Automation basics: Categories of emergency stops

BY **ROYAL MARTY**

EVERYWHERE YOU TURN you see a big red button from elevators, escalators, and on your machinery backstage. There is never a question about what the big red button does, it stops the machine from moving in case of an emergency. In the entertainment industry, we rely on the emergency stop (e-stop) to save actors and technicians from the moving scenery and effects. As effects in live entertainment have gotten larger and faster a safe and reliable e-stop circuit has become imperative to ensure safety. While there are many safety implications that go into the e-stop system there are also many features implemented in the circuit to ensure the e-stop works and works reliably.

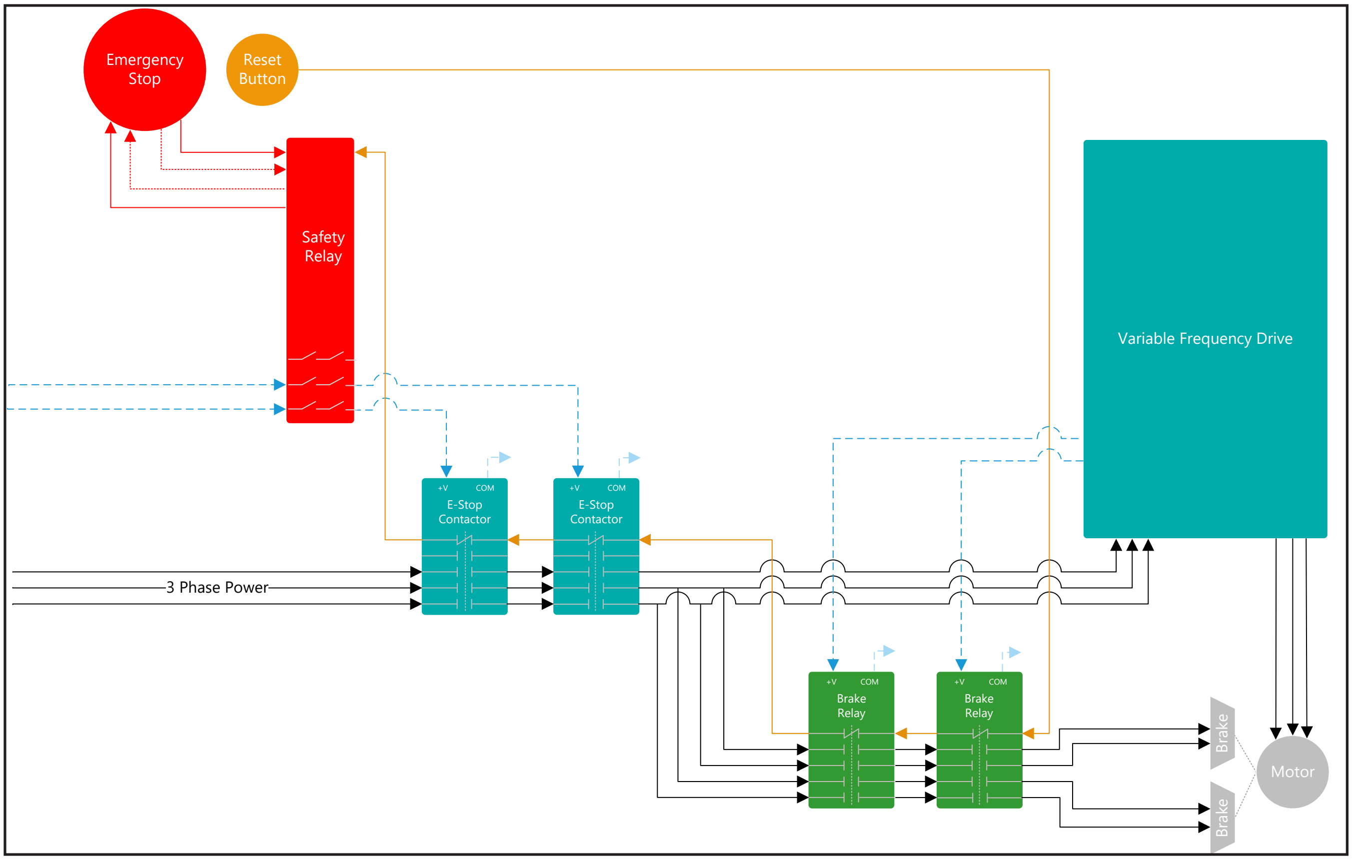
In the recent decades, there have been many standards and directives developed that apply to the e-stop system in the entertainment industry such as *ANSI E1.6 – Entertainment Technology – Powered Hoist Systems*; *ANSI E1.42 – Entertainment Technology – Design, Installation, and Use of Orchestra Pit Lifts*; *ANSI E1.43 – Entertainment Technology – Performer Flying Systems*; and Safety Integrity Levels (SIL).

