**UNIVERSITY OF VAASA**

**SCHOOL OF TECHNOLOGY AND INNOVATIONS**

**ENERGY TECHNOLOGY**

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# MOTOR-DRIVE SYSTEM EFFICIENCY INTERNAL CALCULATION TOOL AND PRODUCT INFORMATION DATABASE AUDIT BASED ON IEC 61800-9-2 STANDARD

Master´s thesis for the degree of Master of Science in Technology submitted for inspection

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Bonimira Doykova.

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# SYMBOLS AND ABBREVIATIONS

*Symbols*

| | |
|---|---|
| $B_{max}$ | The peak value of flux density in the |
| $F$ | The number of complete magnetization cycles per second |
| $f$ | Supply frequency in Hz |
| $I$ | Current |
| $I_s$ | Stator current |
| $I_0$ | No-load current |
| $K_e$ | Eddy current coefficient |
| $N_s$ | Rate rotation of synchronous machine’s magnetic field |
| $p$ | Number of poles |
| $P_{Cur}$ | Copper losses in rotor conductors |
| $P_{Cus}$ | Copper losses in stator conductors |
| $P_e$ | Eddy current losses |
| $P_{Fe}$ | Iron losses |
| $P_h$ | Hysteresis losses |
| $P_{in}$ | Input power |
| $P_{Lfw}$ | Friction and windage losses |
| $P_{LHL}$ | Additional harmonic losses |
| $P_{LL}$ | Additional losses |
| $P_{LS}$ | Stator winding losses |
| $P_{LR}$ | Rotor winding losses |
| $P_{Mech}$ | Mechanical losses |
| $P_N$ | Rated output |
| $P_{out}$ | Output power |

| | |
|---|---|
| $P_\rho$ | Friction losses |
| $P_\delta$ | Air-gap power |
| $R$ | Resistance |
| $r$ | Indice stand for the rotor |
| $r_{HL}$ | A ratio of the additional harmonic losses to the losses for a sinusoid motor supply |
| $R_{DC}$ | DC resistance |
| $s$ | Indice stand for the stator |
| $T$ | Temperature |
| $U_N$ | Rated voltage |
| $t$ | The thickness of laminations in m |
| $V$ | Volume of core in $m^3$ |
| $x_i$ | The actual observations time series |
| $\alpha$ | The resistance temperature coefficient |
| $\eta'$ | Hysteresis coefficient |

*Abbreviations*

| | |
|---|---|
| ABB | Asean Brown Boveri |
| AC | Alternating current |
| BU | Business Unit |
| CDM | Complete Drive Module |
| DC | Direct current |
| DOL | Direct-on-line |
| DTC | Direct torque control |
| EMC | Electromagnetic Compatibility |
| EN | European Standard |
| Eta | Efficiency |
| ePID | Electrical Product Information Database |
| EU | The European Union |
| IE | International Efficiency |
| IEC | International Electrotechnical Commission |
| IES | International Efficiency of Systems |
| OMS | Order management service |
| PC | Personal computer |
| PDS | Power Drive System |
| PF | Power factor |
| RCDM | Reference Complete Drive Module |
| RM | Reference Motor |
| RPDS | Reference Power Drive System |
| SSE | Sum of Squared Errors |
| VnP | Variants and Prices |

**VAASAN YLIOPISTO**
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Diplomityön tavoitteena oli tutkia ABB:n sisäisten laskentatyökalujen valmiutta käsitellä uuden IEC 61800-9-2-standardin mukaisesti valmistettuja sähkömoottoreita. Mitattujen arvojen simuloinnissa käytettiin Adeptin perusohjelmaa FCSmek:iä, jossa simuloinnit suoritettiin Sinusoidal (Direct-on-line)- ja Simple 2-level direct torque control-laskentaprofiileilla sekä S113-laskentaprofiililla. Lisäksi samat arvot simuloitiin DriveSizellä. Sinusoidal-laskentaprofiililla oli paras laskentatarkkuus. Sekä Simple 2-level direct torque control-laskentaprofiililla että DriveSizella puolestaan oli epätarkin laskentatarkkuus. S113-laskentaprofiiililla oli toiseksi paras laskentatarkkuus ja laskenta tällä profiililla oli paljon nopeampi kuin Sinusoidal-laskentaprofiililla. Tällä hetkellä ei ole riittävän tarkkaa laskentaohjelmaa, vaikka osa simuloiduista arvoista oli melko lähellä mitattuja arvoja.

**AVAINSANAT:** IEC 61800-9-2 standardi, sähkömoottori, sisäinen laskenta, Adept, DriveSize

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## ABSTRACT

The purpose of this thesis was to investigate the ability of ABB internal tools to process engines that are manufactured according to the IEC 61800-9-2 standard. To simulate measured values, Adept’s basic program FCSmek was used. The calculations were completed using Sinusoidal (Direct-on-line), Simple 2-level direct torque control and S113 calculation profiles. The same values were also simulated with DriveSize. Results showed that Sinusoidal calculation profile has the best calculation accuracy. Simple 2-level direct torque control calculation profile and DriveSize have the lowest degree of calculation accuracy. S113 calculation profile has the second best calculation accuracy and superior in speed than Sinusoidal calculation profile. Currently there is not an internal tool that would calculate accurately the measured values, despite some simulated values are quite close to measured values.

**KEYWORDS:** IEC 61800-9-2 standard, electric motor, calculation, Adept, DriveSize

# 1 INTRODUCTION

In March 2017, the International Electrotechnical Commission (IEC) published a new product standard IEC 61800-9, Ecodesign for power drive systems, motor starters, power electronics and their driven applications, that deals with the energy efficiency of power drive system (Danfoss 2017).

IEC 61800-9-1 and IEC 61800-9-2 are based on the European Standard EN 50598-1 and EN 50598-2 that have been in effect since 2014. It is expected that the IEC 61800-9 standard will replace EN 50598 as EN 61800-9. There are minor differences between these two standard. The majority of differences consist of editorial and mainly of adjustments to the grid voltages and frequencies (50 Hz/60 Hz) around the world. The content is the same in both standards. (Danfoss 2017.) As a result this thesis focuses on IEC 61800-9-2.

ABB is a leading company in power and automation technologies. The head office is located in Zürich, Switzerland. The company employs worldwide approximately 135 000 people in over 100 different countries. ABB`s business activities are divided in four global divisions units; Electrification Products, Industrial Automation, Robotics and Motion and Power Grids. (ABB 2017a.)

This master thesis is written for ABB Motors and Generators. This unit is a part of Robotics and Motion division and represented in Helsinki and Vaasa. Globally, ABB’s motor and generator business employs 14 000 people in 11 countries. In Finland, the business employs 530 people in Vaasa and 910 people in Helsinki. (ABB 2017b.)

The purpose of this thesis is to investigate the ability of ABB internal tools to process engines that are manufactured according to the IEC 61800-9-2 standard.

Upon commencement of this thesis, there are fundamental information in regards to different motor types, energy efficiency classification, different losses in components, European Standard EN 50598-2 and International Standard IEC 61800-9-2. Chapters 3-5 focus on ABB internal tools as DriveSize, MotSize, Adept and Electrical Product Information Database (ePID). Chapters 6-8 investigates how compatible the measured values and the simulated values compare to each other. To simulate measured values Adept was used. The calculations were done with Sinusoidal (Direct-on-line) and Simple 2-level direct torque control calculation profiles, and S113 calculation profile. Additionally similar values were simulated with DriveSize. Some of simulated values were close to measured values, however not comparable. Chapter 9 contains the conclusion from this thesis and Chapter 10 summarizes this thesis.

# 2 THEORY

In this chapter there is a section about different motor types, energy efficiency classification, different losses in components, European Standard EN 50598-2 and International Standard IEC 61800-9-2.

## 2.1 Electric motor

Electric motor is an electro-mechanical machine that converts the electrical energy into mechanical energy. The working principle of the electric motor in general depends on the interaction of magnetic and electric field. The electric motor is mainly classified into two types, the alternating current (AC) motor and the direct current (DC) motor. (Kothari and Nagrath 2010: 3.)

The main components of an electric machine are shown in Figure 1. All electric machines have two main parts: the rotating part called the rotor and the stationary part called the stator, with the intervening air-gap. Both components are made of magnetic material that conducts the magnetic flux, which depends on the process of energy conversion. The rotor has an axial shaft which is supported by bearings at each end, located in end covers bolted to the stator. The shaft usually extends out at the one end of the end cover and it is connected to either the prime mover or the load. (Kothari and Nagrath 2010: 3.) The main field is created by field poles excited with DC and AC. The winding that is on the field poles is called a field winding. The relative motion of the field passes the second winding that is located in the other part that causes an electromotive force in it. The armature winding exchanges the current with the outer electric system depending on the circuit conditions and it handles the load power of machine, while the field winding consumes a small percentage, from 0.5 % to 2 %, of the rated load power. The load current is a load that is dependent on armature current. (Kothari and Nagrath 2010: 3.)

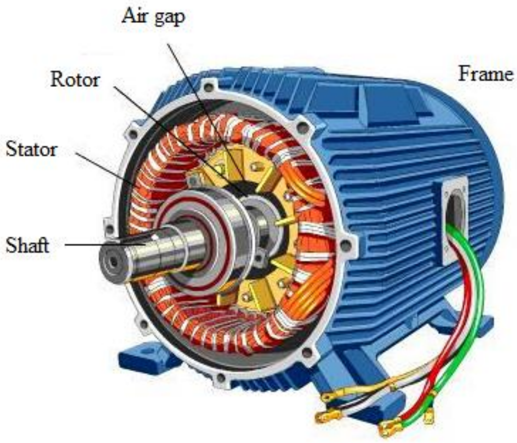


Figure 1. The main components of an electric machine (Electrical Knowhow 2013).

## 2.2 Induction motor

The most commonly used motor for industrial applications is an induction (asynchronous) motor, which requires a slip in order to create torque. The popularity of the motor is driven by the relatively low cost and simplicity of the build, which eases the processes of construction and maintenance.

A rotating magnetic field is created by the current that is led to the motor. This magnetic field causes a voltage in the rotor bars that form a closed circuit, in which current that begins to circulate forming a second magnetic field. The interaction of the magnetic fields of the stator and the rotor leads to rotor starting to follow the magnetic field of the stator and producing torque. (ABB 2014a: 43.)

The rotor of asynchronous motor is not usually able to keep up with speed of the magnetic field of the stator. Increase in the mechanical load of the motor shaft leads to a greater difference in speed and a higher torque produced. (ABB 2014a: 43.)

The number of stator windings is used to differentiate between the different types of induction motors. There are two types of these motors: a self-starting three phase induction motor and a not self-starting single-phase induction motor. The latter has only one stator winding, the main winding, and uses a single-phases power supply to operate. (Parekh

2003: 3.) A three-phase motor can also be made into a single-phase machine by using a capacitor.

The ordinary parts of an induction motor are presented in Figure 3. The stator consists of several thin steel laminations that are punctured and clamped together in the shape of a hollow cylinder, with slots for the stator windings. This is known as the stator core. An electromagnet (a pair of poles) is formed from every group of coils or windings together with the core it surrounds when alternating current is supplied. (Parekh 2003: 1.) The production of the rotor reminds that of the stator. It is also made of various thin laminations of steel with aluminum or copper bars that are evenly spaced along the axis of the motor. The rods form a circuit together with the short circuit rings that they are connected with. The interaction of the windings together with the magnetic fields produce a torque to turn the shaft, which causes the rotation of the rotor. (Parekh 2003: 2.) The transportation of the created mechanical energy from the rotor to the load is done by the rotating shaft, which itself is supported by bearings that are placed at both ends of the rotor. The rotor is mounted on the shaft using these same bearings (Parekh 2003: 2). Physical contact between these two components is eliminated by an air gap between the stator and rotor.

There are two different rotor types: the more commonly used squirrel cage rotor and a wound rotor (Parekh 2003: 1). These rotor types are presented in Figure 2.


Figure 2. Rotor types of an induction motor (Raj 2016).

The stator windings are connected directly to the power source. Internally, the windings are connected so that applying AC supply creates a rotating magnetic field. By connecting the three-phase power supply to the stator windings in the desired rotation order, the rotating magnetic field can be formed. (Parekh 2003: 1.)

The frame and end shields together form the component protection. The core parts of the motor are covered by the frame, which also provides electrical connections. A bearing, contained in the end shields, allows the rotor shaft to turn freely on its axis. (ABB 2012: 3.)

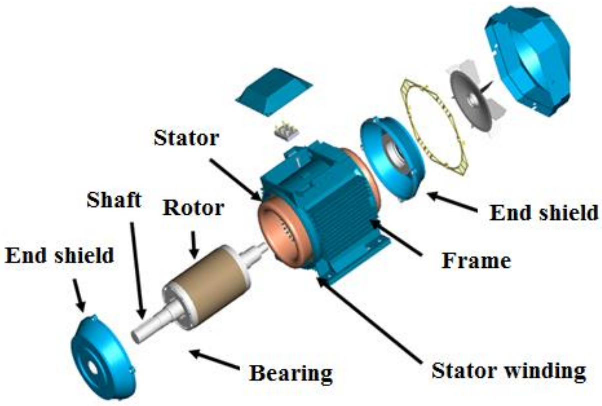


Figure 3. The basic parts of an induction motor (ABB 2012: 3).

## 2.3 Synchronous motor

A synchronous motor is an AC motor in which the speed under steady-state conditions is proportional to the frequency of the current in its armature. The designs of synchronous motor and induction motor do not differ from one another too much. (Pyrhönen 2014: 389). Synchronous motor has the same physical stator as an induction motor, with differing rotor constructions, which consists of a cylindrical iron frame with generally three-phased windings located in slots around the inner perimeter. The rotor includes some means to a source of DC, usually in the form of an insulated winding connected through slip rings. (Encyclopædia Britannica 2018.)

