The Increasing Complexity of Appliance Motors
The need for new standards to address new technologies
Historically, motor and motor-compressor protection technologies have used discrete devices, such as a thermal sensing devices embedded in the motor windings or on the motor-compressor enclosure, to directly monitor temperature or current (or both) and to manage motor over temperature. However, decreased component costs, the emergence of electronically commutated motor technology and increased demand for more energy efficient operation have led to greater use of electronic protection schemes. These can monitor additional motor operation parameters and do so in increasingly sophisticated ways.

These electronically protected motors and motor-compressors differ significantly from traditional designs in the manner in which motor overheating is prevented. Adapting to this new norm requires that the safety implications of the technology be fully understood and that end-product appliance safety standards be updated to document their proper evaluation.

Introduction

Appliances employing motors perform functions such as drying hair, opening cans, cleaning carpets and conditioning the home environment. Seeking to minimize the risk of fire, electric shock and injury hazard from overloading of these motors, UL Safety Standards for appliances have requirements for motor protection. Increasingly, low cost yet sophisticated electronics are being used for this purpose, especially where electronically commutated motors are being employed to improve energy efficiency. This paper examines the forms of motor protection employed by appliances, and addresses the direction that UL appliance standards are taking toward the application of requirements for electronic motor protection.
Installation Code
The US National Electric Code (NEC®), NFPA 70, provides for the “practical safeguarding of persons and property from hazards arising from the use of electricity.” One or more Articles of the Code cover appliances equipped with motors. For example:

- Article 430 — Motors and Motor Protection in Motors, Motor Circuits and Controllers
- Article 440 — Air Conditioning and Refrigeration Equipment in Air-conditioning and Refrigerating Equipment
- Article 442 — Other appliances, including those incorporating small motors, such as: portable appliances, waste disposals, central vacuums, and trash compactors, in Appliances

Figure 1 is a simplified version of NEC® Figure 1. It illustrates the various components employed within the motor supply circuit, and the forms of protection accepted by the Code.

This white paper will focus on motor elements D through G in Figure 1 where these are integral to the appliance. The Code requirements for these elements also serve as the basis for motor protection requirements in UL Safety Standards for appliances. UL Standards can and do expand upon, and often exceed, the Code requirements but are not in conflict with them.

Thermal motor protectors (Element G in Figure 1) are a particular form of protection that protect against motor overload and hazardous overheating. They are commonly installed as integral parts of smaller, single-phase motors (1 hp or less), but are not considered a substitute for the branch circuit overcurrent protection (Element A) required by Article 240 of the NEC®.

Overload protection for larger motors is generally provided by remotely located overcurrent devices (such as magnetic motor starters) that may be controlled by heaters or temperature sensing devices embedded within the motor. These protection devices are outside the scope of this white paper.

IEC TC61 is the international standards body responsible for appliances.
UL holds the Secretary (Ms. Sonya Bird) and Assistant Secretary (Ms. Margie Burk) roles.
UL also maintains similar roles on the US Technical Advisory Group (TAG) for the US National Committee (USNC) for IEC TC61.
UL has technical staff participating in leadership and expert roles on several National Committees and maintenance teams associated with TC61, including:

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Appliance Standards

UL appliance safety standards typically have a section devoted to motor protection. But how the requirements are presented may vary significantly due to the diversity of the maintenance cycle of the various standards. In addition, certain portable appliances are not required to have integral motor protection (e.g., canister vacuum cleaners). Therefore, it is always important to refer to the specific end-product standard to determine which motor protection requirements are applicable.

The most common approach to motor protection requirements in appliance standards is to specify whether protection is required, and then to evaluate options on how it may be accomplished. The options include Thermal Protection, Impedance Protection and Other (protection that is shown by test to be equivalent to Thermal Protection). Historically, other protection included devices that provide overcurrent protection or some combination of thermally sensitive devices (e.g., temperature limit control) and appliance design.

The appliance standard does not typically specify all the construction and performance requirements for the protective device. Instead, it is the component standard that determines its use in combination with the motor. The appliance standard, in turn, specifies end-product performance tests (normal and abnormal) to determine if the motor protection is suitable for the application when used in combination with the appliance.