The SIL standard has become more prevalent in the entertainment industry. There are four different levels of SIL, SIL:1 being the least safe and SIL:4 being the safest. In the entertainment industry, we often aim towards a SIL:3 level. It is important to remember that SIL is about the probability of failure and what harm would result from that. The SIL levels aren't just individual component ratings, they are for rating a complete system. The complete system rating is key because it doesn't necessarily meet a certain SIL level such as SIL:3 just because the system contains all SIL:3 rated components. A system can be SIL compliant by using SIL components and SIL recognized circuits, but for the system to be SIL certified it must be certified by a third party.

With the guidance of the safety standards introduced to the traditional stage automation system, there are two ways to stop the machinery; a soft stop (category 2) and an e-stop (category 0 or 1). A soft stop is a controlled deceleration that is traditionally applied by the motion control software in which power is left available to the actuator, e.g. motor, upon stopping. An e-stop is a stop in which the motion is halted with logic and components isolated from the motion control software. A category 0 e-stop is defined as halting the motion immediately by removing power from the actuator, while a category 1 e-stop is defined as an immediate controlled stop prior to removing power from the actuator, a stop is applied with a defined time (i.e. a 0.5 second deceleration). It is important for the automation operator to know the differences between a soft stop and e-stop, not only for emergency instances, but also for using the appropriate stopping function for the different scenarios.

> . . . a proper risk assessment should always be performed on the complete system of each installation.

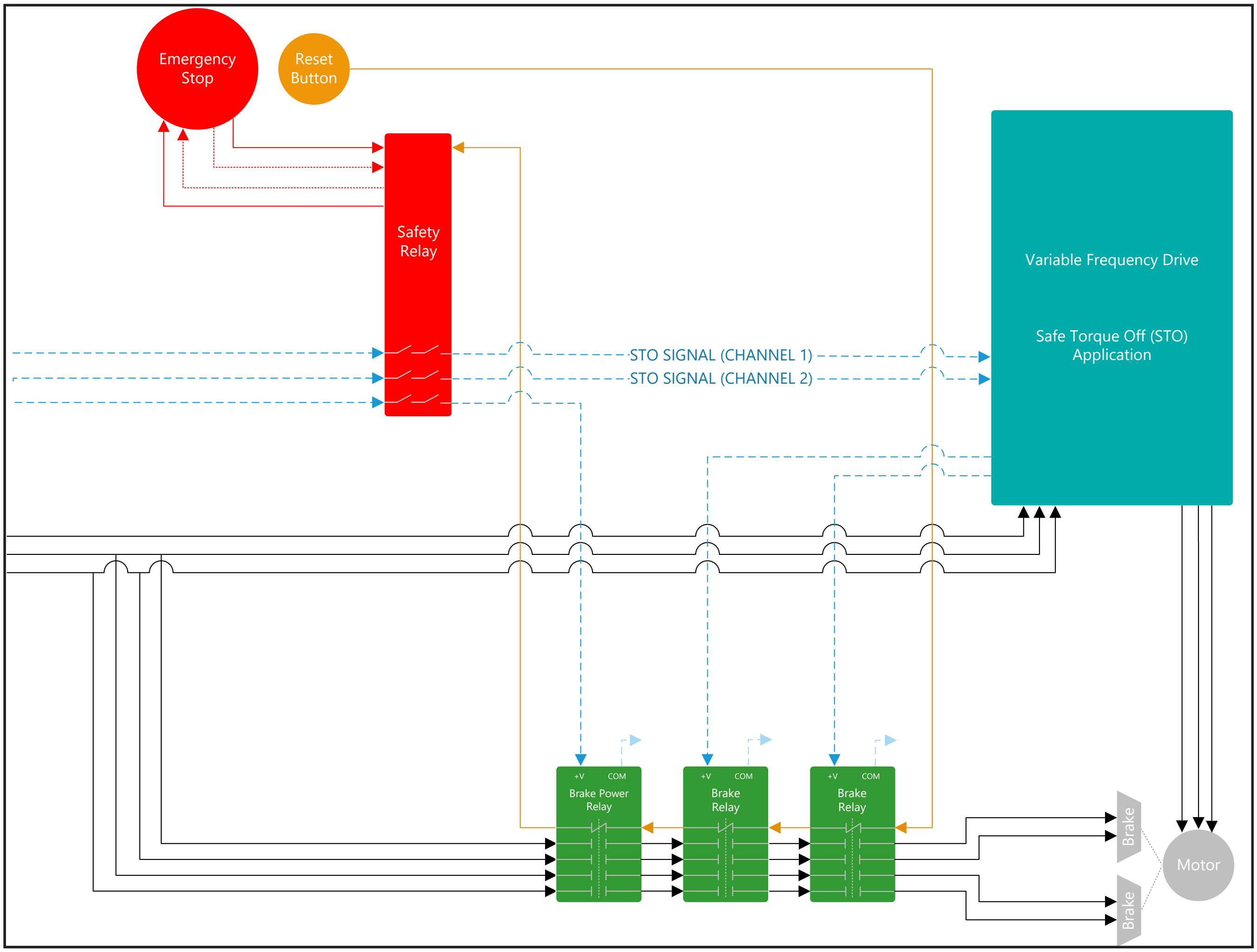
For example, take a show with an automated turntable loaded with actors and scenery in which the system is equipped with a soft stop and category 0 e-stop. If a rehearsal is happening and the director wants to pause while the turntable is moving to rework the scene the operator should use the soft stop function to bring the turntable to a controlled stop because nobody is in danger—in fact, a sudden stop might endanger someone. If you take the same scenario, but now an actor has gotten a foot stuck in between the main stage and the turntable—that calls for an e-stop. The automation operator should always be running a risk assessment in their head while the automation is moving so they can quickly determine what stop is appropriate. Although a soft stop is important, an e-stop is required for system operation.