Normally the rotor and the revolving field in the machine rotate at the same speeds. For synchronous motors there are two types of rotors that are used, cylindrical pole rotors, known as non-salient rotors, and salient-pole rotors. These two rotor types are presented in Figure 4.

In the cylindrical rotor the rotor is, as suggested by its name, in cylindrical form with DC field windings embedded in the rotor slots. This way of construction is typically used in applications that require great speed intensity and fewer machine poles, usually motors with two or four poles, but it also allows for more accurate dynamic balancing and offers greater mechanical strength. In the salient-pole rotor type the rotor poles are projecting out from the rotor core. Construction like this is used in applications where the required number of machine poles is large and speed intensity is lower. (Kothari & Nagrath 2010: 444.) The principle operation of a synchronous motor can be understood by considering the stator windings as connected to a three-phase AC supply.

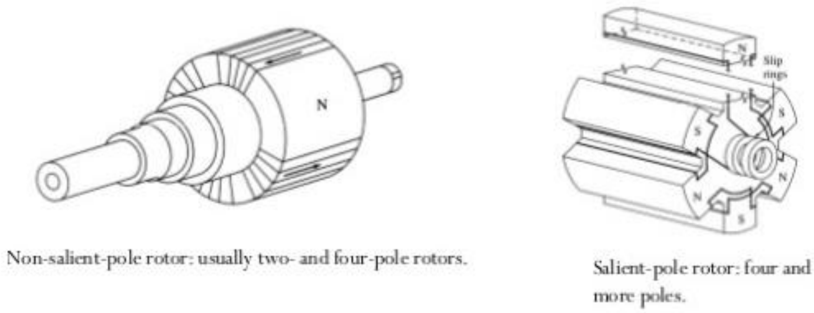


Figure 4. Two rotor types of a synchronous motor.

The principle operation of a synchronous motor can be understood by considering the stator windings as connected to a three-phase AC supply. The synchronous speed of a synchronous motor is given in r/min by the equation

$$N_s = 120 \frac{f\ (\mathrm{Hz})}{p}, \tag{1}$$

where $N_s$ is rate rotation of synchronous machine’s magnetic field, $f$ is frequency and $p$ is number of poles.

## 2.4 Permanent magnet motor

Permanent magnet motors can be categorized into two main types, based on electrical flow and design. These two types are permanent magnet synchronous motors and brushless DC motors, both being synchronous motors that include a permanent magnet, rotor, axle, the basic components of an enclosure and wound armature that rotates while the magnetic field stays stationary (IQS®Directory 2017). However, these motors are not identical. As an example, the brushless DC motors and permanent magnet synchronous motors have different characteristics and requirements for operating due to them having trapezoidal and sinusoidal back electromotive forces. (Pragasen & Ramu 1991:986).

The rotor construction differs from that of induction motors, although some properties are identical, such as stator winding technology, frame and bearings. There are several possibilities for rotor configurations for permanent magnet motors (Melfi, Evon & McElveen 2009: 29) and the most commonly used constructions are illustrated in Figure 5.

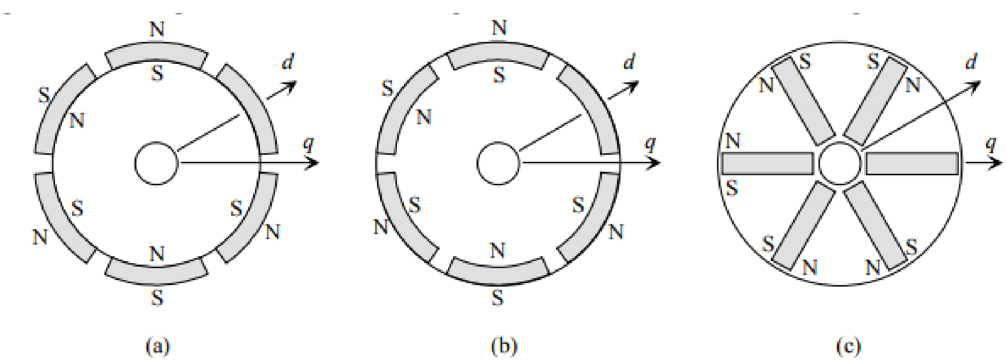


Figure 5. (a) Non-salient surface magnet rotor. (b) Salient pole surface magnet rotor with inset magnets, which is basically the same as a), but this type produces also some reluctance torque. (c) Embedded magnets in the rotor. (Puranen 2006: 27.)

## 2.5 Energy efficiency classification

The losses make it possible to find the motor's efficiency which, according to the new IEC 61800-9-2 standard, can be compared to a table of values and by doing so determine International Efficiency (IE)-classification.

Motor efficiency is simply the ratio of output power to input power, and represented as a percentage.

$$\text{Efficiency (\%)} = \frac{\text{Output power (kW)}}{\text{Input power (kW)}} \tag{2}$$

Power losses also matter in the sense that they are converted into heat which must be transported out of the motor so that the temperature of motor does not raise too high.

The international IEC 60034-30-1 standard, which has been published in March 2014, defines four International Efficiency (IE) classes (ABB 2018a: 1):

- IE1 (Standard Efficiency)
- IE2 (High Efficiency)
- IE3 (Premium Efficiency)
- IE4 (Super Premium Efficiency).

Efficiency ratings of IE-classes are shown in Figure 6. The scope of classification is determined for single speed (single and three phase) electric motors and continuous running electric motor with 2, 4, 6 or 8 poles. The rated output $P_N$ ranges from 0.12 kW to 1 000 kW, the rated voltage $U_N$ is above 50 V up to 1 kV, and the frequency is between 50 Hz and 60 Hz. The scope also includes ambient temperature within the range of -20 °C to +60 °C and an altitude of up to 4 000 m above sea level. (ABB 2017d.)

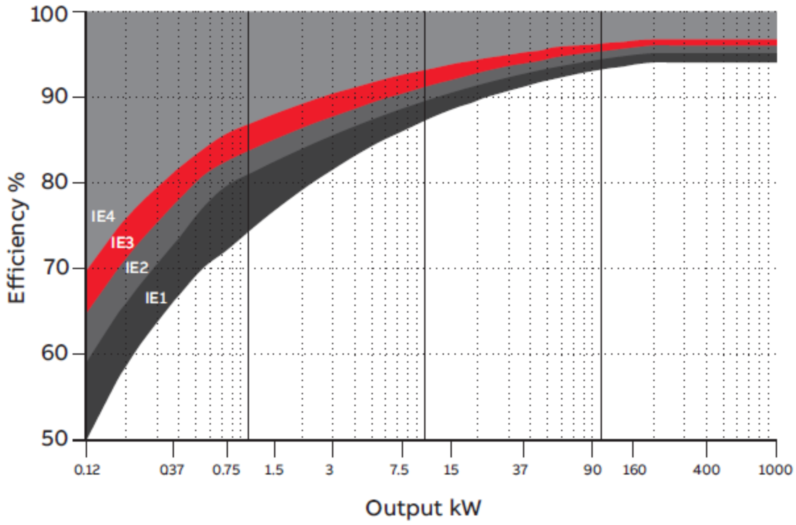


Figure 6. Efficiency ratings of IE-classes (ABB 2017d).

The IE classification of direct-on-line (DOL) motor is based on the efficiency of the motor in percent and it is visible on the motor's nameplate. The IE class is determined at the motor’s 100% torque and 100% speed measured or calculated values. (ABB 2017c.)

## 2.6 Losses in electrical machine

Losses in electrical machine can be categorized either by the location where they occur in the motor, or by their electromagnetic origin. For example based on their location, losses are divided into iron losses and friction and windage losses. (Boldea & Nasar 2002: 2.) Typical losses are important when computing the energy savings, while worst case losses shall be considered when guaranties are involved and when the losses are to be measured.

The most commonly used classification uses both the location and the electromagnetic origin, and in that all of the primary electromagnetic losses are caused by the winding and iron losses, all motor losses are included in friction and windage losses, and the term additional load losses is used for the combination of all harmonic losses (Kärkkäinen 2015:15). Figure 7 illustrates the power balance of a typical totally enclosed 4 kW IE3 induction motor.

Power losses in electrical machines are composed of the following elements:

- Resistive losses (called also Joule losses or copper losses)
  - In stator conductors $P_{Cus}$
  - In rotor conductors $P_{Cur}$
- Iron losses in the magnetic circuit $P_{Fe}$
- Mechanical losses $P_{Mech}$
- Additional (load) losses, also called stray-load losses $P_{LL}$ (Pyrhönen 2014: 524).

The losses can also be divided into no-load losses and load losses:

- No-load losses
  - Stator iron losses
  - Windage losses and friction losses
- Load losses
  - Stator winding losses
  - Rotor losses
  - Stray-load losses (ABB 2014a: 61).

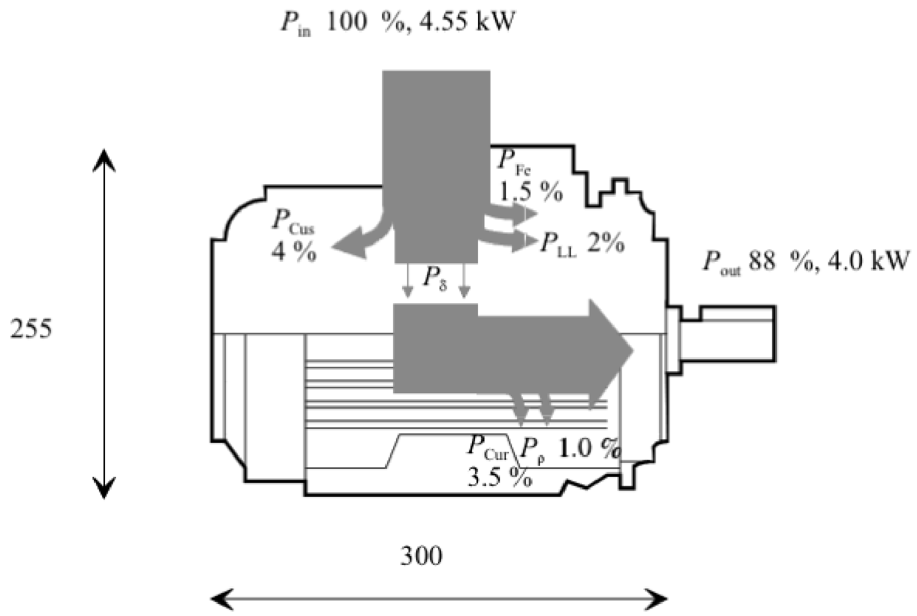


Figure 7. Sankey diagram of a two-pole induction motor, where $P_{Fe}$ is iron losses, $P_{Cus}$ is resistive losses of the stator, $P_{LL}$ is additional losses, $P_{\delta}$ is air-gap power, $P_{Cur}$ is resistive losses of the rotor and $P_{\rho}$ is friction losses. The total losses are 550 W. (Pyrhönen 2014: 525.)

### 2.6.1 Resistive losses

Resistive losses, also called copper losses ($I^2R$) or Joule losses, are caused by currents that flow in the wires. Stator copper losses are caused by heating from the current flow through the resistance of the stator winding. (ABB 2014a: 61.)

The stator and rotor Joule losses for a three-phase motor are

$$P_{\mathrm{Cus}} = 3I_{\mathrm{s}}^2 R_{\mathrm{s}}^2 \quad (3)$$

and

$$P_{\mathrm{Cur}} = 3I_{\mathrm{r}}^2 R_{\mathrm{r}}^2, \quad (4)$$

where $R$ is the resistance per phase and $I$ is the current per phase and the indices $s$ and $r$ stand for the stator and rotor (Kylander 1995: 22).

The Joule losses change as a function of the temperature, the resistance increases directly proportional to the temperature

$$R = R_{\mathrm{DC}}(1 + \alpha T\Delta), \quad (5)$$

where $R_{\mathrm{DC}}$ is the DC resistance, α the resistance temperature coefficient and T the temperature. (Puranen 2006: 113) The temperature coefficient for copper is 3.9·10-3 1/K and for aluminium 4.0·10-3 1/K (Mäkelä 2010: 177).

### 2.6.2 Iron losses

Iron losses occur in the magnetic core materials of the stator and rotor, and they are proportional to frequency and the peak flux density. Frequency of the rotor current is proportional to slip, which is typically only a few percent. Because of this iron losses in the stator are more significant than in the rotor. Iron losses of the stator are nearly independent from the load but rotor iron losses depend on slip, which depends on load. (Kärkkäinen 2015: 17.)

There are two types of iron losses: eddy current losses and hysteresis losses. Eddy current losses are caused by variable magnetic fields which generate heat by inducing eddy currents in the laminations. Hysteresis losses on the other hand arise as the alternation of the magnetic field leads to frictional movement of the magnetic domains in the core laminations. (Baggini 2016: 7.)

The iron losses can be expressed theoretically by the equation below

$$P_{\mathrm{Fe}} = P_{\mathrm{h}} + P_{\mathrm{e}}, \tag{6}$$

where $P_{\mathrm{Fe}}$ is Iron losses, $P_{\mathrm{h}}$ is hysteresis losses and $P_{\mathrm{e}}$ is eddy current losses.

The hysteresis losses per second or watts is given by the equation

$$P_{\mathrm{h}} = \eta' B_{\mathrm{max}}^{1,6} f V \text{ watts (or)} \frac{\mathrm{J}}{\mathrm{s}}, \tag{7}$$

where $\eta'$ is the hysteresis coefficient, $B_{\mathrm{max}}$ is the peak value of flux density in the core, $f$ is the supply frequency in Hz and $V$ is the volume of core in cubic meters (Parthasaradhy and Ranganayakulu 2014: 87).