This approach, separating the requirements into the end-product and component standards, has worked well over the years where the motor protection was provided by discrete components that were operationally independent of other control functions. However, electronic motor protection is now often integrated into other control functions of an appliance and the application of motor protection requirements is a more complex and challenging task. (See Figure 2 for examples of motor, control and protection scenarios).

Component Motor Protection Approaches

UL component motor standards are intended to provide a consistent roadmap for the evaluation of motor design variations in their ability to provide the over temperature protection when used in end-product applications. This methodology is intended to ensure that the motor will provide service that is reasonably free from the risk of fire, electric shock or injury. This over temperature protection generally relies upon the ability of the motor itself, or some external or integral means, to limit motor winding temperatures to a level consistent with the limits of the insulating system materials, thereby allowing the motor to function effectively without premature degradation.

Maximum motor winding operating temperatures are set by motor industry conventions and are documented in NEMA MG 1, the Standard for Motors and Generators. These limits correlate with defined Classes of motors as follows:

- Class A — 105°C
- Class E — 120°C
- Class B — 130°C
- Class F — 155°C
- Class H — 180°C
- Class N — 200°C
- Class R — 220°C

Provisions are made for setting higher temperature limits for short excursions (periods of time) that do not lead to premature degradation of insulating materials. These limits are documented in Table 41A.1 (Locked Rotor) and 41C.1 (Running Heating) of UL 1004-3 — Standard for Thermally Protected Motors.

Motor Protection Category Control Numbers (CCNs)

UL’s motor protection certifications are based on the specific protection method employed, and are categorized as follows:

XEIT2 — Impedance-Protected Motors are motors in which thermal protection is provided by the inherent impedance of the motor winding to limit winding current to a level where the l2R heating will, in turn, limit motor winding excursion temperatures to an acceptable level (below the Class limit).

XEWR2 — Thermal-Device-Protected Motors are motors provided with a thermal motor protector (TMP), a physical device responsive to current and temperature that acts to limit winding excursion temperatures by opening the motor power supply lead(s) when the set point is exceeded.
**XDNW2** — Electronically-Protected Motors are motors protected by an electronic circuit. There are various protection schemes used by manufacturers, but a few “standard” algorithms have emerged. These schemes may be augmented by one or more TMPs embedded in the motor windings to back up the electronic circuit.

**XGFW2** — Motor Thermal Protection Systems are defined as the combination of a thermal motor protector and a relay or contactor. This construction is employed when the size (current) of the motor precludes the use of a TMP to interrupt the motor source directly.

**XDAM2** — Dual-Scheme Thermally Protected Motors are motors provided with two, separate and independent motor protection methods (i.e. TMP with impedance protection, TMP with electronic protection, etc.). The basic concept of this CCN is that both protection methods are independently and separately evaluated as effective.

**XFJZ2** — Over Temperature-Protected Fan Motors, was formerly used to cover a specific type of fan motors, but is now largely obsolete.

The CCN of the motor protection depends upon which thermal protection method is relied upon. Thus, if an electronic circuit is relied upon, the motor CCN is XDNW2. Likewise, if the TMP is relied upon, the motor CCN is XEWR2. Figure 3 provides a complete overview of the motor and motor protector CCNs, standards and their interrelation.
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Appliance Scenario A

**Induction Motor**
- Electronic speed control
- Electromechanical thermal protector on windings or integral impedance protection

Appliance Scenario B

**Induction motor**
- Electronic speed control
- Electronic thermal protector on motor (Temperature sensor on motor driving a relay or contactor)

Appliance Scenario C

**Induction motor**
- Electronic speed control with integral motor protection provided via motor temperature, current, and/or motion sensing technology.
- No supplemental thermal protection on motor

Appliance Scenario D

**Induction motor**
- Electronic variable speed drive
- NEC® Article 430 overcurrent protection (e.g., overload relays, overload heaters)

Appliance Scenario E

**Hermetic motor compressor**
- Electronic control providing on/off
- Electromechanical or electronic thermal protector mounted on compressor

Appliance Scenario F

**“Inverter-type” hermetic motor compressor**
- Protective Electronic control with programmable chip
- No supplementary thermal protection or NEC Article 440 overcurrent protection

Figure 2: Appliance motor / control protector scenarios (not a complete list)
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Figure 3: Motor and Motor Protection Interrelations
Motor Protector Performance

Motors are subject to mechanical loads which, when excessive, may cause overheating. Motor thermal protection must demonstrate that temperature limits of the insulation system will not be exceeded under load (i.e., without the protector acting and under locked conditions). The test load is primarily dictated by the intended end use of the motor.

