Electric Motors

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Abstract

This article shows the main functioning of electric motors and standardisation of the motors. This overview is made while studying electrical drives and should be seen as notes taken during this study.

Electric motors are used in many industrial and offshore applications. This article should be seen as part of multiple articles explaining electric drives to mechanical engineers. The first step was to link mechanical and electric systems [2] and to explain the basic principles and basic formulas. Others describe frequency drives [1] and the application of magnetics in drives [3].

This article is mainly aimed at the electric drives themselves, meaning the classification, standardisation and some special types of motors. It is mainly aimed at the practical application of electrical drives.

1 IEC Duty Cycle

The International Electrotechnical Commission (IEC) has defined ten different duty cycles in standard IEC 60034-1. The duty cycles define the load cycle to which the motor is subjected. This includes starting, electric braking, no load and de-energized periods of time. Below all ten cycles will be explained. See also Figure 1 for a representation of each duty cycle.

1.1 Duty cycle S1: Continuous operation

The first duty cycle S1 is defined as the maximum constant load / torque that allowed even when the motor equilibrium temperature is reached. That means that the S1 duty cycle can be done without time constraint, as the motor may heat up to the equilibrium temperature.

The abbreviation used is S1.

1.2 Duty cycle S2: Short time cycle

The motor works at constant load, not long enough to reach equilibrium temperature. After the short time cycle, the motor can cool down to ambient temperature.

The abbreviation is S2 with the duration of the duty (e.g. S2 45min).

1.3 Duty cycle S3: Intermittent periodic duty

Sequential and identical run and rest cycles with constant load. Motor temperature equilibrium is not reached. Starting current should have little effect on temperature of motor.

The abbreviation is the duty cycle S3 followed by the duty cycle factor, i.e. the percentage of the time it is allowed to run. Example is S2 25%, which means it may run at 25% of the time.

1.4 Duty cycle S4: Intermittent periodic cycle with starting

Similar as an S3 duty cycle, but here the starting is a significant effect on the motor temperature.

The abbreviation is the duty cycle S4 followed by the duty cycle factor, the inertia of the motor and the inertia of the load (in case of a gear box, load inertia as seen on the motor shaft), e.g. S4 25% $I_m = 0.15kg\,m^2$ $I_{load} = 0.7kg\,m^2$.

1.5 Duty cycle S5: Intermittent periodic duty with regenerative braking

Duty cycle S5 has sequential and identical cycles of starting, running at constant load and regenerative (also called electric) braking.

The abbreviation is the duty cycle S5 followed by the duty cycle factor, the inertia of the motor and the inertia of the load (in case of a gear box, load inertia as seen on the motor shaft), e.g. S5 25% $I_m = 0.2kg\,m^2$ $I_{load} = 0.8kg\,m^2$.

1.6 Duty cycle S6: Continuous operation with periodic duty

Sequential and identical periods of load and no load, while the motor is continuously running (so not rest periods).

The abbreviation is the duty cycle S6 followed by the duty cycle factor, i.e. the percentage of the time it is allowed to run. Example is S6 25%, which means it may have the load 25% of the time.

1.7 Duty cycle S7: Continuous operation, periodic duty with electric braking

Sequential and identical duty cycle of continuous running, including regenerative braking, accelerating and working at constant load.