The eddy current losses can be expressed theoretically by the formula below

$$P_{\mathrm{e}} = K_e f B_{\mathrm{m}}^2 t^2 V \text{ watts (or)} \frac{\mathrm{J}}{\mathrm{s}}, \tag{8}$$

where $K_{\mathrm{e}}$ is the eddy current coefficient which depends upon type of core material, $f$ is the number of complete magnetization cycles per second, $B_{\mathrm{m}}$ is the maximum flux density in $\mathrm{Wb/m^2}$, $t$ is the thickness of laminations in meter and $V$ is the volume of core in cubic meters (Parthasaradhy & Ranganayakulu 2014: 88).

### 2.6.3 Mechanical losses

Mechanical losses consist of bearing friction losses, windage losses of rotating rotor and ventilator losses (Pyrhönen 2014: 527).

The friction of the bearings in the machine causes friction losses, while windage losses are caused by the friction between the moving parts of the machine and the air inside the casing of the motor (Chapman 2005: 262). Both friction and windage losses are principally independent from the load, but proportional to the speed of the motor.

Air flow, fan design, improved bearing design and bearing seal selection affect these losses. The fan must be large enough to handle sufficient heat removal, but not to reduce efficiency and increase noise. (ABB 2014a: 61.)

### 2.6.4 Additional losses

Additional losses, known also as stray-load losses, can be calculated by taking the difference between the total losses and the sum of all the other losses, namely mechanical losses, stator and rotor iron losses, and stator and rotor resistive losses. These losses are all measured or calculated from the measured results according to IEC 60034-2-1: Standard methods for determining losses and efficiency from tests. (Pyrhönen 2014: 526.)

They are caused by several different phenomena, some of them are very difficult to model or calculate accurately. (Pyrhönen 2014: 526.)

The additional losses are the losses, which the load current and its spatial harmonics cause in windings, laminations, frame and other construction parts. These losses are not taken into account when calculating resistive and iron losses, and that is why they are called additional load losses in the standard IEC 60034-2-1. “The measured additional load losses are used when the efficiency of a motor is calculated indirectly from the loss measurements.” (Pyrhönen 2014: 526.)

If additional loss tests have not been done, the additional load losses of an induction motor are assumed to be

$$P_{\mathrm{LL}} = 0{,}025 P_{\mathrm{in}}, for\ P_{\mathrm{out}} \leq 1\mathrm{kW} \quad (9)$$

$$P_{\mathrm{LL}} = \left[0{,}025 - 0{,}005 \log_{10} \frac{P_{\mathrm{out}}}{1\mathrm{kW}}\right] P_{\mathrm{in}}, for\ 1\mathrm{kW} < P_{\mathrm{out}} < 10\,000\ \mathrm{kW} \quad (10)$$

$$P_{\mathrm{LL}} = 0{,}005 P_{\mathrm{in}}, for\ P_{\mathrm{out}} \geq 10\,000\ \mathrm{kW}, \quad (11)$$

where $P_{\mathrm{LL}}$ is additional (load) losses, $P_{\mathrm{in}}$ is the input power and $P_{\mathrm{out}}$ is the output power of the motor. (Pyrhönen 2014: 527.)
Additional losses can be calculated as follows:

$$P_{LL} \sim (I_s^2 - I_0^2) f^{1,5}, \quad (12)$$

where $I_s$ is stator current, $I_0$ is no-load current and $f$ is frequency. Using this formula, if the additional losses are known for one pair of current and frequency, they can be determined for other pairs of current and frequency as well. (Pyrhönen 2014: 527.)

## 2.7 No-load losses

The no-load losses are constant regardless of the motor load. In Figure 8 are shown types of no-load losses: stator iron losses and friction and windage losses.


Figure 8. Two types of no-load losses (ABB 2017e).

Stator iron losses are due to the energy required to magnetize the core material, and include losses due to creation of eddy currents that flow in the core (ABB 2017e). They can be decreased by using better and thinner electromagnetic steel and extending the iron core. (ABB 2017e). Figure 9 shows stator iron losses and Figure 10 shows how stator iron losses can be decreased.

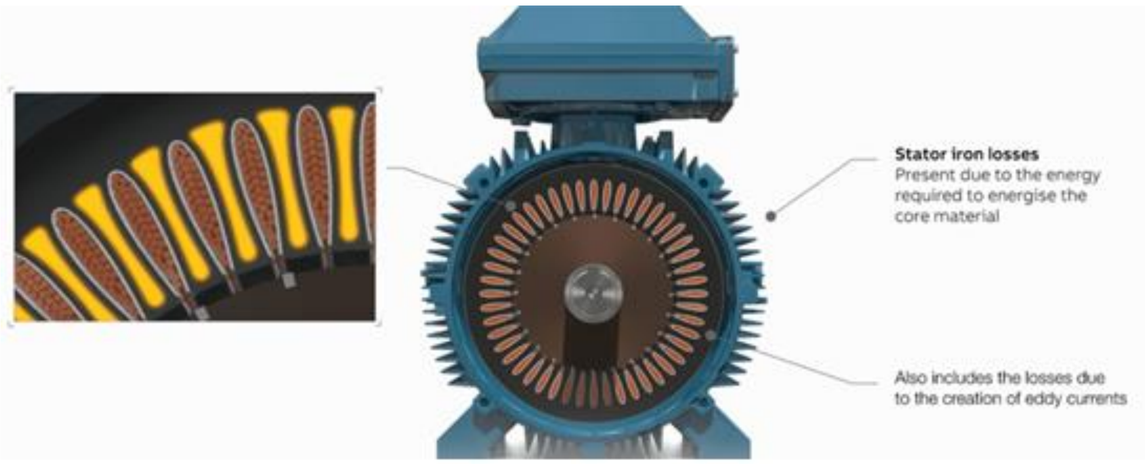


Figure 9. Stator iron losses (ABB 2017e).

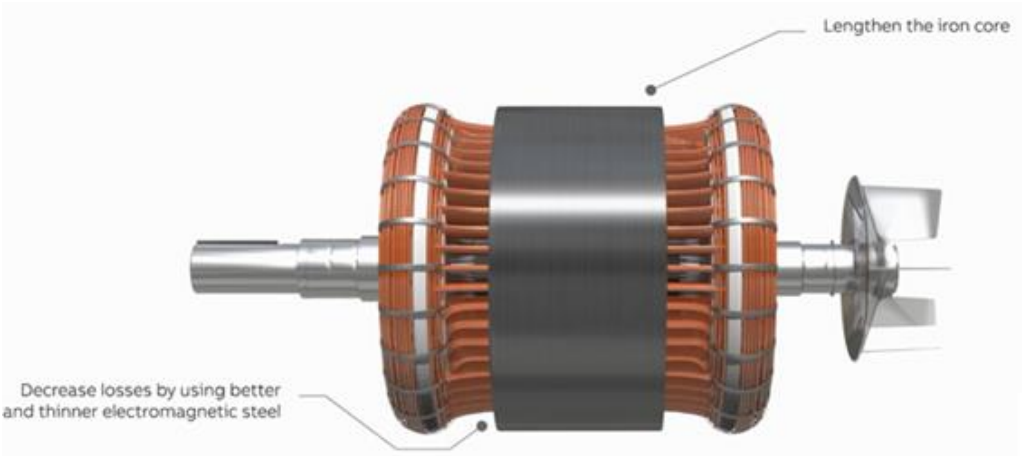


Figure 10. Stator iron losses can be decreased by using better and thinner electromagnetic steel and lengthening the iron core (ABB 2017e).

Friction losses are caused by friction in bearings and shaft seals, and can be decreased by correct dimensioning and selection of bearings. Air resistance in fans is caused by windage losses. These losses can be reduced by correct dimensioning and selection of bearings and optimized fan and air flow design. These losses are shown in Figure 11. (ABB 2017e.)


Figure 11. Friciton and windage losses (ABB 2017e).

## 2.8 Load losses

There are three types of load losses: additional load losses, stator winding losses and rotor losses (ABB 2017e). These are shown in Figure 12.


Figure 12. Three types of load losses (ABB 2017e).

Figure 13 shows stator winding losses, also called $I^2R$ losses that are present due to the current flow through the resistance of stator winding. Figure 14 shows that stator iron losses can be reduced by optimizing stator slot design with the tightly packed windings, to ensure a good slot fill in ratio, together with an optimized iron core, to maximize the strength of the magnetic field. (ABB 2017e.)

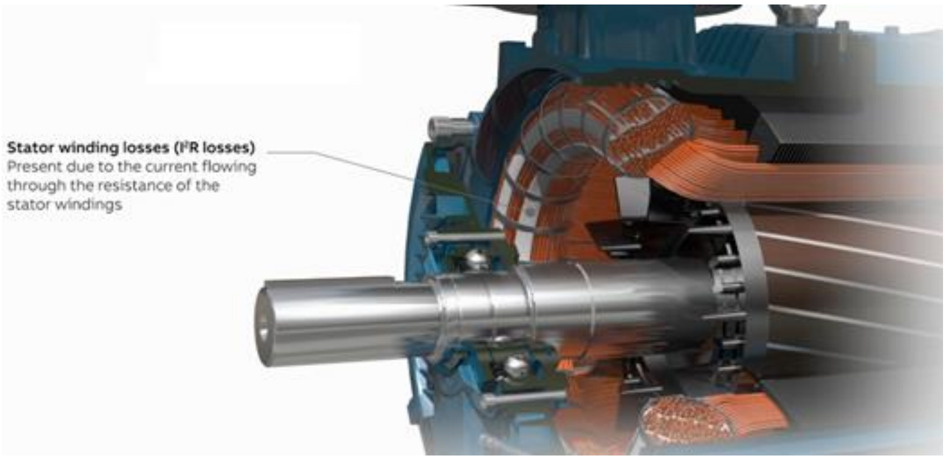


Figure 13. Stator winding losses, also called $I^2R$ losses (ABB 2017e).

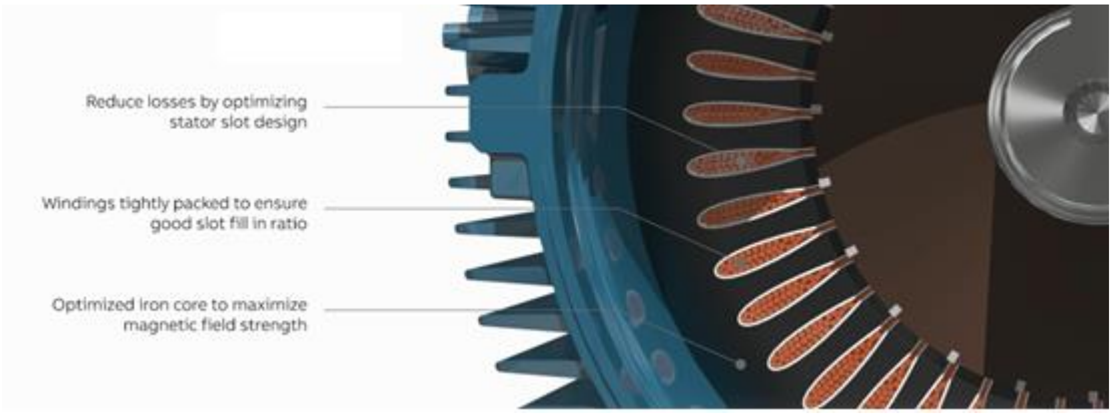


Figure 14. Methods how to reduce stator iron losses (ABB 2017e).

Rotor losses that are shown in Figure 15 are caused by the rotor currents and iron losses that are caused by the magnetic flux that interacts with the rotor core. (ABB 2017e). Figure 16 shows how these losses can be reduced.


Figure 15. Rotor losses (ABB 2017e).

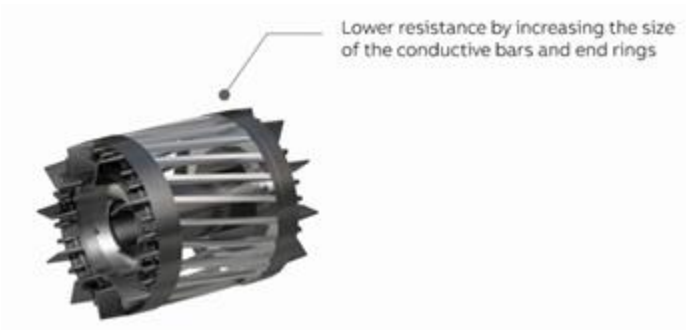


Figure 16. Rotor losses can be reduced by increasing the size of conductive bars and end rings to produce lower resistance (ABB 2017e).

The leakage flux that is caused by variations in the windings, mechanical imperfections in the air gap and irregularities in the air gap flux density are caused additional losses that are known also as stray-load losses. They can be decreased by improving slot geometry and minimizing deviation in the air gap. (ABB 2017e.) The reasons why additional load losses are caused are shown in Figure 17. Losses can be kept to a minimum by using higher quality materials, cutting edge motor designs, and manufacturing in high precision automated factories.