Locked Rotor — It is always assumed that the motor may become locked due either to internal wear or damage or external interference. When the shaft of a motor locks, the reactance of the motor goes to zero, the motor winding becomes purely resistive, and all of the energy being delivered is converted to I^2R heat. UL motor standards dictate that a motor shall withstand this test condition for 18 days without temperature limits being exceeded and without exhibiting signs of an increased risk of fire or electric shock.

Running Heating — This test simulates a motor loaded such that maximum heating occurs without causing the protector to deenergize the motor. The motor is subject to an incrementally increased load, allowing temperature stabilization at each step. Load increases are continued until the motor protector de-energizes the motor (trips). The criteria for acceptance are similar to that for a Locked Rotor, but the maximum allowable temperatures are lower, since this condition may go undetected.

Hermetic Refrigerant Motor-Compressors

Hermetic refrigerant motor-compressors are covered under Motor-Compressors, Hermetic Refrigerant (SLIS2). While similar to other motors, hermetic refrigerant motor-compressors (M-Cs) are a unique subset of component motors, used within vapor-compression refrigeration systems. The M-C is hermetically sealed, and the thermodynamic conditions under which the refrigeration system operates determine the temperature of the motor insulation system. For this reason, Locked Rotor is the only condition of operation that can be investigated independently of the refrigeration system.

Thermal Device Protection — Typically, smaller-sized M-Cs have automatic reset TMPs. These devices provide automatic reset action (see Motor protector action), but are typically located externally and mounted against the M-C enclosure. This location difference is due to an enclosure temperature limit of 150°C (302°F) under Locked Rotor conditions instead of winding temperatures. When internal protectors are employed, their intended purpose is to limit motor enclosure temperatures to 150°C (302°F) or less.

Overcurrent Protection — Larger M-Cs utilize overcurrent protection based on the M-C rated-load current (RLA). Overcurrent protection is generally required in each phase of a 3-phase circuit, and is required to open the electrical circuit supplying the motor-compressor at any value that exceeds 140% of the M-C RLA (430.32 of NEC®). M-C RLA is not typically determined as part of a M-C investigation. As a result, overcurrent protection values are set as part of the end-product evaluation when actual M-C end-use RLA is established.

Overcurrent protection of this type is typically provided by Listed UL 508 Auxiliary Devices (NKCR) as part of the end-use equipment.

Motor Protector Action

Motor thermal protection is provided by one of the following actions. Action is a term used to describe how a control (or protection) function automatically responds to manual or automatic actuation (e.g., user adjustment, bimetal movement). Though TMPs are available in each of these actions, other protection schemes, such as electronic protection, can use one or more of these actions.

Inherent Protection — The impedance-protected motor best illustrates this action. The design requires no action or change of state; the motor simply does not overheat.

Automatic Reset — In this action, the windings approach the temperature limit of a motor insulation system class, and protection (such as a TMP) opens and deenergizes the motor. The motor cools to a point, enabling the protector or protection scheme to reset itself, and the motor again begins to increase in temperature. This cycle can repeat indefinitely. However, in some cases, the cycle will repeat a prescribed number of times, after which the motor will be “permanently” deenergized. In general, UL requires a motor to withstand continuous cycling for not less than 18 days.

Manual Reset — In this action, the motor reaches a temperature limit appropriate for the insulation system class, and the protection deenergizes the motor circuit.
Manual intervention is required for reset. UL requires that the motor and manual reset protection withstand 60 cycles of opening and reset.

**Thermal Cutoff (Thermal link)** — This is an action in which the motor exceeds the temperature limit of the insulation system Class, or a lesser value chosen by the manufacturer. The protection permanently de-energizes the motor under over-temperature conditions. Replacement of the motor or a part of the equipment is required to restore functionality.

**Single-operation Devices (SODs)** — This action prevents the motor from restarting unless power is removed and the motor and the motor protector have cooled to -35°C or lower. This minimum temperature assumes that environmental conditions will not automatically reset the device.

