The Motor Systems Tool
 - An outcome of Task B of the 4E EMSA project

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Abstract

The goal of Task B of the 4E EMSA project is the creation of an online Technical Guide for the proper design of Motor-Driven Systems.

A newly developed Motor Systems Tool will be created and used to analyze such Task B topics as motor selection (size and type), control system design, transmission system losses and primary machinery (fan, compressor & pump) operating characteristics.   Various equipment configurations will be analyzed with the tool's capabilities demonstrated through consideration of practical examples.. This tool is designed to assist users to develop a proper and energy efficient design of complete motor systems.   An optimal design would meet process requirements while not oversizing components which is a tendency often seen with excess energy use as a direct consequence.

This paper will show why the tool is useful for motor system design, how it is constructed and how it works.

The Motor Systems Tool
Task B has, in corporation with Danish public means, produced a new, impartial calculation tool in which the efficiency of complete motor systems is calculated. The aim was to create a tool which is easy to use, available for a broad audience, and that gives good technical support for choosing components and designing an optimal motor system.

The tool takes all four main parts of a motor system into account including primary load, transmission, motor and controls.   The complete system efficiency is determined by calculating the load and efficiency for each system component. The Motor Systems Tool is unique because it dynamically calculates the impact in the complete chain when changing system speed, duty point or any system component.

The "engine room" of the tool contains standardized models for pumps, fans, compressors etc. as well as belt drives, gearboxes, motors, variable speed drives and combinations of these.

This paper shows and describes the Motor Systems Tool with a few calculation examples combined with illustrations of the standard models used.

The Motor Systems Tool is available for download for free
 – *registration required* – at the EMSA website: http://motorsystems.org

Introduction

Optimizing motor driven systems is about choosing the right components and getting them to work well together - thereby achieving maximum energy efficiency of the entire system.

A motor driven system is defined as the entire system from the wall outlet to the power delivered by the application (pumps deliver hydraulic power). This definition doesn't take into consideration whether, for example, the airflow and pressure drop in ducts are optimal for a ventilation system, or whether the insulation of a cold storage room is suitable; neither does it provide information as to whether the pressure levels of an air compressed system are optimized and leakage is minimal, or whether the rate of flow in a pump system is optimal.

In other words, conditions which are related to a process separated from the motor driven unit are not included in the definition of a motor driven system.

A motor driven system consists of the following four components:

- The driven machine – load (pump, fan, compressors, conveyor belts etc.)
- The transmission – if any (belts, gears, gear motor etc.)
- The motor
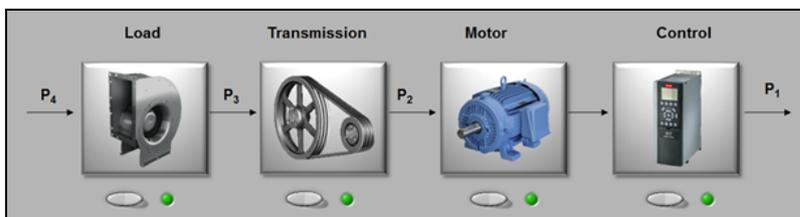- The drive (soft starter, frequency converter or other VSD)

Figure 1 Components of a motor driven system

There has been a long tradition in Denmark of looking at entire motor driven systems as a hole, trying to optimize, when taking the respective influences of all parts into account.
Several papers have also been published on the subject – including a paper at the most recent EEMODS ´09 where Mr. Claus Hvenegaard presented "Small Changes – Big Savings!" [1]

This Danish work supplements Task B in the EMSA work perfectly as the headline is Technical Guide for Motor Systems, which again was the major reason for Denmark to take the task leadership of task B within EMSA.

The next logical step within systems optimization was to find/create a PC tool as a "playing ground" for all interested, where the user has the ability to change components and component efficiencies on the fly and see the result immediately – and make this tool easy to access.

Having screened the market for existing tools on the subject the decision was made to make our own solution as it proved very difficult to find anything complying with the wishes of the workgroup of task B.