Example of a safety circuit by removing power to the motor drive.

The nature of the category 0 e-stop halting the motion almost immediately is both its largest advantage and disadvantage. The advantage is that when the user actuates the e-stop button the motion will halt almost immediately, you are only relying on gravity, inertia, and physics at that point for the unit to come to a stop. The disadvantage is that the forces seen upon a category 0 e-stop can become so high due to the sudden deceleration that the forces are indeterminable at some points. The shock load of these high forces become an issue for the system because the machine (frame, brakes, shafts), lifting medium, pulleys, and rigging structure must be adequately sized to experience these high forces. With a category 1 e-stop the system sees a decreased shock load, thus putting less force on the entire system. The trouble that a category 1 e-stop presents is that the machine and object being moved can drift a considerable distance during the stop. If your system has a 0.5 second deceleration programmed for a category 0 e-stop and the machine has a velocity of 6' per second the machine will move 1.5' before coming to a stop after the e-stop button is pressed. A proper risk assessment should be performed to determine which category of stopping the system should use. For example, there is a 1,000 lb. portal that is hoisted in and out during the show with a velocity of 6' per second over performers should probably be a category 0 stop. If those same performers are performing on an automated wagon moving at 8' per second, the automated wagon should probably be on a category 1 e-stop, lest the sudden stop cause them to be hurtled off of the automated wagon. This example is brought up to show that there is no hard and fast rule for using a category 0 or a category 1 e-stop, a proper risk assessment should always be performed on the complete system of each installation. It is important to note that different machines or effects might require a different category of e-stop while using the same emergency stop system.

At the heart of every e-stop circuit is a safety relay or a safety monitoring device. A safety relay is an electrical component that is made for safety sensitive functions such as e-stop circuits. The safety relays have specific internal designs and meet requirements of a defined SIL level, usually SIL:2 or SIL:3. A safety relay is a force-guided relay, meaning all of the contacts are mechanically linked together. This means if one contact switches state all of the contacts will switch state. Each internal circuit in a safety relay consists of two parallel circuits, each with redundant switches/relays. The goal is that no single failure will result in the safety relay being unable to stop the system from moving (creating an e-stop). A safety relay is crucial for integrating a dual channel e-stop circuit. Most dual channel safety relays are actuated by a circuit that switches +24 VDC and a parallel circuit that switches 0 VDC. This allows the safety relay to detect faults in the circuit, such as a short circuit



Example of a safety circuit utilizing Safe Torque Off.

in the input circuit, which will cause it to switch to its safe state.

Once the e-stop has been pressed it must be released. In most systems, releasing the e-stop button doesn't mean the system is ready and the machine can move. The operator must actuate a reset circuit for the system to restore to a healthy state and begin movements after actuating the e-stop button. This circuit is used to detect any single point failures in the e-stop system. Between the reset button and the reset input on the safety relay the circuit is wired in series to pass through a normally closed (NC) circuit for every safety critical relay in the electrical system, including every safety relay, brake relays, and e-stop contactors. The reason for routing them through the normally closed circuits is to ensure that any single failure of a safety component causing it to be in an unsafe state will prevent the e-stop system from being able to reset, therefore the machine will be unable to move.

The part of the safety circuit that the operator has the most interaction with is the hold-to-run (HTR) switch, sometimes referred to as the dead-man switch. The HTR is often a wrist positioned button or foot pedal that the operator must hold down to allow for movement. This is to prevent any accidental machine movement from happening as well as ensuring the operator does not leave the control station while motion is happening. If the HTR is released at any point of movement the machine e-stop will be initiated. This is usually a category 1 or 2 stop. One method of implementing a category 1 stop is to wire

The ideal e-stop circuit is designed with risk analysis for the application and redundancy in mind . . .