**Voltage-maintained Protectors (Self-holding Protectors)** — These devices combine a PTC thermistor, resistor or other similar device and an automatic-reset protector. When the protector opens, power is directed through the PTC or similar device, which acts as a heater to keep the protector open. Resetting requires removing voltage and allowing the protector to cool and reset naturally.

**Duty-cycle Shifting** — Electronic motor protection circuits often change the duty-cycle or pulse width of the power supply to the motor to allow subtle, automatically activated, on-demand cooling.

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**Electronic Motor Protection**

In the past, motor protection technologies used discrete devices (such as a thermal sensing device embedded in the motor windings) to directly monitor temperature or current, and to manage motor over temperature. However, decreased component costs and increased demands for energy efficiency have led to greater use of electronic protection schemes that can monitor additional motor operation parameters. A sampling of the most common electronic protection schemes is briefly described below.

**Current sensing** — Virtually all circuits employ some sort of current sensing, programmed either by firmware or hardware to respond when motor current exceeds some upper normal limit.

**Motion sensing** — Motor circuits typically employ motion (rotation) sensing, either Hall effect sensors or resolvers, or tachometers coupled to the rotating member, to sense when rotation has stopped or slowed to some unacceptable level.

**Direct Temperature Measurement** — Circuits which have some temperature responsive device (i.e., thermocouple, RTD, PTC, thermistor, etc) embedded in the motor, which “reports back” to the circuit.

**Back Electromotive Force (EMF) Sensing** — Sensing of back EMF provides the circuit (or software) with a sense of motor loading.
Calculated Temperature Measurement —
Circuits exist which take change of resistance measurements of the motor windings during a brief off period (such as in a washing machine) to measure the hot resistance and then calculate the motor temperature using the stored cold resistance value.

Note that most motors employing electronic protection often rely on several schemes in parallel. Further, these schemes are not protection per se but sensing schemes which need to be coupled to a protection circuit and, sometimes, software to provide motor protection.

From a protection standpoint, an electronic control may perform many functions, but UL only evaluates and tests that part of the control relied upon for compliance with the end-use product requirements. Identification of that part is best made in collaboration with the motor or control manufacturer/designer.

Manufacturers frequently provide a sophisticated motor protection circuit and software along with a TMP. In practice, the TMP may never operate, but the use of such a device may enable the electronic control to be considered as optional from a safety perspective. In this case, the circuit becomes operating instead of protective, and UL only evaluates whether the circuit itself poses a risk of fire or electric shock.

Electronically Commutated Motors
An electronically-commutated motor (ECM) incorporates a control circuit that is required for the operation of the motor. The circuit commonly converts a single phase AC signal into a pulsed signal to drive a brushless DC motor (BLDC) or brushless AC motor (BLAC).

There are essentially two types of ECMs — sensor and sensorless. The sensor-type design relies on current sensors, positional sensors (Hall effect), temperature sensors (thermistors) or other sensors for their required input. The sensorless design relies on the back EMF (BEMF), space vector control (system of coordinates) or other means generated by the motor. The input signals are compared to the desired values (specified by the rating, etc.), and the output (speed) is adjusted accordingly.

One can dissect this design into the aforementioned three elements, as noted below:

- **Input** — sensors (hall, NTC, shunt resistors)
- **Logic Solver** — microcontroller
- **Output** — power triac or insulated-gate-bipolar-transistors (IGBTs)

The vast majority of small BLDC motors are simple basic circuits with input and logic hardwired into the design.

Some motor control circuits consist of an input stage that converts line AC (60 Hz) into a DC rectified signal. The DC rectified signal is then converted by the microcontroller into a variable-duty-cycle switch signal (PWM) to drive the motor (see Figure 4). Based on the motor feedback signals received, a microprocessor (via complex software algorithm and routines) typically generates a dynamic signal that controls the gate of three pairs of solid-state transistors, in a precise, sequential manner. The on-off timing sets the pulse width of the PWM signal and the frequency of operation, which translates into speed and/or torque for the motor.
Depending on the input, the motor speed can be varied by changing the characteristic parameters of the PWM signal. For very simple BLDC motors, this precise sequential timing of pulses to the motor coils is designed into the hardware, and no real “logic” is used.