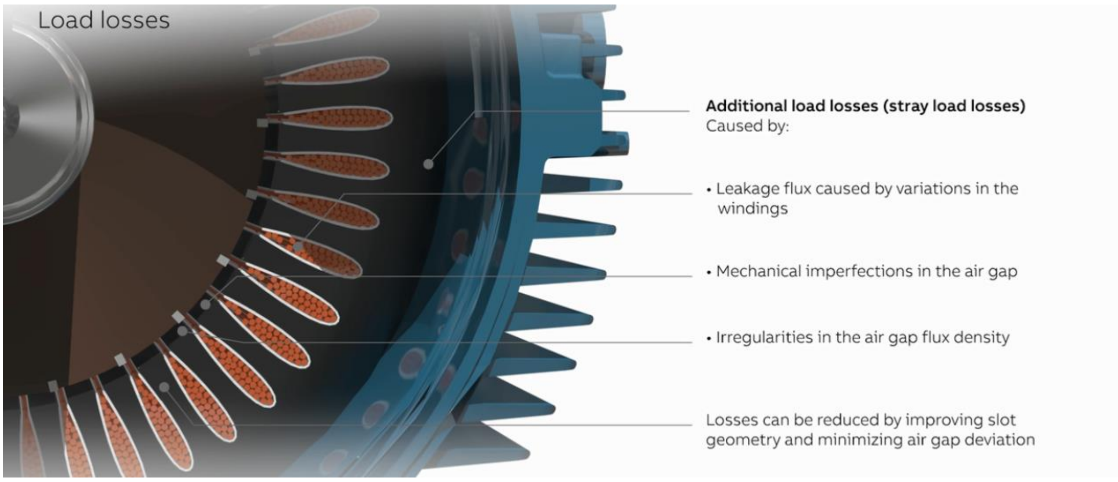


Figure 17. Additional load losses, called also stray-load losses (ABB 2017e).

### 2.9 IEC 60034-30-2 TS Energy Efficiency Interpolation

The efficiency classes for line-operated electric motors range from the Standard Efficiency (IE1) to Super Premium Efficiency (IE4) and are defined by the international standard IEC 60034-30-1. They are specified for alternating current motors that operate at rated torque and speed. (Bauer Gear Motor 2016: 2.)

On the $8^{th}$ of December in 2016 the new standard IEC Technical Specification 60034-30-2 was released and will remain unaltered until 2019. This concerns the energy efficiency classification of those alternating current motors rated for variable voltage and frequency electric machines that were not covered in IEC 60034-30-1. (IEC 2016: 5.)

This classification is only applicable to machines that are designed for operation with sinusoidal fundamental current that are not designed to be operated direct-on-line grid. These kind of machines are for example synchronous machines with DC field windings, sinusoidal reluctance synchronous machines, permanent magnet synchronous machines with and without additional reluctance torque, and induction machines designed exclusively for variable speed action. (IEC 2016: 6.)

Motors that are AC motors, rated for both on-line grid operation and variable speed operation (dual rated motors) for example most induction-motors or line-start permanent-magnet motors and fall under both IEC 60034-30-1 and IEC 60034-30-2 standards shall bear the IE efficiency class according to the procedures laid out in IEC 60034-30-1 only. (IEC 2016: 10.)

Stator winding losses $P_{\mathrm{LS}}$ and rotor winding losses $P_{\mathrm{LR}}$

$$P_{\mathrm{LSR}}\,(f,T) = P_{\mathrm{LSR}}\,\frac{I_0}{I_{\mathrm{N}}} + P_{\mathrm{LSR}}\left(1 - \frac{I_0}{I_{\mathrm{N}}}\right)T^2 \tag{13}$$

Iron losses $P_{\mathrm{Fe}}$

$$P_{\mathrm{Fe}}\,(f,T) = \frac{1}{2}P_{\mathrm{Fe}}\,f + \frac{1}{2}P_{\mathrm{Fe}}\,f^2 \tag{14}$$

Friction and windage losses $P_{\mathrm{Lfw}}$

$$P_{\mathrm{Lfw}}\,(f,T) = \frac{1}{2}P_{\mathrm{Lfw}}\,f + \frac{1}{2}P_{\mathrm{Lfw}}\,f^3 \tag{15}$$

Additional (load) losses $P_{\mathrm{LL}}$

$$P_{\mathrm{LL}}\,(f,T) = \frac{1}{2}P_{\mathrm{LL}}\,f + \frac{1}{2}P_{\mathrm{LL}}\,f^2 \quad (16)$$

Additional harmonic losses $P_{\mathrm{LHL}}$

$$P_{\mathrm{LHL}}(f,T) = P_{\mathrm{LHL}} \quad (17)$$

Interpolation

$$P_L\,(f,T) = A + Bf + Cf^2 + Df^3 + ET + FT^2, \quad (18)$$

where *A*, *B*, *C*, *D*, *E* and *F* are analytical determined coefficients and they are defined from formulas 13-17 , *T* is torque and *f* is frequency (Doppelbauer 2017: 7).

## 2.10 European Standard EN 50598-2

European Standard EN 50598 is a three-part standard (EN 50598-1, EN 50598-2 and EN 50598-3) looking at Ecodesign for power drive systems and their driven applications (ABB 2017c).

EN 50598-2, Energy efficiency indicators for power drive systems and motor starters, released in December 2014. It defines energy efficiency indicators (IE and IES) for the complete drive module (CDM) and the power drive system (PDS). (EN50598-2, 2014:12.) The standard includes methodology to determine the CDM and PDS losses, assigning the IE and IES values. This standard applies to motor driven equipment with a voltage range of 100 V to 1000 V and a power range of 0.12 kW to 1000 kW. (ABB 2017c).

## 2.11 International Standard IEC 61800-9-2

In March 2017, the International Electrotechnical Commission (IEC) published a new product standard IEC 61800-9, Ecodesign for power drive systems, motor starters, power electronics and their driven applications, specifies energy efficiency indicators of power electronics (CDMs), PDS and motor starters, all used for motor driven equipment. It specifies the methodology for the determination of losses of the CDM, the PDS and the motor system. (IEC 2017.)

EN 50598 series has been converted into a global IEC standard: IEC 61800-9 series. IEC 61800-9-1 and IEC 61800-9-2 are heavily based on the European Standard EN 50598-1 and EN 50598-2. It is expected that the IEC 61800-9 standard will replace EN 50598 as EN 61800-9. There are some differences between these two standard, but they are mainly editorial and minor and consist mainly of adjustments that cover the different grid voltages and frequencies (50 Hz/60 Hz) around the world. So the content is practically the same in both standards**.** (Danfoss 2017.)

### 2.11.1 Reference motor

Reference motor (RM) is defined by mathematical equations and/or power losses, used as a basis for comparing other motors (CENELEC 2014: 15). The purpose of RM is to enable converter manufacturers to determine the IES class of a power drive system (PDS) without knowledge of the real motor and its manufacturer. The measured or calculated losses of an individual motor are compared to the losses of a reference motor that are derived from the 50 Hz IE2 efficiency classification of four-pole asynchronous motors according to EN 60034-30-1, taking into account the $r_{HL}$ (ratio of the additional harmonic losses to the losses for a sinusoid motor supply) factor. The losses of the RM are also applied to 60 Hz applications. (Vem-group 2014: 3.)

The power losses at a limited number of specific eight points are specified for the RM in Figure 18, for the RCDM in Figure 20 at page 35 and for the RPDS in Figure 22 at page 37.

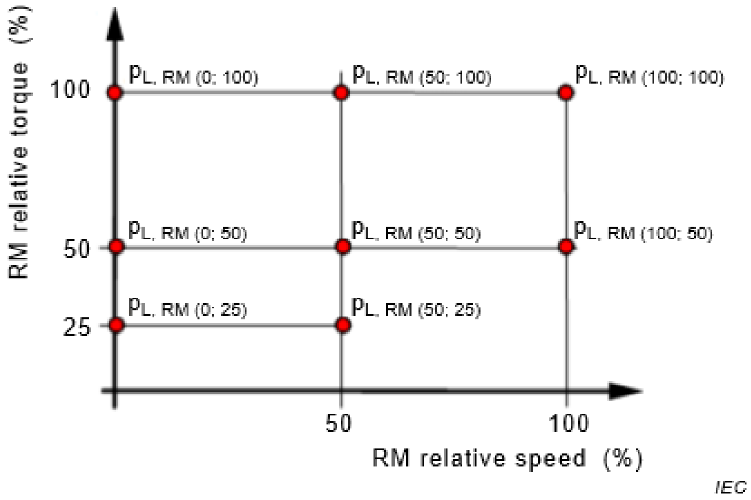


Figure 18. Illustration of the operating points (shaft speed, torque) for the determination of relative losses of the RM (IEC 2017: 26).

### 2.11.2 Complete drive module IE classification

Complete drive module (CDM) consists of the electronic power converter connected between the electric supply and a motor as well as extension such as protection devices, transformers and auxiliaries (IEC 2017: 14). CDM is defined by mathematical equations and/or power losses (CENELEC 2014:15).

Standard EN 50598-2 (converted into IEC 61800-9-2) defines the relative losses of a CDM in efficiency classes IE0 to IE2. The IE class of the CDM is determined by its relative losses at the point (90,100), meaning 90 % motor stator frequency and 100 % torque current, as it is shown in Figure 19. (Siemens AG 2018.)

The measured or calculated losses of an individual DCM are compared to the losses of the reference complete drive module (RCDM) that are declared with efficiency class IE1.

Figure 19 shows that a CDM of efficiency class IE2 has 25 % lower losses and a CDM of efficiency class IE0 has 25 % higher losses than reference value (Siemens AG 2018).

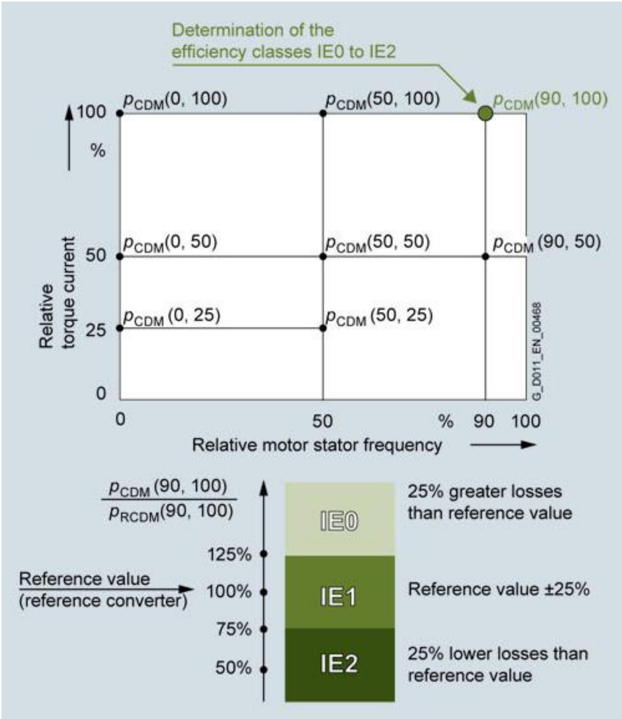


Figure 19. The IE class for CDM is determined in a single operation point at 90 % motor stator frequency and 100 % torque current (Siemens AG 2018).

### 2.11.3 Reference complete drive module

Reference complete drive module (RCDM) is used as a basis for determining the IE class of an individual CDM (CENELEC 2014:15) and it for example enables manufacturers of motor to determine the IES class of a power drive system (PDS) without knowing the real CDM and its manufacturer. (Vem-group 2014: 3.)

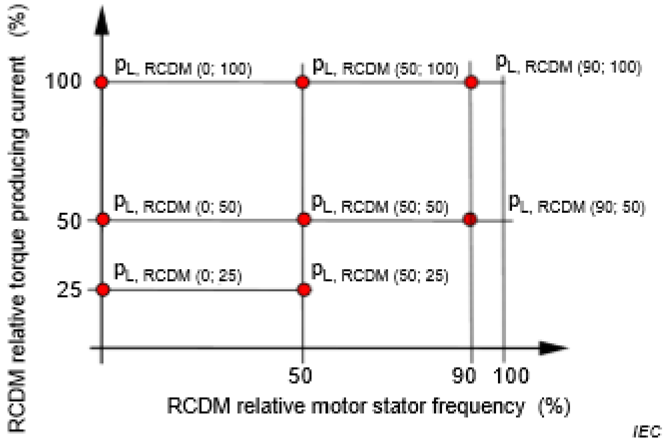


Figure 20. Illustration of the operating points (relative motor stator frequency, relative torque-producing current) for the determination of losses of the RCDM (IEC 2017: 26).

### 2.11.4 Power drive system IES classification

Power drive system (PDS) consists of a CDM and a motor. Standard EN 50598-2 (converted into IEC 61800-9-2) defines the relative losses of a PDS in efficiency classes IES0 to IES2. The ‘S’ after ‘IE’ stands for system (Siemens AG 2018).

The efficiency classes of PDSs refer to the point (100,100), meaning 100% speed and 100% torque, as it is shown in Figure 21 (Siemens AG 2018).

The measured or calculated losses of a real PDS are compared to the losses of the reference power drive system (RPDS) that are defined to efficiency class IES1. Figure 21 shows that a PDS of efficiency class IES2 has 20 % lower losses and a PDS of efficiency class IES0 has 20 % higher losses than reference value (Siemens AG 2018).

