "computer revolution," and in many ways are more appropriate for beginning students of digital electronics to explore than their larger, general-purpose counterparts.

Notes 32

Note that I did not bother to explain my extremely terse answer. This is a subject I desire students to think long and hard about, for the real answer(s) to this question are the reasons driving all development of programmable digital devices.

Notes 33

The purpose of this question is for students to realize that the microcontroller must be told to "loop" through the light blinking instructions. Really, this is just an illustration of loops in a practical context.

In case you're wondering why I write in pseudocode, here are a few reasons:

- No prior experience with programming required to understand pseudocode
- It never goes out of style
- Hardware independent
- No syntax errors

If I had decided to showcase code that would actually run in a microcontroller, I would be dooming the question to obsolescence. This way, I can communicate the spirit of the program without being chained to an actual programming standard. The only drawback is that students will have to translate my pseudocode to real code that will actually run on their particular MCU hardware, but that is a problem guaranteed for some regardless of which real programming language I would choose.

Of course, I could have taken the Donald Knuth approach and invented my own (imaginary) hardware and instruction set . . .

Notes 34

The purpose of this question is for students to understand what a "WHILE" loop represents in practical terms: a loop with condition(s). It also contrasts conditional looping against unconditional looping, and shows how both play a part in interactive systems such as this one.

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Notes 35

Although this logic function could have been implemented easier and cheaper in hard-wired (gate) logic, the purpose is to get students to think of performing logical operations by a sequenced set of instructions inside a programmable device (the MCU). This is a conceptual leap, basic but very important.

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Notes 40

The purpose of this long-winded question is not just to have students figure out how to replace a BJT with a MOSFET, but also to introduce them to the concept of the microcontroller, which is a device of increasing importance in modern electronic systems.

Some students may inquire as to the purpose of the diode in this circuit. Explain to them that this is a *commutating diode*, sometimes called a *free-wheeling diode*, necessary to prevent the transistor from being overstressed by high-voltage transients produced by the solenoid coil when de-energized ("inductive kickback").

Notes 41

Identifying multiple faults should be quite easy in this circuit. The real value of this question is the opportunity for explanation and discussion that it generates for your students as they share their answers with each other.

Notes 42

Ask your students how they arrived at their solution for this question. There is definitely more than one way to do it!

Notes 43

If you want to add more challenge to this question, ask your students to come up with practical component values. Of course, you will need to provide some base values such as:

- Maximum motor current (locked-rotor)
- Motor supply voltage
- Relay coil current
- Transistor β

Notes 44

This question affords students the opportunity to relate something they probably never have had exposure to (a differential protective relay) to something they may see every day (a GFCI-protected power receptacle). The purpose of this comparison, of course, is to give students a familiar context in which to understand something new.

Notes 45

At first, students may be dismayed at the appearance of the current transformers being short-circuited to each other. If so, remind them that it is perfectly *normal* to short the output of a current transformer. In fact, opening the secondary of a CT can be dangerous!

It should be noted that the protective relay itself is but a part of a complete protection system. On its own, it can only monitor for current differences. In order to actually protect anything, it must be tied into the control circuitry supplying power to the motor. That is, just like an overload contact (O.L.) tells a motor contactor to de-energize, the protective relay must command a contactor or a circuit breaker to open in order to actually interrupt power to the faulted section of a circuit.

I must say that I am indebted to C. Russell Mason's wonderful text, The Art and Science of Protective Relaying. Not only is it comprehensive, but also very lucid in its presentation.

Notes 46

This question poses some interesting concepts for review, as well as synthesizing old and new concepts in electronics for your students to consider. Be sure to allow plenty of time for discussion on this question, as well as any necessary review time for power factor calculations!

Notes 47

This circuit provides students an opportunity to analyze the workings of a delayed-start motor control circuit, where some other action (a siren in this case) takes place during the motor's delay. Have your students present both their analyses and the methods behind the analyses as you work through this question with them.

Notes 48

This is a good problem-solving exercise, figuring out how to creatively combine time-delay relays to perform a specific function.

Notes 49

The real purpose of this question is to get students to recognize an impossibility in timing diagrams. As an instructor, I see students mistakes such as this once in a while. Those students who have trouble answering this question may not yet fully understand how to interpret timing diagrams!

Notes 50

Some students may mistakenly base their time calculations on the 10 kΩ resistor and/or the 0.1 μF capacitor. Discuss the role of these two components in triggering the 555 timer, and how the time delay of the relay is actually set by the *other* R and C.

Notes 51

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

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The two diodes in this circuit are a matter of necessity: getting the circuit to work with only two sets of switch contacts per relay. Ideally, each relay would be 3PDT with separate contact sets for latching, interlocking, and motor power. To use a DPDT relay requires that one of these contact sets do double-duty. In this case, one of the contact sets on each relay handling power to the motor must also handle the job of seal-in (latching). Without the diodes in place, both relays chatter when either motion button is pressed. This is because both relay coils receive power: one coil directly through the switch; the other through the same switch, back through the motor, and then through the seal-in (latching) connection. The diodes prevent this "feed-through" to the other relay coil from happening, without interfering with the normal latching function.

Notes 53

Here, I let students choose appropriate values for $R_{pulldown}$ and R_{limit}, rather than specify them as given conditions.

Notes 54

The purpose of this report form is to familiarize students with the concept of time management as it relates to project completion. Too many students have a tendency to do little or nothing until just before their project is due. By assigning a grade value for progress made each day, you help them learn time management skills and also help them complete their projects sooner (and better!).

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Notes 56

The idea of a troubleshooting log is three-fold. First, it gets students in the habit of documenting their troubleshooting procedure and thought process. This is a valuable habit to get into, as it translates to more efficient (and easier-followed) troubleshooting on the job. Second, it provides a way to document student steps for the assessment process, making your job as an instructor easier. Third, it reinforces the notion that each and every measurement or action should be followed by reflection (conclusion), making the troubleshooting process more efficient.

Notes 57

The purpose of this assessment rubric is to act as a sort of "contract" between you (the instructor) and your student. This way, the expectations are all clearly known in advance, which goes a long way toward disarming problems later when it is time to grade.