For complex ECMs, the performance and the safety attributes of the motor are dependent on the efficacy of the software algorithms and the state machine logic design implemented in the microprocessor. For example, if the motor is locked or in an overload condition, the sensor may send a signal back to the microprocessor indicating an abnormal condition. The processor would then de-energize the power drivers and switch off power to the motor. However, if there is a fault in any of these components in the critical thread (including software), the motor could be energized continuously, creating a potential fire or electric shock hazard. Therefore, the reliability of the safety critical circuits responsible for each protective function must be considered, including discrete and solid-state components with or without programmable components.

Reliability of Electronic Protection

In addition to confirming that the electronic motor protection performs under locked rotor and running heating (if necessary), the reliability of the protection must be investigated. Failure modes and effects analysis (FMEA) for that circuit is conducted to determine if there are single points of failure that could compromise the protective function. Those that are identified can be mitigated by employing diverse redundancy or by evaluating the component for its reliability.

Depending upon the end-product application, programmable components are also investigated for their hardware and software reliability. UL 1998 (Standard for Software in Programmable Components) and UL 60730-1A, Clause H.11.12 (Standard for Automatic Electrical Controls for Household and Similar Use, Part 1: General Requirements) have requirements that address faults due to software code errors and EMI effects, power line perturbation, etc. on microelectronics.

UL 60730-1A provides requirements for both hardware and software reliability, as does UL 1998 when used in conjunction with UL 991 (Standard for Tests for Safety-Related Controls Employing Solid-State Devices).

Applying Electronic Motor Protection Requirements

The starting point for determining what motor protection requirements are applicable to a motor within an appliance is its function and intended use. An end-product standard may already take into account relevant assumptions. If not, the standard requirements will typically distinguish between intermittent vs. continuous use, fixed fan vs. other loads, manual vs. automatic starting, attended vs. unattended use, and possible other criteria.

Once the function and use are established, the need for motor protection is determined by the appliance standard. The specific form of protection, if required, is not prescribed; instead, the manufacturer chooses the form of protection that is most appropriate for the application. Depending upon that choice, the end-product standard specifies the applicable requirements.

Individual UL appliance standards are evolving toward the UL 1004 series of motor/motor protection standards. However, there remain a number of standards that refer to legacy motor protection requirements (e.g., UL 519, UL 547 or UL 2111). These legacy requirements are generally applicable where the standard specifies. Where the referenced standard has been withdrawn or superseded, the requirements contained in the superseding standard apply, except in the case of electronic motor protection (an issue not anticipated or addressed in earlier standards).

Once the appliance motor function and use has been established, the electronic motor protection requirements from a series of standards (Figure 5) are applied to the motor/protection combination. The basic construction requirements are specified in UL 1004-1. If the electronic motor protection employs a form of thermal protection, the relevant performance requirements of UL...
1004-3 (Thermally Protected Motors) are applicable. UL 1004-7 (Electronically Protected Motors) specifically describes how the requirements of UL 1004-1 and UL 1004-3 are to be applied, as well as UL 60730-1A in connection with the electronics.

**Control Correlation Tables**

UL 60730-1A does not anticipate a specific end-product application. Instead, UL 60730-1A is a horizontal standard written to provide requirements for the broadest possible cross-section of controls. Due to this horizontal nature, the component and end-product standards that make reference to UL 60730-1A must establish the level of safety functionality that is required, the portions of UL 60730-1A apply and the sections that are not applicable.

All of the requirements contained in UL 60730-1A are dictated by the contents of its Table 7.2. This Table is intended to define the features and operating characteristics of a control by way of either declaration or other informative methods. These entries determine the test and evaluation program specified in the remainder of the document. The motor control correlation table defines the required safety functionality by reference to the Table 7.2 entries.