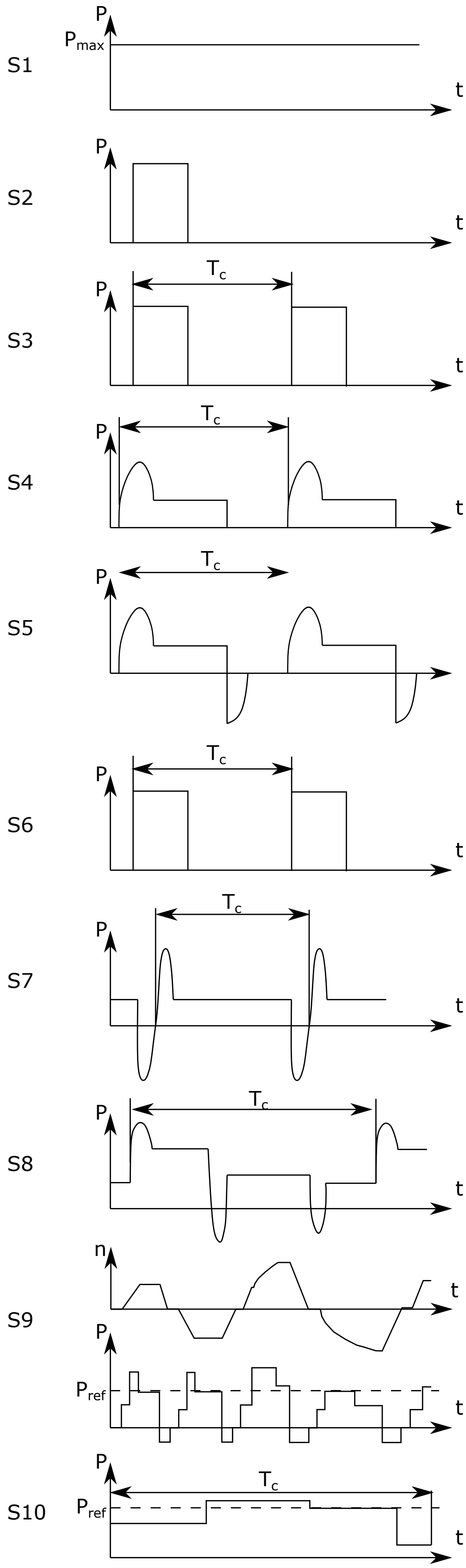

Figure 1: Examples of the ten IEC duty cycles

The abbreviation is the duty cycle S7 followed by the inertia of the motor and the inertia of the load (in case of a gear box, load inertia as seen on the motor shaft), e.g. S5 $I_m = 0.4kg\,m^2$ $I_{load} = 7.5kg\,m^2$.

1.8 Duty cycle S8: Continuous-operation periodic duty with related load / speed

Sequential and identical duty cycles run at constant load at given speed, where the load and speed vary between duty cycles. There are no rest periods.

The abbreviation is the duty cycle S8 followed by the moment of inertia of the motor and the inertia of the load (in case of a gear box, load inertia as seen on the motor shaft), together with the load, speed and cyclic duration factor for each speed condition. For example S8 $I_m = 0.4kg\,m^2$ $I_{load} = 7.5kg\,m^2$ 16kW 750rpm 30% 40kW 1500rpm 30% 25kW 1000rpm 40%.

1.9 Duty cycle S9: Non-periodic load and speed variations

Load and speed variates within operating limits of the motor. Overloading may occur for short time periods, motor equilibrium never to be reached.

The abbreviation is S9.

1.10 Duty cycle S10: Discrete constant loads and speed

Duty with discrete number of load and speed combinations, with these maintained long enough to reach motor thermal equilibrium. For this duty type a constant load appropriately selected and based on duty type S1 shall be taken as the reference value 'Pref' for the discrete loads. The maximum overload factor shall not exceed 1.15 times the reference load on S1.

The abbreviation is the duty cycle S10 followed by the unit quantities p/Δt for the respective load (so factor of reference load) and its duration (all durations together shall be equal to 1) and the per unit quantity TL for the relative Thermal Life (TL) expectancy of the insulation system. The reference value for the thermal life expectancy is the thermal life expectancy at rating for continuous running duty and permissible limits of temperature rise based on duty type S1. For a time de-energized and at rest, the load shall be indicated by the letter r. The value of TL should be rounded off to the nearest multiple of 0.05. For instance: S10 p/Δt = 1.1/0.4; 1/0.3; 0.9/0.2; r/0.1 TL = 0.6.

2 IEC Insulation classes of motors

Premature failing of motors occurs often due to too high temperatures of the motor coils. As a rule of thumb, every 10^oC increase above the allowable temperature means a possible lifetime reduction to 1/2. Note that the standard lifetime is approximately 20.000 to 25.000 hours, unless otherwise specified by the manufacturer.

Table 1: The four insulation classes with the operational ranges

Class	Max ambient temperature ^oC	Maximum temperature rise ^oC	Hot-spot over-temperature ^oC	maximum winding temperature ^oC
A	40	60	5	105
E	40	75	5	120
B	40	80	10	130
F	40	105	10	155
H	40	125	15	180

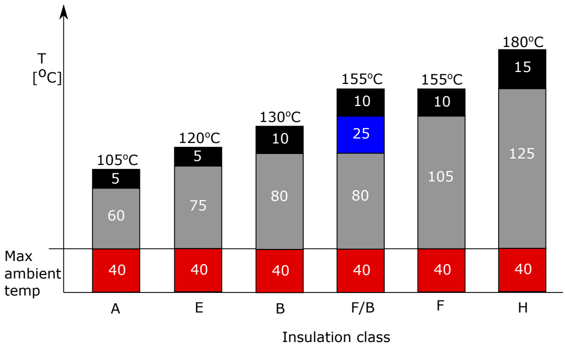

Figure 2: The five IEC insulation classes

The main contributor to heating are the copper losses in the motor windings. These copper losses are:

$$P_{copper} \propto I^2 \, R \tag{1}$$

$$E_{copper} \propto I^2 \, R \, t \tag{2}$$

This shows the quadratic relationship between the current and the dissipated energy, which results in heating of the motor.

To standardise the allowable temperatures in the motors, the insulation classes are defined. In principle there are five classes: A, E, B, F and H, of which B and F are the most common. The NEMA standard, used often in North America, does not recognize the E class, so the NEMA has only four insulation classes (which are identical to the IEC classes). Each class defines the starting temperature, allowable temperature rise, allowable extra hot-spot temperature and thus the maximum winding temperature, as shown in Table 1. These are also shown in Figure 2.