Quick stops and Newton's Second Law

By Karl G. Ruling

A few weeks ago, I received an email asking about braking forces when a chain hoist carrying a load comes to a stop. My correspondent wrote that he could find stopping times in the product literature, but not force specifications. I wrote back that force and deceleration rate are described by Newtonian physics: $f = ma$. He wrote that was what he thought, but, as the stopping time approaches zero, the force approaches infinity. I replied, "Right."

Instantaneous stops might sound like a good thing, but truly instantaneous stops are impossible because infinite force is impossible, and very fast stops require high forces. Those forces, if not carefully considered in stage machinery design, can destroy the load, the stage machinery, the supporting structure, or all three.

Newton's Second Law of Motion can be mathematically expressed as f = ma. The Second Law, as stated in Andrew Motte's 1846 English translation of Sir Isaac Newton's *Philosophiæ Naturalis Principia Mathematica*, is:

> The alteration of motion is ever proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

Modern renderings of this law often refer to "net forces." There may be many forces acting on a body, but motion only results when opposing forces are not equal, causing a net motive force. That is, if you are reading this and not hurtling toward the center of the earth, it is because the floor supporting you is pushing up with a force equal to the force of gravity pulling you down. If the forces were not equal, you would either float into the air or sink into the floor, gradually accelerating as you fly or fall. As Newton's First Law states:

> Every body perseveres in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed thereon.

Returning to the Second Law, let's assume we have a large chandelier with a mass of 200 kg. (about 440 lb.) and it flies in, covering 9 m at a constant velocity in 3 seconds, and then has to decelerate to a stop in half a second. How much force would be needed to stop its motion and bring it to rest?

The deceleration is the rate of change of velocity. The chandelier is moving downward, a negative direction if upward is positive, at -3 m/s and then half a second later is moving at 0 m/s.

$$a = (v - v_0)/t$$

where v is the final velocity and v_0 is the initial velocity, and t is time in seconds.

$$a = (0\text{m/s} - (-3\text{m/s}))/0.5\text{s}$$
$$a = (3\text{m/s})/0.5\text{s}$$
$$a = 6\text{m/s}^2$$

It will need to decelerate at a rate of six meters per second per second.

Therefore, using $f = ma$, we have:

$$f = 200\text{kg} \bullet 6\text{m/s}^2$$
$$f = 1200\text{ N } (\approx 270\text{ lb.-force})$$

This 1,200 newtons to slow the descending chandelier must be in addition to the force to support it, which is about 1,957 N, for a total of 3,157 N (710 lb.). Not a lot, but what happens if the fly system has a 0.1 second emergency stop specification?

$$a = (0\text{m/s} - (-3\text{m/s}))/0.1\text{s}$$
$$a = (3\text{m/s})/0.1\text{s}$$
$$a = 30\text{m/s}^2$$

$$f = 200\text{kg} \bullet 30\text{m/s}^2$$
$$f = 6000\text{ N}$$

Now, the total force to stop the load would be 7,957 N (≈1,789 lb.-force). If the chandelier is supported by a half-ton hoist (a load rating more than twice our chandelier's weight), it might not stop the load in 0.1 seconds because the brake will slip. In any case, we should be concerned about the strength of the entire load path, since we are now dealing with forces that are more than four times the static load of the chandelier. This is not a problem if the system is designed for it, but it might be a problem if the design analysis only considered the static load and not the deceleration or acceleration forces.

the HTR button to the motion controller and also a timer relay or PLC in the e-stop circuit. In this case, if the HTR is released, the motion controller brings the machine to a controlled stop (category 2), while the timer relay is timed to do a category 0 e-stop at the same time as the end of the controlled stop. The largest advantage to designing the hold-to-run circuit with the emergency circuit is that there is redundancy in the circuit, meaning the operator can ensure releasing the HTR to halt movement even if there was a failure in the motion controller.

There is no cut-and-dry answer for what the e-stop circuit should look like or how it should perform other than it should ensure the machine will stop moving. Having a good understanding of the differences between a category 2 soft stop, category 0 stop, and a category 1 stop is crucial for both the system designer and system operator. The ideal e-stop circuit is designed with risk analysis for the application and redundancy in mind: no single point failure should be able to stop the operator from stopping the machine. ■

Royal Marty is Director of the eZ-Hoist Division at ZFX, Inc. He has designed machinery and control equipment for theaters, permanent installations, as well as art installations. Royal has a BFA in Technical Direction with a minor in Mathematics.