The control correlation table examples (see Tables 1 and 2) illustrate two unique methods of communicating this information.
UL 60730-1A Table 7.2DV item number | Information | Motor Control Requirement
---|---|---
6 | Purpose of control | Protective control (temperature)
7 | Type of load controlled | AC motor load
29 | Type of disconnection or interruption | Any defined
39 | Type 1 or Type 2 action | Type 2
40 | Additional features | Must be declared as automatic or manual reset
49 | Pollution degree | Pollution degree to be determined by reference to UL 1004-1, Table 18.5.
52 | The minimum parameters of any heat dissipater (heat sink) not provided with an electronic control but essential to its correct operation | Must be specified
53 | Output waveform if other than sinusoidal | Must be specified
58 | Required protection/immunity from mains borne perturbations, magnetic and electromagnetic disturbances | Required
60 | Surge immunity | IEC 61000-4-5 installation Class 3. Overvoltage category to be determined by reference to UL 1004-1, Table 18.6.
69 | Software Class | Software Class B
74 | External load and emission control measures to be used for test purposes | Intended motor

Table 1: UL 1004-7 Control Correlation Table

Application of UL 991 and UL 1998

Conduct a failure-mode and effect analysis (FMEA) for the protective circuits and functions providing required motor protection.

A control becoming permanently inoperative and disconnecting power meets the criteria for mitigating the risk.

Assumed temperature ranges are as follows:
- **Indoor Use**: 0.0 ± 2°C (32.0 ± 3.6°F) and 40.0 ± 2°C (104 ± 3.6°F)
- **Outdoor Use**: -35.0 ± 2°C (-331.0 ± 3.6°F) and 40.0 ± 2°C (104 ± 3.6°F)

Cycling test duration shall be 14 days. Endurance test duration shall be 100,000 cycles.

Radio-frequency electromagnetic field immunity:
- **Immunity to conducted disturbances** — When applicable test level 3 shall be used
- **Immunity to radiated electromagnetic fields** — field strength of 3 V/m shall be used

For exposure to humidity, the following conditions shall apply:
- **Indoor Use**: 21.1 — 26.7°C (70 — 80°F) and minimum 50 %t relative humidity
- **Outdoor Use**: minimum 98 percent relative humidity

Electrical fast transient/burst immunity such that a test level 3 shall be used for all equipment other than outdoor use equipment.

Test level 4 shall be used for outdoor use equipment.

- **Surge immunity test** — Test with installation Class 3 used for other than outdoor use protective devices. Class 4 shall be used for protective devices intended for outdoor use.

- **Electrostatic Discharge Test** with a Severity Level of 3 having Contact Discharge at 6 kV to accessible metal parts and air discharge at 8 kV to accessible parts of insulating material.

Table 2: HVAC Control Correlation Table (Currently proposed in UL HVAC standards)

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a For the purpose of the tests specified in Annex H, Section 26 of UL 60730-1A, the products covered by this Standard should be considered as:
- Installation Class 3 (see Annex R, UL 60730-1A),
- Overvoltage Category III for controls intended to be permanently wired,
- Overvoltage Category II for controls intended to be cord connected.
Application of UL 60730-1A

Based on the requirements of the end-product appliance standards and the motor/motor protection standards, UL 60730-1A is applied to determine the reliability of the electronic motor protection. The particulars will depend on the design of the control circuit. However, there are a number of considerations in common to all motor protection designs.

Open-Loop Controls — A type of protective control system design that does not have a feedback loop to determine if its input has achieved the desired goal/setting. A true open-loop system does not engage in any “learning” and cannot adjust the output to compensate for disturbances in the system. Simple BLDC motors often use open-loop controls.

Closed-Loop Controls — A type of protective control system design in which a feedback loop compares the desired response to the measured response, and initiates actions to bring the actual system response in line with the desired response. Closed-loop controls can use many forms of sensing.

The investigation begins with understanding the application and theory of operation of the control as it relates to the end-product. A review of relevant schematics, block diagrams and instruction manuals is needed to understand the product’s functionality and capabilities.

All required protective functions of the control are identified as dictated by the end-product standard. For example, over temperature protection is considered a protective function and the conditions that result in over temperature may be locked rotor, running overload, loss of phase, no load, etc. It is important to understand the difference between a cause and an effect. Loss of phase, etc. is a cause, while over temperature is an effect. The required safety functionality is that the motor shall not overheat. It is not required that a control detect loss of phase but, when loss of phase occurs, the motor should not overheat.