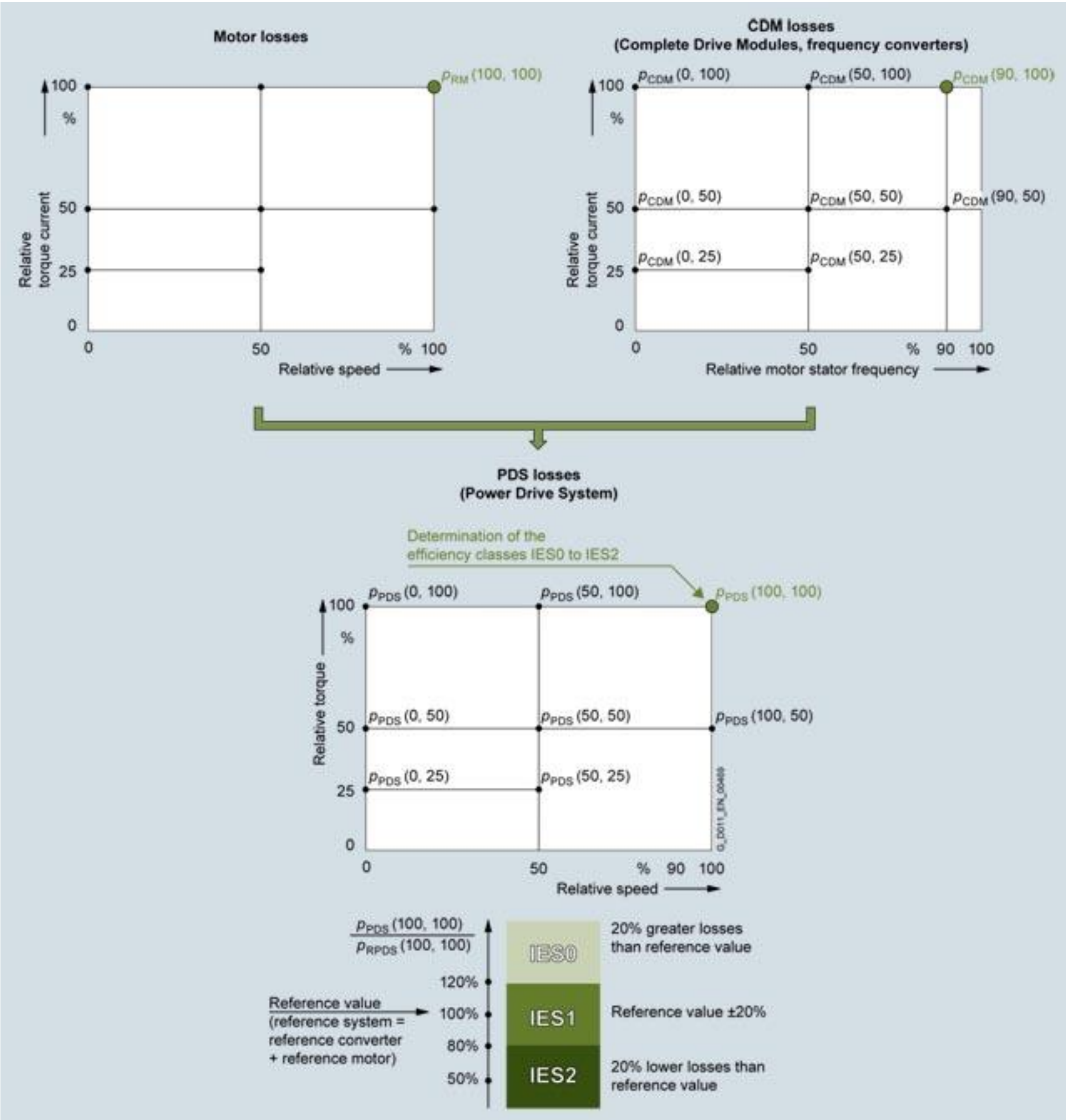


Figure 21. The IES class for PDS is determined in a single operation point at 100 % speed and 100 % current (Siemens AG 2018).

### 2.11.5 Reference power drive system

Reference power drive system (RPDS) is consisted of RM and RCDM and it, for example, enables a pump manufacturers to define the energy efficiency index of an expanded product, in this situation a pump based on the RPDS, without knowledge of the real PDS or the motor and CDM and their manufacturer(s) (Vem-group 2014: 3). Illustration of the extended product with included motor system is shown in Figure 23.

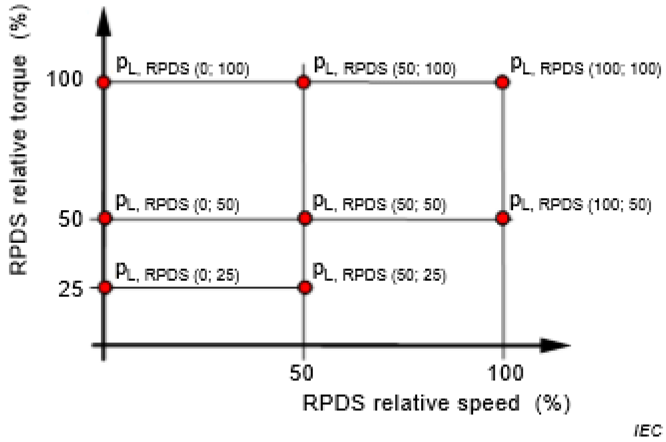


Figure 22. Illustration of the operating points (shaft speed, torque) for the determination of relative losses of the power drive RPDS (IEC 2017: 25).

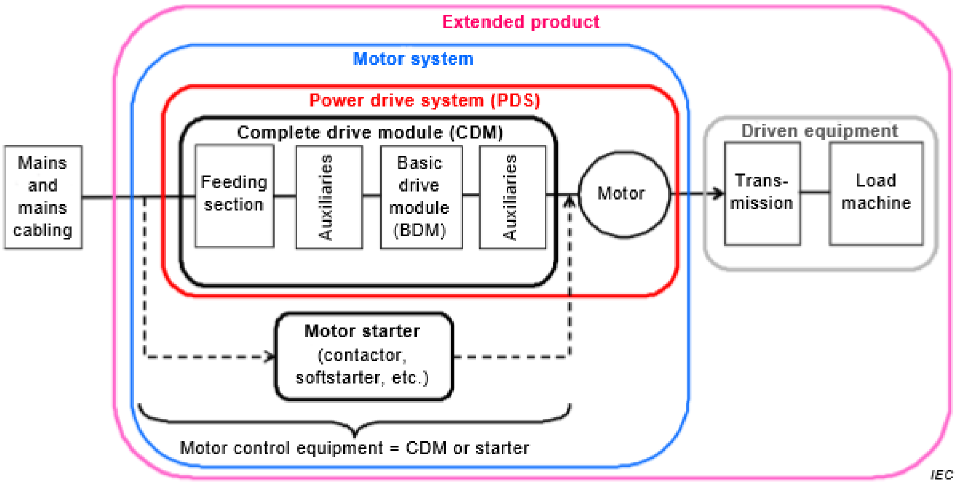


Figure 23. Illustration of the extended product with included motor system (IEC 2017:15).

# 3 DRIVESIZE AND MOTSIZE

DriveSize and MotSize are a Windows 7/10 PC programs that help to select an optimal low voltage motor and frequency converter particularly in cases where a straightforward selection from a catalog is not possible. They are also able to be used to compute network harmonics and to create documents about the dimensioning and contain current versions of ABBs motor and drive catalog. (ABB 2018b.)

BU Drives had at first approximately twelve different tools for AC drive dimensioning. DriveSize was created as there was a need for a user friendly and reliable tool. It helps to select an optimal motor, drive and transformer and standardizes the rules for dimensioning thus insuring that results were accurate. It is used to calculate system harmonics, efficiencies and power losses, inverter load currents and the loads of supply unit. Along with these the tool also provides results in graphical and numerical format and makes it possible to print and save the results to be used as part of drive offer. (ABB 2014b: 2.) MotSize was created by BU Motors and Generators as an integrated part of DriveSize, but with the release of ver 4.0.0 DriveSize and MotSize has been separated. (BU Motors and Generators Training 2014: 3-4.)

## 3.1 DriveSize

DriveSize consists of a user interface, computing part and product databases that contain about 85 000 data rows for catalog motors with many voltages, thousands of drive types and the modules of the drives. The computing of customer-specific motors is based on ABB Sophiè, which has been developed by ABB Oy / Machines and it is included in the DriveSize installation. (DriveSize Manual 2018.)

DriveSize contains the following items for electric drive dimensioning:

- Ambient conditions for drives and motors
- Four different mechanical load types for motor:
  - Constant power

  - Constant torque
  - Constant torque and power
  - Squared torque (Pump/fan)
- Overload types available:
  - One-time at start
  - Simple cyclic
  - Multiform cyclic
- Drive selection based on loading currents
  - Simple cyclic
  - Multiform cyclic
- Selecting an alternative inverter, a motor and a line supply unit manually
- Network harmonics calculation for drives or supply units and combined harmonics
- Heat loss calculations for most motors and drives
- Show IEC61800-9-2/EN50598-2 loss numbers for most new drives
- Mass flow and thermal loss for liquid cooled multidrives
- Results in numerical form
- Results in graphical form (load, motor, inverter)
- Generating reports in openXML format for saving or printing
- Saving and retrieving projects with *.AC and *.MAC files
- Save information in XML format to be used with other software
- Option to consider motor load RMS or not
- Option to Utilize temperature reserve of IEC34 motors or not.
- Handling of regional variants of drives
- Transformer selection results and reserves
- Lock option to keep selected motor.

Three parts of DriveSize's main window are shown in Figure 24. The first part of DriveSize's main window is system configuration, the second one is input and specifications and the third one is select data and results, which includes the catalog data of the selected item. (ABB 2014b: 9.)

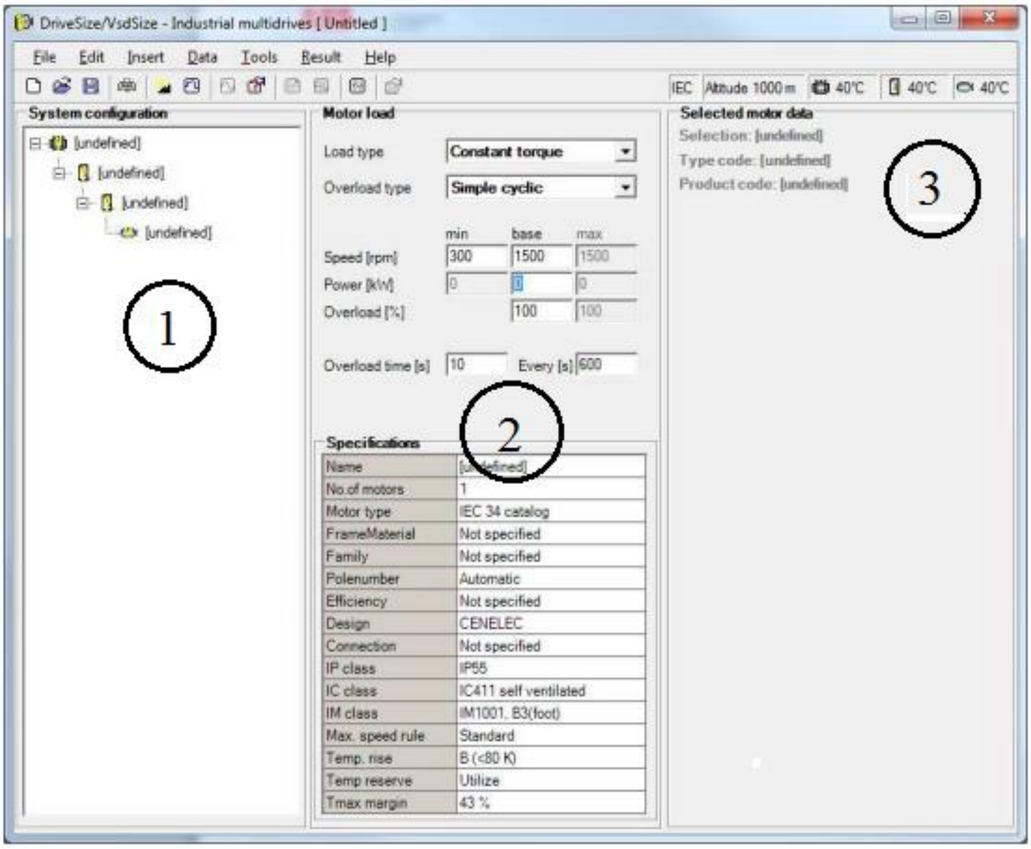


Figure 24. Three parts of DriveSize's main window (ABB 2014b: 9).

The Result view shows the results in a numeric form for the item which is highlighted and the view is similar for motors, inverters and incoming units. The Specifications data shows the user requirements. The Catalog data displays the name plate/catalog data. The Selection data has columns for the required data that is calculated from the user load demands, the result data that is based on selected unit like motor and drive and the margin values that indicates the percentage of capacity still available. (DriveSize Manual 2018.) The Results view is shown in Figure 25.

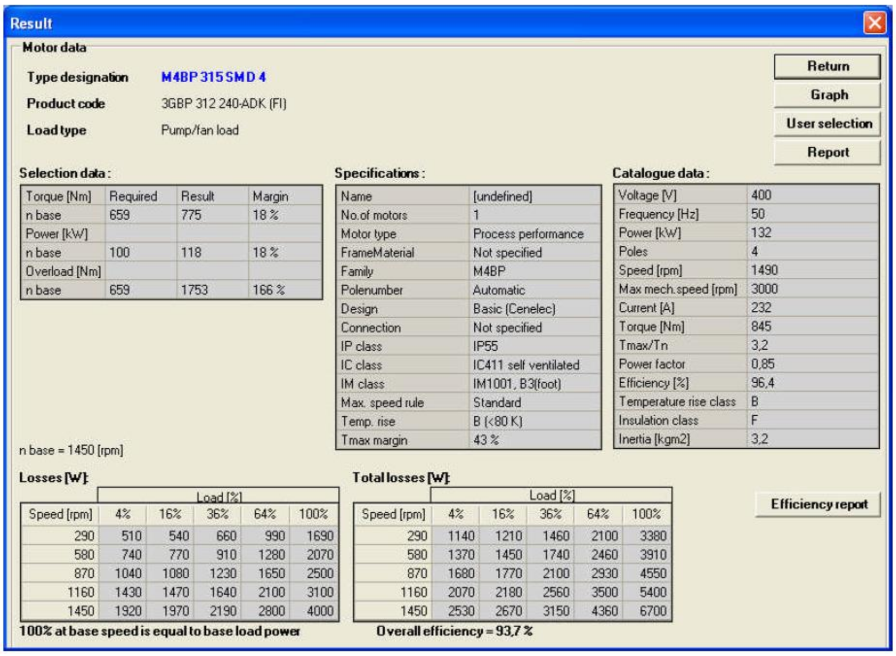


Figure 25. Result view for motors (DriveSize Manual 2018).