The Motor systems Tool

The keywords when trying to build a software package for calculating complex motor systems included words like: user friendly, easy access, keep it as simple as possible (kiss) which turned out to be a rather difficult task. Therefore the compromise inside the "engine room" is simplified models of standard components based on real life measurements during the last decade in former energy projects, carried out at the laboratories of the Danish Technological Institute.

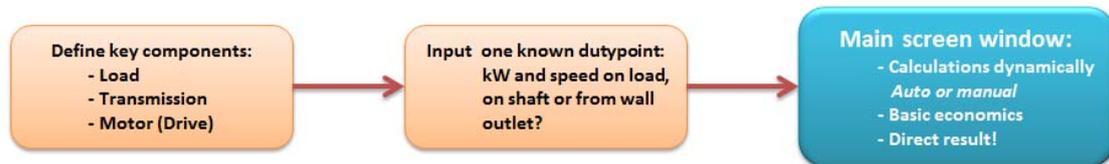A simple flow chart was carried out to define the program structure:

Figure 2 MST flowchart

When selecting load and motor – suggestions are provided by the tool if you're in doubt regarding your system. Quite often in real life the available information is limited.
In this way you can get a very good estimation of your system performance – even with very little knowledge about your actual system.

Stage 1 – Input the key components

The intro screen of The Motor Systems Tool (MST) lets you pick your components in random order. Below is the screen for load selection where the input is one of four possible torque profiles – there's help text next to selections for guidance:
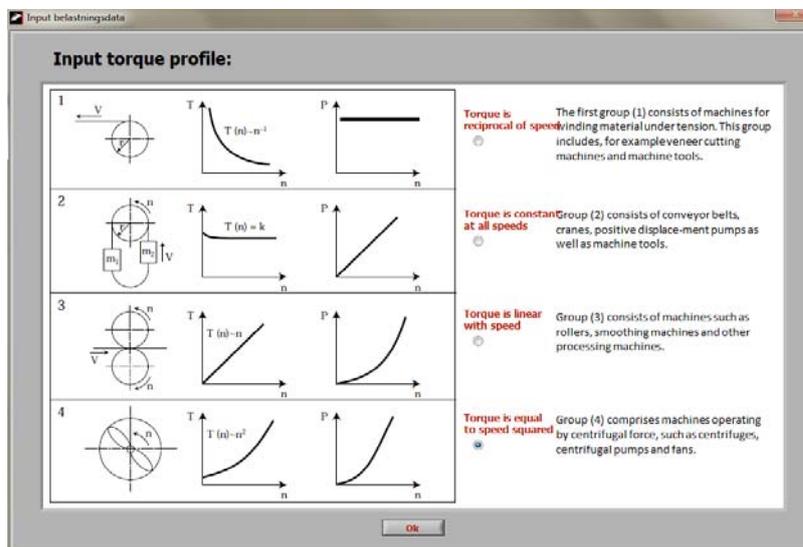

Figure 3 Load selection screen of MST

Motor and drive

When selecting the motor on an existing system, it's not always the case that the motor nameplate information is available. When possible the user can input the actual motor nameplate data but when such information is not available, the user has the possibility of choosing a standard motor model (from the IEC 60034-30 table definition, IE1, IE2 and IE3 can be selected). This is of course only a good guess, but it ensures that the user can continue the program and proceed to the system evaluation.
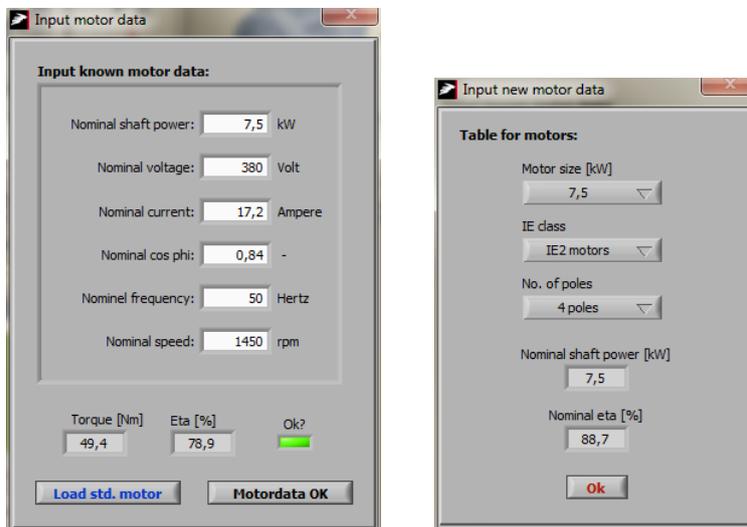