At the macro level, noncompliance as a result of loss of protective functionality is evaluated. The motor protection must provide the protective functionality safely, reliably and consistently through all normal and reasonably anticipated abnormal events. Fault conditions may include individual component open, short, drift of the activating quantity or abnormal operation of the control. The control engineer then considers mitigating methods.

At the micro level, the schematic and the risk analysis (when required) are reviewed. The safety critical threads for electronic motor protection are established for each safety function within the control’s design, starting from the sensor to the logic solver and then to the actuator (output). Each component of the safety critical thread is examined for reliability.

Electronic circuit designs commonly involve multiple safety circuits, and often, operating circuits on a single circuit board. The end-product standard should be consulted to determine the relevant protective functions and required level of assessment.

If a circuit board has more than one motor protective function, it is necessary to collaborate with the manufacturer to determine which circuit to rely on for compliance. This is increasingly becoming more challenging as identifying and isolating individual circuits on a single circuit board may not be easy. Manufacturers also may choose to declare all circuits are safety circuits and to evaluate beyond what the specific end-product requires. This approach is most common for circuit boards that are intended for multiple applications where a specific end-product use is not declared.

In some cases, controls use software or firmware to enable the circuit to perform safety-related functions. Consequently, UL 1998 and UL 60730-1A, clause H.11.12 address systematic software defects and microelectronic faults (which UL 991 does not cover), and provides requirements for the fail-safe execution of safety-related functions. In practice, the software elements are considered in the same way as hardware components from a reliability-engineering standpoint.

Hazard Mitigation/Fault Avoidance

When employing protective electronics, manufacturers often use alternate fault avoidance measures or mitigation schemes to address the hazards anticipated by the end-product standard. Options do exist and some fault avoidance measures do reduce the extent of the evaluation required. Common mitigation methods and fault avoidance techniques include the use of diverse, independent, and redundant circuits, the addition of supplemental, discrete,
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protective devices and the use of a power supply that reduces the risk of fire or electric shock.

**Diverse and Independent Redundant Components** — Figures 6 and 7 illustrate the meaning of “diverse and redundant.” In Figure 6, the sensor, NTC, is a critical component which could fail and lead to the loss of protective functionality if it doesn’t have reliable software to detect sensor failure. In Figure 7, the same circuit has been modified to incorporate an additional independent sensor, so that a malfunction of one of the two sensors will not result in the loss of protective functionality. Since the microprocessor software is not essential for protective functions, the extent of the evaluation may be reduced.

Other forms of hazard mitigation include:

**Supplemental Discrete Protective Devices** — Motor manufacturers routinely use this method by providing a TMP in a motor that has electronic protection. If the TMP can be relied upon to provide the required safety functionality, the protective control becomes an operating control, to be evaluated only as the possible point of origin of a fire or electric shock hazard. This mitigation approach can be evaluated more quickly and inexpensively than evaluating the reliability of a protective circuit.

**Supplemental Inherent Winding Protection** — An extremely limited number of motors are designed such that their windings can withstand the maximum available locked rotor current from the supply. These motors are tested with the electronic protection function defeated and the protection is similar in concept to impedance protection. While a seemingly simple approach, the circuitry configuration required to do this test, can be time consuming and complex.

**Class 2 Supply** — As stated in Article 725.2 of the NEC®, employing a Class 2 supply mitigates the risk of electric shock, but the risk of fire requires further consideration. (Article 725.2 does not address risk of injury.)

**Limited Available Power** — In many applications involving small motors the supply source is power limited. If the available power to the motor is reliably limited to levels below that which would constitute a risk of fire, then fire risks can be considered appropriately mitigated.

**Non-combustible Enclosure** — Motors and end-products may be provided with a metal or other non-combustible enclosure so that, if overheating were to occur, the enclosure would prevent the spread of fire. (However, the risk of electric shock must still be considered).

**UL 508C vs. UL 60730-1A**

UL 508C, Power Conversion Equipment, is intended for industrial applications and is not necessarily applicable to residential or commercial end-product applications. However, UL 508C has been used for electronic motor controls in some appliances, and is still in effect for these uses until the end-product standards are updated with the requirements cited throughout this white paper.

An investigation under UL 508C differs from an investigation under UL 60730-1A in that the motor control is evaluated for inherent electrical safety related to the risk of electric shock and fire. The safety functionality required to respond to abnormal conditions of the product is verified through an operation test, but its ability to perform this function in a reliable and consistent manner is not determined.