The Graph view helps to check how well the unit fits the requirements. The graphs display load and motor torques, load and motor powers and load and inverter currents. Figure 26 shows the graph for load and motor torques as a function of speed.

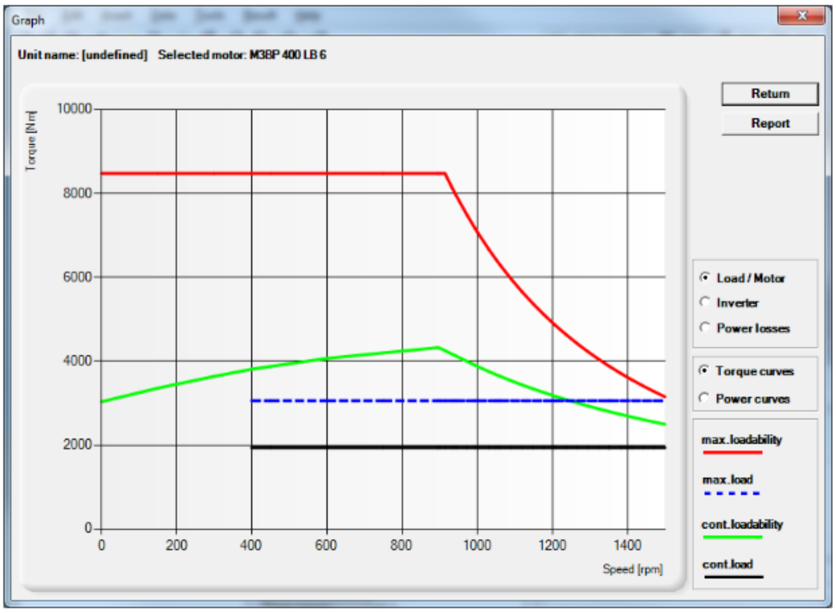


Figure 26. Graphs for load and motor torques as a function of speed (DriveSize Manual 2018).

## 3.2 MotSize

Figure 27 shows the main screen of MotSize. You have to select voltage and frequency and to select a motor, you have to press the icon which is circled with red in the figure below. (BU Motors and Generators Training 2014: 9.) DriveSize and MotSize are in the end quite similar.

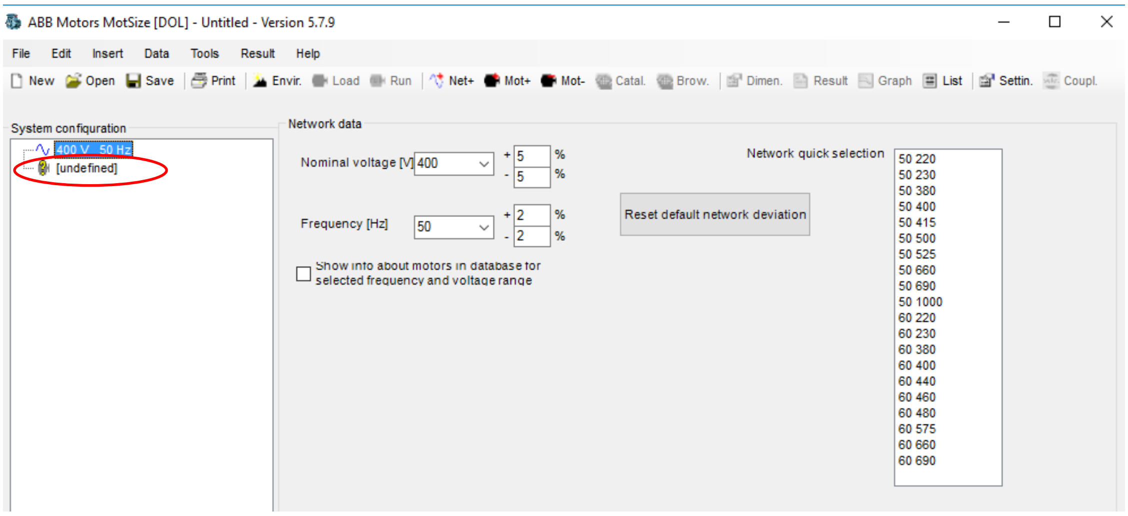


Figure 27. Motor can be chosen by pressing the icon, which is circled with red (BU Motors and Generators Training 2014: 9).

# 4 ADEPT

Adept is ABB's electric machine design tool, which is intended for daily design and development work. Adept enables for example to dimension asynchronous and synchronous machines, investigate starting times and temperature rises, create graphics and various documents. The role of Adept is to act as a user interface to machine data and many calculation tools. There are many analytical (for example S113) and finite element based calculation tools under Adept that can be used and no matter what calculation engine is used the inputs and results are handled in Adept the same way. (Adept Manual 2018.)

Adept provides fast analytical tools and Finite Element Method (FEM) tool, which is a part of Adept, to develop and analyse new machines that cannot be done with analytical tool (Adept Manual 2018).

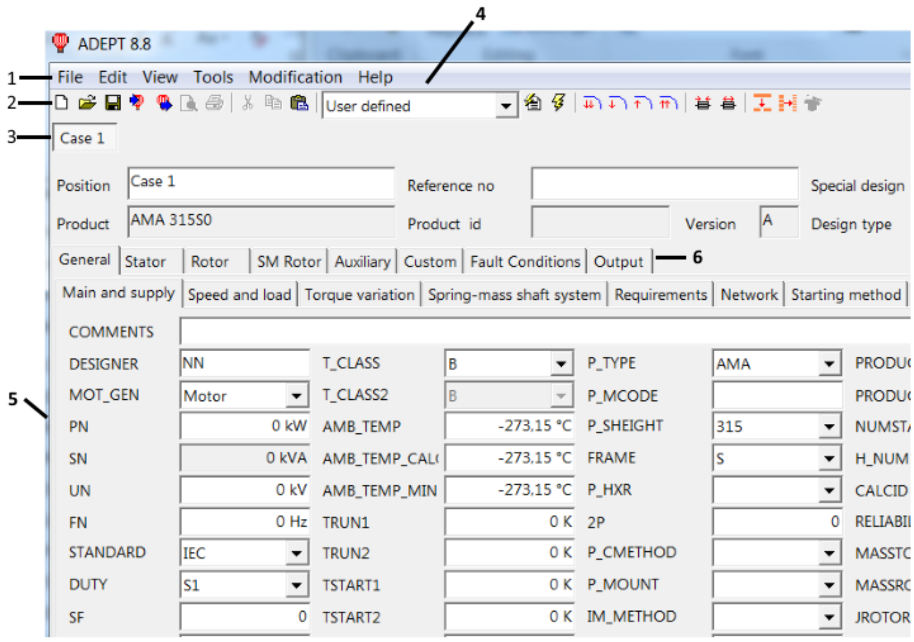


Figure 28. Adept general view (Adept Manual 2018).

Adept general view contains of:

1. Menu Functions
2. Shortcuts for menu functions. There is also available shortcut and functional key.
3. Calculation Cases
4. Calculation Profile

5. Common Input and Output.
6. Output tab, which contains the results of calculation output. How many subpages can be seen under output tab depends on, among other selections, calculation profile and its selections.

All calculation data including output and input data is stored in databases (Adept Manual 2018).

# 5 ELECTRICAL PRODUCT INFORMATION DATABASE

Eelectrical Product Information Database (ePID) is a web-based application for maintaining technical electrical data for PG IEC Low Voltage Motors standard products. It has replaced formerly used PID Lotus Notes database, which included electrical data for catalog motors and was used as a master database for motor data published in printed catalogs and sales tools like DriveSize, MotSize, Optimizer and Order management service (OMS). (ePID User Manual 2018.)

ePID has been integrated with the following systems (ePID User Manual 2018):

- Adept: electrical data (calculation and stamping row data) calculated with Adept is automatically transferred to ePID via Trinity
  - Creation of a motor code is done in ePID by attaching stamping row data within a calculation to motors (catalog motor code, for example product code without information about voltage code and mounting arrangement) and complementing data for the motor with additional attributes.
- ElApp rating plate application: ePID works in same system environment and applications are fully integrated in a way that all calculation data handled in ElApp is stored in ePID database. Thus, all calculation data for catalog and order specific motors exist in one system environment. With an integrated environment data conflicts in published documentation and rating plate are avoided.
- Variants and Prices (VnP): ePID works in same system environment and there is an interface from ePID to VnP taking care of automatically updating product data to VnP.
- MotSize/DriveSize tool: product database used by MotSize or DriveSize is generated from ePID data. Database generation is done once a week as a background job. Data to be published in MotSize or DriveSize is controlled via publishing flags in ePID application.
- Optimizer tool: product database by using Optimizer application is generated from ePID data. Database generation is also handled as a background job. Data published in Optimizer application is controlled via publishing flags in ePID application.
- OMS: there is an interface from ePID to OMS that is used for product creation. All Standard motors have been created through the interface for last two years. Now the scope has been widen and also Pre modified- and Special-motors will be created through this interface.
- Sales configurator (2018): There is a new interface under development. Data from ePID will be transferred to new sales configurator in 2018.

## 5.1 Product data management

ePID is the master place for product data published in catalogs and sales tools.

- New catalog codes are created by attaching stamping rows to products, assigning the catalog code created into product tree and giving additional data for the motor. The information are not included in the electrical data part.
- Publishing information for a product in product catalog determines into which tools the data is published (VnP, Optimizer, MotSize and DriveSize).
- Complete product code creation to different applications.

## 5.2 Calculation management

ePID is the master place for calculation and stamping row data.

- New calculation and/or stamping row is created in Adept, and, the data flows to ePID via Trinity interface.
- Electrical values for a stamping row received from Adept are automatically placed into so called calculated scope. Calculated values are automatically copied to working scope, engineering can change values based on test results. Values in working scope will be the same as final published values unless tolerances are used.
- Stamping rows are categorized based on whether they are used as rating plate rows only or if they are used for a catalog product. Attaching stamping rows to catalog products are handled in calculation management part of ePID application.

# 6 METHODS

To simulate measured values, Adept's basic program FCSmek was used. The calculations were completed using Sinusoidal (Direct-on-line), Simple 2-level direct torque control and S113 calculation profiles. The FCSmek is two-dimensional calculation tool, which is based on the FEM tool. The S113 is an analytical computing program and it is based to solve the single-phase replacement of an electric motor. The same values were also simulated with DriveSize.

Direct start (DOL) is the simplest method to start the motor. Motor is started by connecting it directly to the mains supply (On Line). The voltage from the mains will be supplied to the winding of the motor as soon as it is connected. The sine wave in Figure 29 is a curve that describes a smooth repetitive oscillation.

The motor can be controlled with the frequency transformer, for example with "Direct Torque Control (DTC) that describes the way in which the control of torque and speed are directly based on the electromagnetic state of the motor" (ATO 2018). The voltage waveforms of DOL and DTC as a function of time are shown in Figure 29.

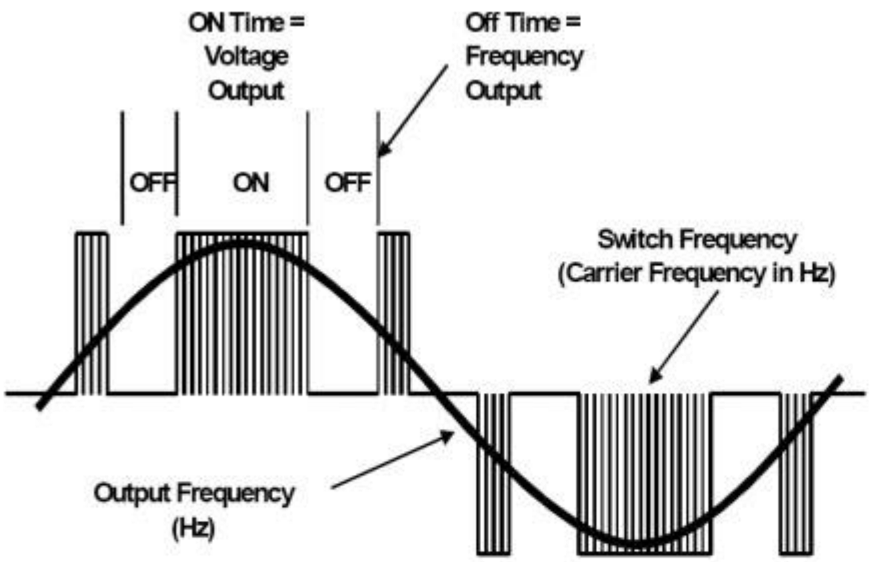


Figure 29. The voltage waveforms of DOL and DTC as a function of time (ATO 2018).

Sixty-five different points were used to simulate measured values. The rotation speeds 750 r/min and 1500 r/min are examined. Sum of Squared errors of all points are calculated and listed in Table 9 and Table 10.

The following parameters values were matched between the simulated and measured motor:

- Electrical power
- Power factor
- Frequency
- Phase voltage
- Current
- Losses
- Efficiency
- Temperature.

The examined values at the rotational speed 750 r/min in the range of 1.4 kW to 5.5 kW and at the rotational speed 1500 r/min in the range of 2.8 kW to 11 kW are the following:

- Current
- Losses
- Efficiency
- Power factor.