Figure 2 shows one additional class: F/B. This is a class B motor, with a safety margin of 25^oC. This means that this motor is able to withstand a higher temperature, thus it is more robust and reliable and will have a longer life expectancy when used as a insulation class B motor.

It is common for motors to have (redundant?) temperature sensors installed. The temperature sensor is then often used to give an alarm 10^oC below the maximum allowable temperature and trip the motor at the maximum allowable temperature.

When a motor is often at low speed or standstill while it needs to deliver torque, the cooling fan of the motor is no longer mounted on the motor axis, but has a separate smaller motor. This forced cooling makes sure that even at low speeds to motor does not overheat.

3 Ingress Protection class

Motors are available in several Ingress Protection (IP) classes that protect against dirt and water ingress. This is defined in EN 60529 and IEC 60529. The class is defined by the letters 'IP' followed by two numbers. The first number shows the protection against dust ingress, the second against water ingress. In general the higher the numbers, the higher the protection level, although this is not completely true for the highest levels of water ingress, as those are more specific to specific situations. A full explanation of the numbers is shown in Appendix A.

Some manufacturers also show IPX classes, where one of the digits is replaced by an X (e.g. IPX4 or IP5X). This denotation of the X means that the rating for either dust or water is missing. If the manufacturer does not further explain, the 0-rating should be assumed to be safe. It does mean that the datasheet should give more detailed information about the ingress protection.

In the past the IP rating could have a third number, denoting the mechanical impact it could withstand. This is changed in 2002 and moved to the EN 62262:2002 norm, which means that this third number is removed. In the past it meant an impact energy (In Joule) of:

- 0: no protection;
- 1: 0.225 J;
- 2: 0.375 J;
- 3: 0.5 J;
- 5: 2 J;
- 7: 6 J;
- 9: 10 J.

Sometimes additional letters are shown. Some mean extra protection to personnel:

- A: Back of hand;
- B: Finger;
- C: Tool;
- D: Wire.

Table 2: The comparison of NEMA with IP-classes

NEMA	**IP class**
1	IP20
2	IP22
3, 3X, 3S, 3SX	IP55
3R, 3RX	IP24
4, 4x	IP66, IP65
5	IP53
6	IP67
6P	IP68
12, 12K, 13	IP54

Other additional letters show the protection against:

- H: High voltage apparatus;
- M: Motion during water test;
- S: Stationary during water test;
- W: Weather conditions.

In North America the NEMA standard is often used. As a comparison, these are shown in Table 2.

References

[1] J.G. Gruijters. Electric frequency drives. *Not published*, 2021.

[2] J.G. Gruijters. Electrical analogy for mechanical engineers. *Not published*, 2021.

[3] J.G. Gruijters. Magnetism and electric drives. *Not published*, 2021.

Appendices

A Table of IP class explanation

This appendix shows the table with the explanation of the numbers of the IP class, as explained in Section 3.

Table 3: The meaning of the digits of IP-classes

1st digit	**Explanation for dust**	**2nd digit**	**Explanation for water**
0	No protection	0	No protection
1	Protection from a large part of the body such as a hand, but no protection from deliberate access, from solid objects greater than 50mm in diameter.	1	Protection against vertically falling droplets, such as condensation. No damage or interrupted functioning of components will be incurred when an item is upright.
2	Protection against fingers or other object not greater than 80mm in length and 12mm in diameter (accidental finger contact)	2	Protection against water droplets deflected up to 15^o from vertical
3	Protection from entry by tools, wires etc, with a diameter of 2.5 mm or more	3	Protected against spray up to 60^o from vertical.
4	Protection against solid objects larger than 1mm (wires, nails, screws, larger insects and other potentially invasive small objects such as tools/small etc)	4	Protected against water splashes from all directions. Tested for a minimum of 10 minutes with an oscillating spray (limited ingress permitted with no harmful effects)
5	Partial protection against dust that may harm equipment	5	Protection against low-pressure jets (6.3 mm) of directed water from any angle (limited ingress permitted with no harmful effects)
6	Totally dust tight. Full protection against dust and other particulates, including a vacuum seal, tested against continuous airflow	6	Protection against direct high pressure jets (12.5mm) from any direction
		6K	Water projected in powerful jets (6.3 mm (0.25 in) nozzle) against the enclosure from any direction, under elevated pressure
		7	Protection against full immersion for up to 30 minutes at depths between 15 cm and 1 metre (limited ingress permitted with no harmful effects)
		8	Protection against extended immersion under higher pressure (i.e. greater depths). Precise parameters of this test will be set and advertised by the manufacturer and may include additional factors such as temperature fluctuations and flow rates, depending on equipment type
		9K	Protection against high-pressure, high-temperature jet sprays, wash-downs or steam-cleaning procedures - this rating is most often seen in specific road vehicle applications (standard ISO 20653:2013 Road Vehicles - Degrees of protection)