However, a motor control investigation combining UL 508C, UL 991 and UL 1998 may be deemed equivalent to an investigation conducted under UL 60730-1A.
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Appliance Standards Revisions to Accommodate Electronic Motor Protection

The critical factor in the consistent application of requirements across products evaluated to a given end-product standard is the inclusion of appropriate motor and electronic control references within the text of the applicable standard.

Appliance standards today address motors and electronic controls in the following ways:

- Direct reference to UL 60730-1A and/or UL 991/UL 1998 within end-product standard, addressing hardware and software reliability
- Direct reference to UL 60730-1A and/or UL 991 within the end-product standard, addressing hardware reliability only
- Direct reference to UL 508C or other inherent safety based control standard
- Direct reference to UL 1004-1 and all applicable UL 1004-x companion standards
- Direct reference to UL 1004-1
- Direct reference to other component standards (e.g. UL 2111 or UL 873) or control requirements embedded within the end-product standard

It is UL’s position that all appliance standards should be revised to consistently cite the UL 1004-x standards and apply UL 60730-1A to determine the reliability of the electronics. This will take time, as the individual appliance standards are maintained by separate Standards Technical Panels and any changes to the Standards must be a result of a consensus process. In the meantime, the present requirements applicable to the specific appliance remain in effect. UL recommends that principal engineers, responsible for interpreting and consistently applying the requirements of the Standards be consulted in any case of ambiguity.

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1 Overload is an operating overcurrent that can result in hazardous overheating if allowed to continue for a sufficient length of time. In addition, motor over temperature can be the result of external heating which has the same potential to cause premature degradation of the electrical and mechanical properties of motor insulating system components.

2 While there are other Classes of motors, these are the most common.

3 This is different from end-product stalled rotor and similar abnormal tests. These seek to address the effect of the abnormal condition on the appliance or on the motor within an appliance.

4 Reference is made throughout this paper to UL 60730-1A. This is the UL standard based on IEC 60730-1 ed. 3.2 and is currently in effect. A new edition of IEC 60730-1 has been published (ed. 4.0). The UL standard based on this new edition is identified as UL 60730-1. There will be a transition over time from ed. 3.2 to ed. 4.0 (UL 60730-1A to UL 60730-1).

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Appendix

IEC 60335-1 and Electronic Motor Protection

IEC 60335-1 (Household and Similar Electrical Appliances — Safety — Part 1: General Requirements) is the relevant IEC standard for all appliances. It is self-contained with respect to motors; all the applicable requirements for motors are included and it is not necessary to reference an IEC component motor standard. It also specifies the requirements for motor protection, which, for electronic motor protection, is considered to be a protective electronic control (PEC) unless Clause 19 can be fulfilled without the protector. This Appendix is intended to illustrate, for comparison purposes, the IEC 60335-1 approach to electronic motor protection.

Using the simple case of a fan motor, the IEC 60335-1 requirements are as follows:

Thermal motor protector in an electric fan is:
- a “self-resetting thermal cutout” (3.7.4)
- tested in combination with its motor per Annex D conditions (24.1.4)
- tested for locked rotor/part conditions (19.7)
- required to “cut out” before motor winding temperatures exceed Table 8 values under both 19.7 and Annex D conditions
- not to permit the conditions described by 19.13

If the thermal motor protector is an electronic device it is:
- tested for fault conditions of 19.11.2 (19.11)

If the thermal motor protector relies on a microprocessor to function correctly it is:
- tested per 19.11.4

The thermal motor protector is:
- tested for fault conditions while rotor/part locked (19.11.3)
- tested for a 19.11.2 fault condition with locked rotor/part condition. (19.11.3)
- tested for immunity (19.11.4)
- investigated for software reliability (22.46)

Although IEC 60730-1 is referenced in Clause 24, a thermal motor protector could comply with IEC 60335-1 only, with no investigation using IEC 60730 except for where Annex R (software) specifically refers to that standard. If a thermal motor protector complies with IEC 60730-1, the construction must still comply with IEC 60335-1 except that internal clearances and creepage distances may comply with IEC 60730-1 (Note 3 of 24.1).