# 7 RESULTS

In this chapter the measured values and the simulated values are compared. In Table 1, Table 3 at page 51, Table 5 at page 54 and Table 7 at page 56 there are listed four measured values at the rotational speed of 750 r/min and simulated values with Adept and DriveSize. In Table 2 at page 50, Table 4 at page 52, Table 6 at page 55 and Table 8 at page 57 there are listed four measured values at the rotational speed of 1500 r/min and simulated values with Adept and DriveSize. The closest simulated value compared to the measured value on each row is marked with green.

## 7.1 Current

It can be seen in Figure 30 and Figure 31 that offset is quite steady with all calculation profiles. The results that are simulated with DOL calculation profile are closest to the original measured values of current and DTC calculation profile gives the most inaccurate values.

Table 1. Measured values of current at the rotational speed of 750 r/min and simulated values with Adept and DriveSize.

| **Measured current** | **Sinusoidal (DOL) calculation profile** | **Simple 2-level DTC calculation profiles** | **S113 calculation profile** | **DriveSize** |
|---|---|---|---|---|
| **8.61 A** | 8.57 A | 7.69 A | 8.42 A | 9.52 A |
| **12.51 A** | 12.42 A | 11.21 A | 12.19 A | 12.4 A |
| **15.71 A** | 15.71 A | 14.18 A | 15.55 A | 16 A |
| **18.87 A** | 18.59 A | 17.12 A | 18.35 A | 20.01 A |

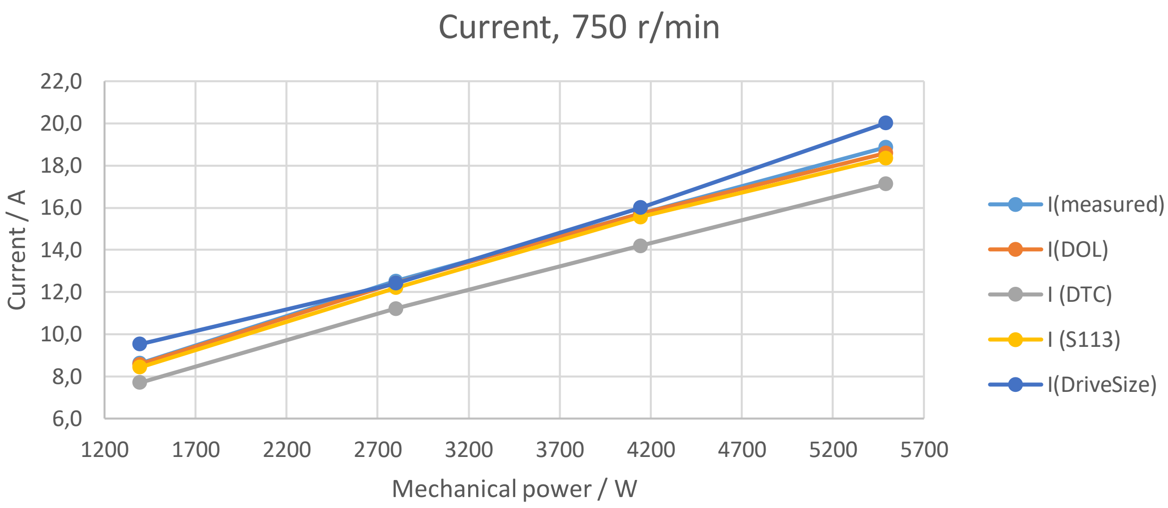


Figure 30. Measured and simulated current as a function of mechanical power at 750 r/min.

Table 2. Measured values of current at the rotational speed of 1500 r/min and simulated values with Adept and DriveSize.

| Measured current | Sinusoidal (DOL) calculation profile | Simple 2-level DTC calculation profiles | S113 calculation profile | DriveSize |
|---|---|---|---|---|
| **22.13 A** | 21.8 A | 20.58 A | 21.43 A | 21.4 A |
| **19.77 A** | 19.56 A | 18.59 A | 19.21 A | 19.5 A |
| **16.97 A** | 16.73 A | 15.59 A | 16.4 A | 16.8 A |
| **8.60 A** | 8.48 A | 7.37 A | 8.37 A | 9.17 A |

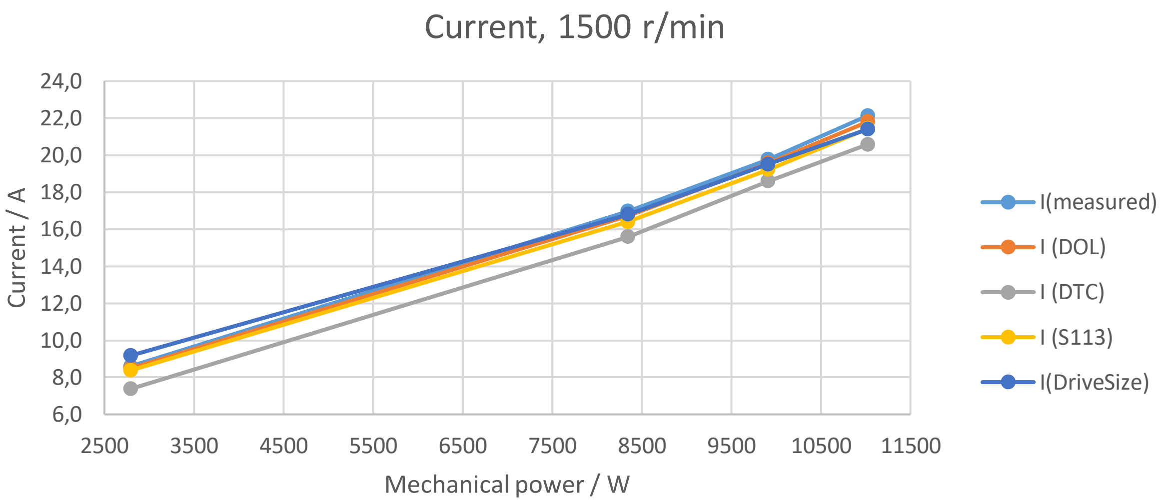


Figure 31. Measured and simulated current as a function of mechanical power at 1500 r/min.

## 7.2 Losses

Figure 32 and Figure 33 shows that none of simulated results match perfectly with original measured values. Results that are simulated with S113 calculation profile are closest to the original measured values of losses and DriveSize overestimates losses.

Table 3. Measured values of losses at the rotational speed of 750 r/min and simulated values with Adept and DriveSize.

| **Measured losses** | **Sinusoidal (DOL) calculation profile** | **Simple 2-level DTC calculation profiles** | **S113 calculation profile** | **DriveSize** |
|---|---|---|---|---|
| **170.7 W** | 165.2 W | 165.4 W | 192.9 W | 201 W |
| **308.3 W** | 287.5 W | 283.7 W | 333 W | 504 W |
| **451.5 W** | 423.2 W | 409.9 W | 482.6 W | 685 W |
| **627.1 W** | 580.5 W | 560.5 W | 642.5 W | 940 W |

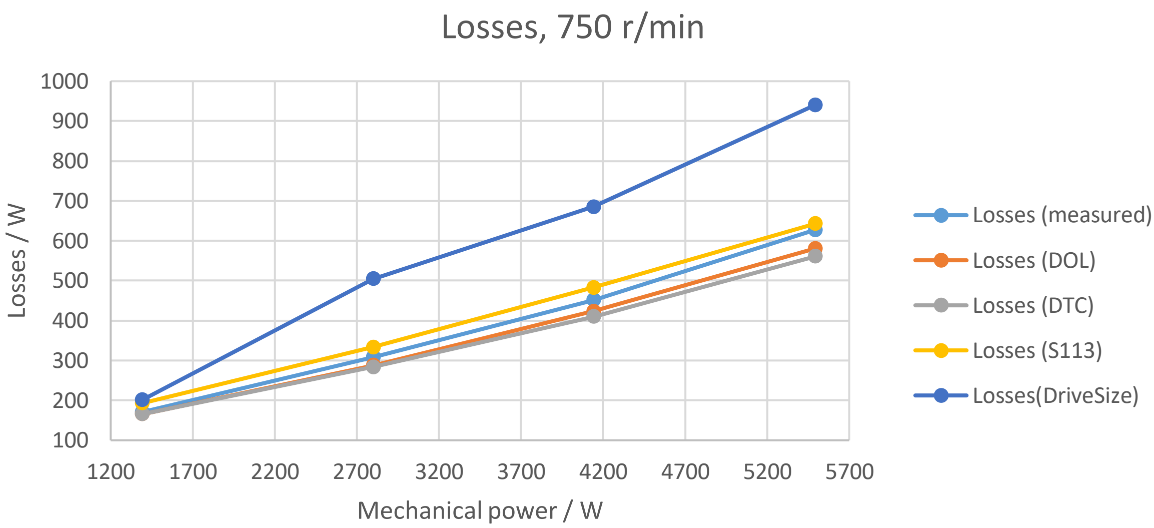


Figure 32. Measured and simulated losses as a function of mechanical power at 750 r/min.

Table 4. Measured values of losses at the rotational speed of 1500 r/min and simulated values with Adept and DriveSize

| **Measured losses** | **Sinusoidal (DOL) calculation profile** | **Simple 2-level DTC calculation profiles** | **S113 calculation profile** | **DriveSize** |
|---|---|---|---|---|
| **1064 W** | 957 W | 956.6 W | 987,4 W | 1480 W |
| **829.2 W** | 791 W | 814 W | 841.7 W | 1280 W |
| **646 W** | 621.4 W | 647.5 W | 691.7 W | 1140 W |
| **249.6 W** | 243.4 W | 261.1 W | 300.6 W | 557 W |


Figure 33. Measured and simulated losses as a function of mechanical power at 1500 r/min.

## 7.3 Efficiency

None of the results in Figure 34 and Figure 34 match with the original measured values of efficiency. In Figure 34 results that are simulated with DOL calculation profile are closest to the original measured values of efficiency and DTC calculation profile gives the most inaccurate values. In Figure 35 results that are simulated with S113 calculation profile are closest to the original measured values of efficiency and DriveSize gives the most inaccurate values.

Table 5. Measured values of efficiency at the rotational speed of 750 r/min and simulated values with Adept and DriveSize.

| Measured efficiency | Sinusoidal (DOL) calculation profile | Simple 2-level DTC calculation profiles | S113 calculation profile | DriveSize |
|---|---|---|---|---|
| **89.1 %** | 89.38 % | 87.24 % | 87.83 % | 87.38 % |
| **90.1 %** | 90.69 % | 89.01 % | 89.36 % | 90.32 % |
| **90.2 %** | 90.71 % | 89.2 % | 89.56 % | 90.2 % |
| **89.7 %** | 90.44 % | 89.38 % | 89.52 % | 89.27 % |

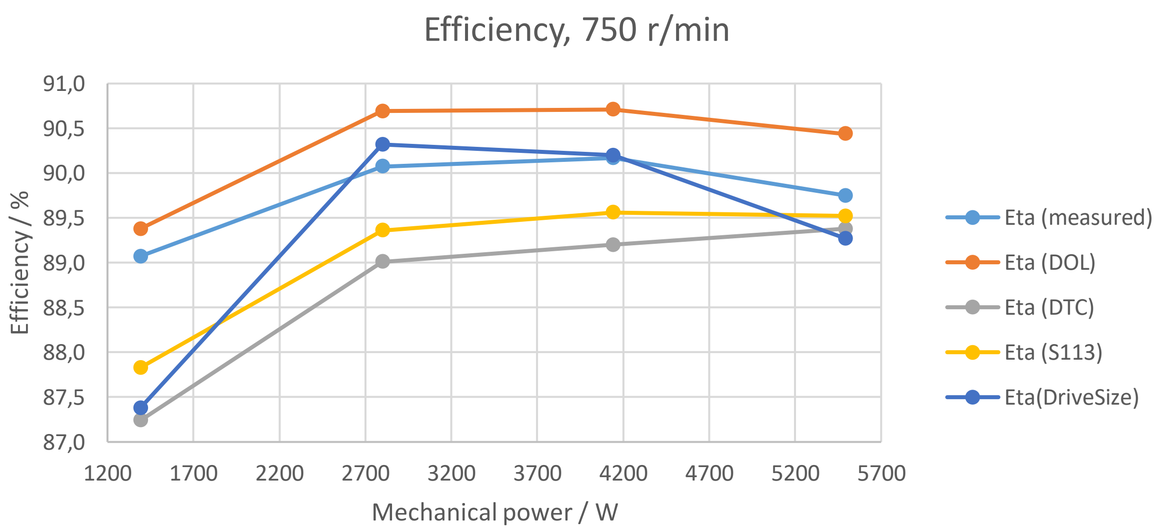


Figure 34. Measured and simulated efficiency as a function of mechanical power at 750 r/min.

Table 6. Measured values of efficiency at the rotational speed of 1500 r/min and simulated values with Adept and DriveSize.

| Measured efficiency | Sinusoidal (DOL) calculation profile | Simple 2-level DTC calculation profiles | S113 calculation profile | DriveSize |
|---|---|---|---|---|
| **91.2 %** | 92.0 % | 91.2 % | 91.8 % | 91.1 % |
| **92.3 %** | 92.6 % | 91.6 % | 92.2 % | 91.5 % |
| **92.8 %** | 93.1 % | 91.9 % | 92.3 % | 91.8 % |
| **90.5 %** | 92.0 % | 89.4 % | 90.3 % | 87.6 % |

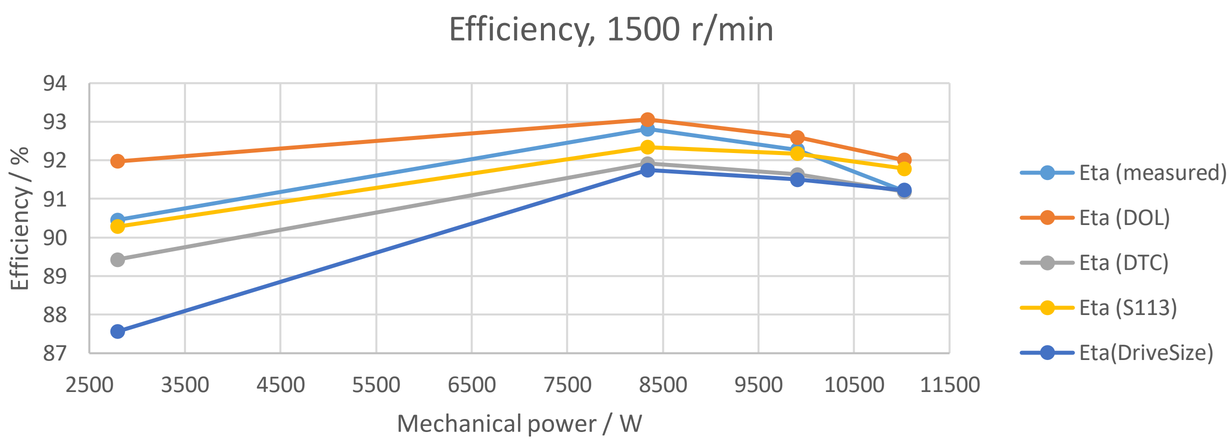


Figure 35. Measured and simulated efficiency as a function of mechanical power at 1500 r/min.

## 7.4 Power factor

None of the results in Figure 36 are close enough with the original measured values of power factor. However, the closest are the results, which are simulated with DOL calculation profile. S113 calculation profile gives the most inaccurate values. In Figure 37 results that are simulated with DOL calculation profile are also closest to the original measured values of power factor and DTC calculation profile gives the most inaccurate values. DriveSize does not determine values of the power factor.

Table 7. Measured values of power factor at the rotational speed of 750 r/min and simulated values with Adept and DriveSize.

| **Measured power factor** | **Sinusoidal (DOL) calculation profile** | **Simple 2-level DTC calculation profiles** | **S113 calculation profile** |
|---|---|---|---|
| **0.6575** | 0.6687 | 0.6764 | 0.693 |
| **0.6941** | 0.7049 | 0.7106 | 0.727 |
| **0.7221** | 0.7208 | 0.7199 | 0.737 |
| **0.7624** | 0.7791 | 0.7821 | 0,794 |

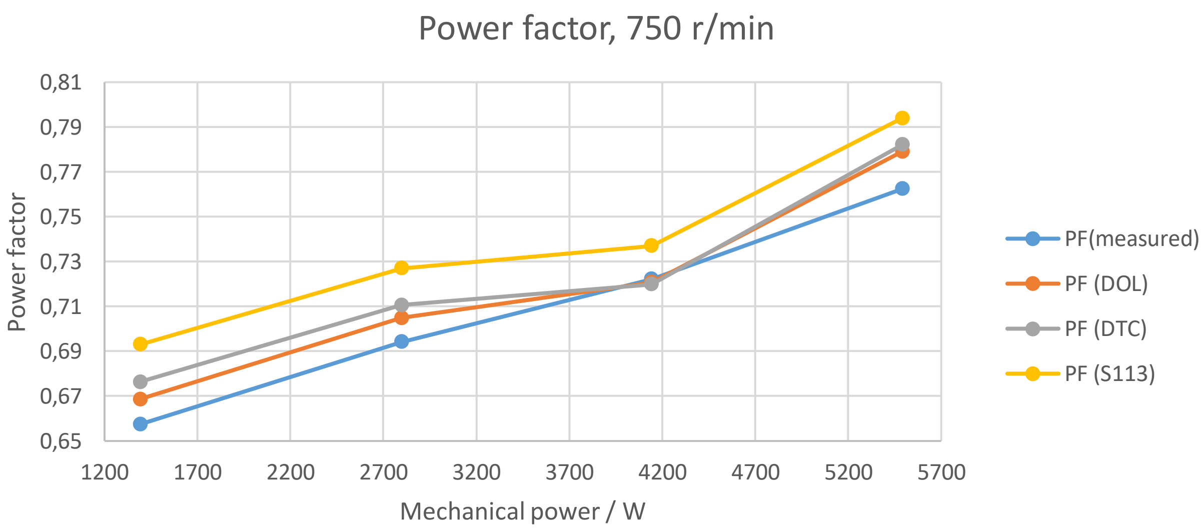


Figure 36. Measured and simulated power factor as a function of mechanical power at 750 r/min.

Table 8. Measured values of power factor at the rotational speed of 1500 r/min and simulated values with Adept and DriveSize.

| **Measured power factor** | **Sinusoidal (DOL) calculation profile** | **Simple 2-level DTC calculation profiles** | **S113 calculation profile** |
|---|---|---|---|
| **0.8450** | 0.8523 | 0.8693 | 0.865 |
| **0.8326** | 0.8402 | 0.8583 | 0.857 |
| **0.8084** | 0.8158 | 0.8431 | 0.837 |
| **0.6719** | 0.6698 | 0.7069 | 0.69 |

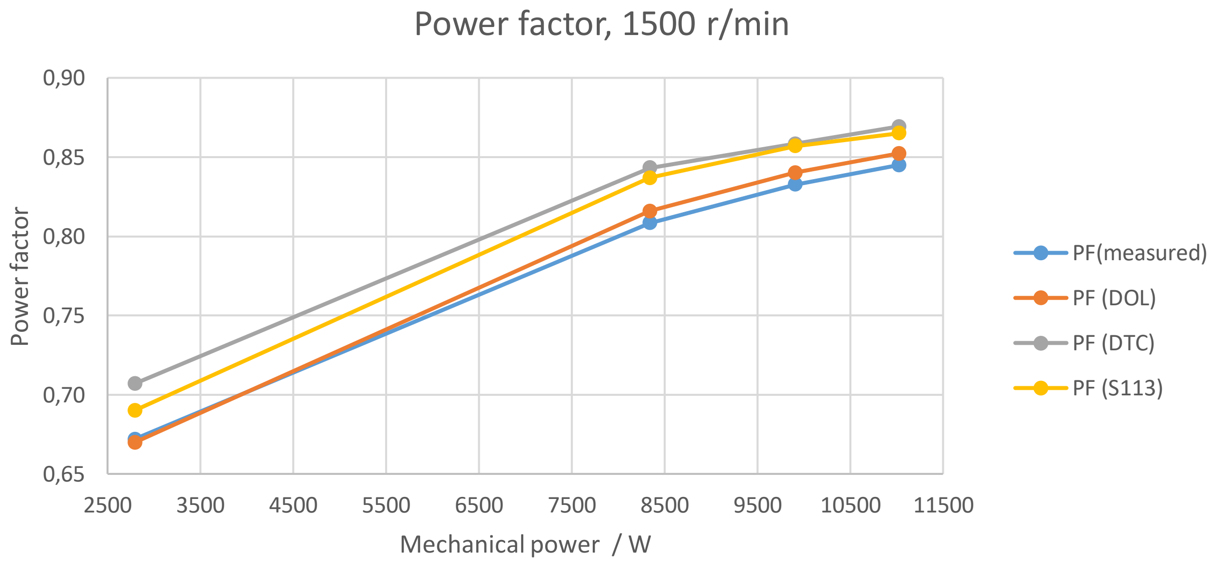


Figure 37. Measured and simulated power factor as a function of mechanical power at 1500 r/min.

## 7.5 Sum of Squared errors

In Table 9 and Table 10 are listed Sum of Squared errors (SSE) of all points. SSE is defined as follows (Spider Financial 2018):

$$\mathrm{SSE} = \sum_{i=1}^{n} (x_i - \bar{x})^2, \tag{19}$$

where $x_i$ is the actual observations time series and $\bar{x}$ is the estimated or forecasted time series. The closer the values are to zero, the closer the simulated values are to the measured values. The best results are marked with green and the worst results with red in Table 9 and Table 10.

Table 9. SSE of all points at 750 r/min.

| | Current | Efficiency | Losses | Power factor |
|---|---|---|---|---|
| **DOL** | 0.0868 | 1.244019 | 3435.3 | 0.000522692 |
| **DTC** | 7.9404 | 5.568499 | 6799.4 | 0.001022748 |
| **S113** | 0.4334 | 2.479139 | 2307.3 | 0.54651051 |
| **DriveSize** | 2.2384 | 3.155719 | 191645.2 | |

Table 10. SSE of all points at 1500 r/min.

| | Current | Efficiency | Losses | Power factor |
|---|---|---|---|---|
| **DOL** | 0.3727 | 5.271293 | 25675.76 | 0.000405687 |
| **DTC** | 13.8278 | 4.501153 | 17748.43 | 0.008550987 |
| **S113** | 2.237371 | 0.859553 | 9384.81 | 0.004553471 |
| **DriveSize** | 1.891509 | 19.53587 | 1393706 | |

Table 9 and Table 10 shows that DTC calculation profile and DriveSize have the worst calculation accuracy. It can be also seen that DriveSize overestimates losses.

# 8 DISCUSSION

Figures 30-37 and Tables 1-10 show that some of simulated values are close to measured values, however not comparable.

Possible reasons why the simulated values are not accurate enough:

- The calculation is based on the existing formulas. Possible reasons could be
  - The differences between calculated theoretical values and real-life results. For example with S113 calculation profile which is based on formulas and element method FCSmek, derive from the fact that the phenomena that are trying to be represented by calculations are more complicated than those that can be described with ordinary mathematics. An example of this is the differences that arise from the production of materials.
  - An exact accuracy is not always required.
- Differences in winding.
- Material variability.

Table 9 and Table 10 shows that DTC calculation profile and DriveSize have the worst calculation accuracy. From Figure 32, Figure 33, Table 9 and Table 10 can be seen that DriveSize also overestimates losses. Possible reasons for this are:

- The safety margin, which is needed to consider IEC 60034 tolerance for efficiency, might be too big for this case.

  - IEC 60034 standard gives the possibility to use quite large tolerance with nominal efficiency (15 % or 10 % more losses) and it leads nominal efficiency values that are higher than measured values. The catalog efficiency of motor is based on this standard. (ABB Oy, Drives 2011.) Sometimes the efficiency of motor is better than the value of catalog, but the promise is in accordance with the IEC standard.

  - In some cases customers demand guaranteed drive efficiency values in one or more operational points. Sometimes these values are linked to penalties so calculation should, at the same time, be as accurate as possible and realistic without high safety margins. There is always some tolerance in the manufacturing and measuring process which shall be recognized as well as the size of penalty. (ABB Oy, Drives 2011.)

- DriveSize will list the worst case losses at each point on report.
- Losses calculation is based on DriveSizes's own formulas.

Sinusoidal (DOL) calculation profile has the best calculation accuracy, steady offset and standard transition, but simulation requires a lot of time. S113 calculation profile has the second best calculation accuracy and it is much faster than DOL calculation profile. Reason why S113 is faster is that this calculation profile calculates the machine by using conventional readymade formulas so it just places the numbers into the equations and by doing so outputs the numbers. DOL calculation profile on the other hand divides the motor into tiny triangles and solves the problem based on field theories. This means that it iterates and runs the program for quite some time.

During simulations it was noticed that for example DriveSize does not give all information, like power factor and there was some defects in exist data. Changes are needed to get all required basic data from motors. If significant changes are made, for example to DriveSize to get more data or Adept to simulate faster, it is necessary to make changes also to ePID and Trinity that the collected data can be saved. Trinity is getting all data from Adept, then Trinity processes and send the data to Teamcenter, ElApp (ePID) and EA-database depending on mode.

# 9 CONCLUSIONS

The findings of the thesis are:

1. Currently there is not an internal tool that would calculate accurately the measured values.
2. Sinusoidal (DOL) calculation profile has the best calculation accuracy, steady offset and standard transition.
3. S113 calculation profile has the second best calculation accuracy.
4. S113 calculation profile is much faster than Sinusoidal calculation profile.
5. DTC calculation profile and DriveSize have the lowest degree of calculation accuracy.
6. DriveSize overestimates losses.
7. DriveSize does not give all information and there has some defects in exist data.
8. The values of a real machine cannot be estimated solely on the basis of calculations.

Based on the above finding, the following conclusions could be drawn:

- A good reference machines are needed for calibrating the calculations and to compare the actual machine values.
- To focus on S113 calculation profile instead of DOL calculation profile.
- Some changes to DriveSize and Adept. For example:
  - There is planned a model to calculate motor and drive losses, effectively and accurately, and it is going to be only for internal use.
  - Thermal time constant should be defined in Adept for all current IEC low voltage products.
  - The accuracy of the calculation algorithm should be improved in all respects, like temperature rises and losses.

# 10 SUMMARY

In March 2017, the International Electrotechnical Commission (IEC) published a new product standard IEC 61800-9, Ecodesign for power drive systems, motor starters, power electronics and their driven applications, which deals with the energy efficiency of power drive system (Danfoss 2017).

The purpose of this thesis was to investigate the ability of ABB internal tools to process engines that are manufactured according to the IEC 61800-9-2 standard. At the end of the thesis, it was looked how well the measured values and the simulated values matched each other and by doing this it was noticed that at the moment there is not an internal tool that would calculate accurately the measured values. To simulate measured values Adept was used, where the calculations were done with Sinusoidal (DOL) and Simple 2-level DTC calculation profiles, and S113 calculation profile. The same values were also simulated with DriveSize. Results showed that Sinusoidal (DOL) calculation profile has the best calculation accuracy and S113 calculation profile has the second best calculation accuracy and is much faster than DOL calculation profile. DTC calculation profile and DriveSize have the worst calculation accuracy.

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