Figure 4 Motor nameplate input - alternatively selection of a standard motor

"Nominal values" are equivalent to "full-load values"

After the motor selection screen the user must input the method by which the motor is connected. The possibilities right now are: direct on-line (D.O.L.), soft starter and frequency converter with both constant flux and automatic energy optimization.

Transmission

Selecting transmission can be a bit more complicated. There are many rules of thumb, good suggestions, good practice (experience!) when it comes to - belt drives. Therefore, the MST project group decided that on belts the user needs to have some knowledge. The user has to decide on quite specific information on the belt drive, otherwise the assumptions inside the MST calculations would be too extreme – and perhaps impossible.

Pop ups are provided with suggestions, good advice and so forth but the user has to take a stand in terms of making some specific choices on the belt drive machines.
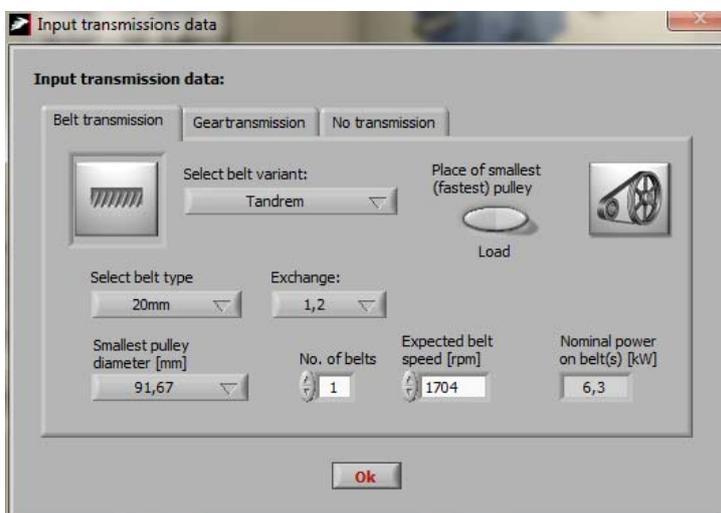

Figure 5 Belt transmission selection

Stage 2 – Input the duty point

When calculating overall efficiency for a complete motor driven system the general idea of The Motor Systems Tool, right from the start, has been to base all calculations on one and only one known duty point. The tool user is free to choose this duty point, based upon equipment design and operating criteria, but all calculations originate from this point. Therefore stage 2 of the Motor Systems Tool is to define a known duty point in the initial phase of the program.
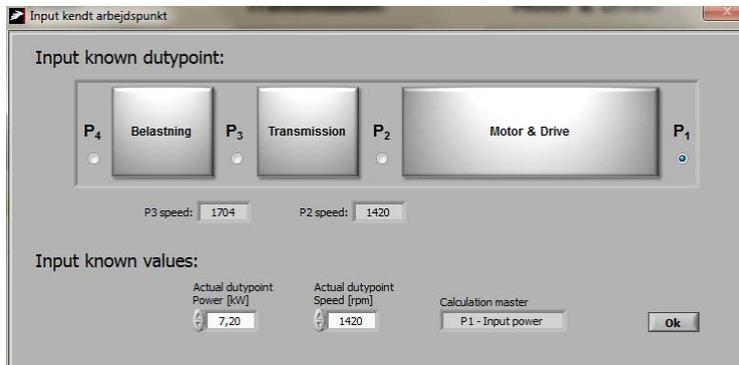

Figure 6 Input the initially known duty point of the system

In the above example the known duty point is the wall outlet where a power consumption of 7,2kW has been measured and the user takes "a good guess" on the speed of the system (speed measurement on a running machine can be complicated)

Having overcome these few steps the user is now presented with the main screen of the Motor Systems Tool:
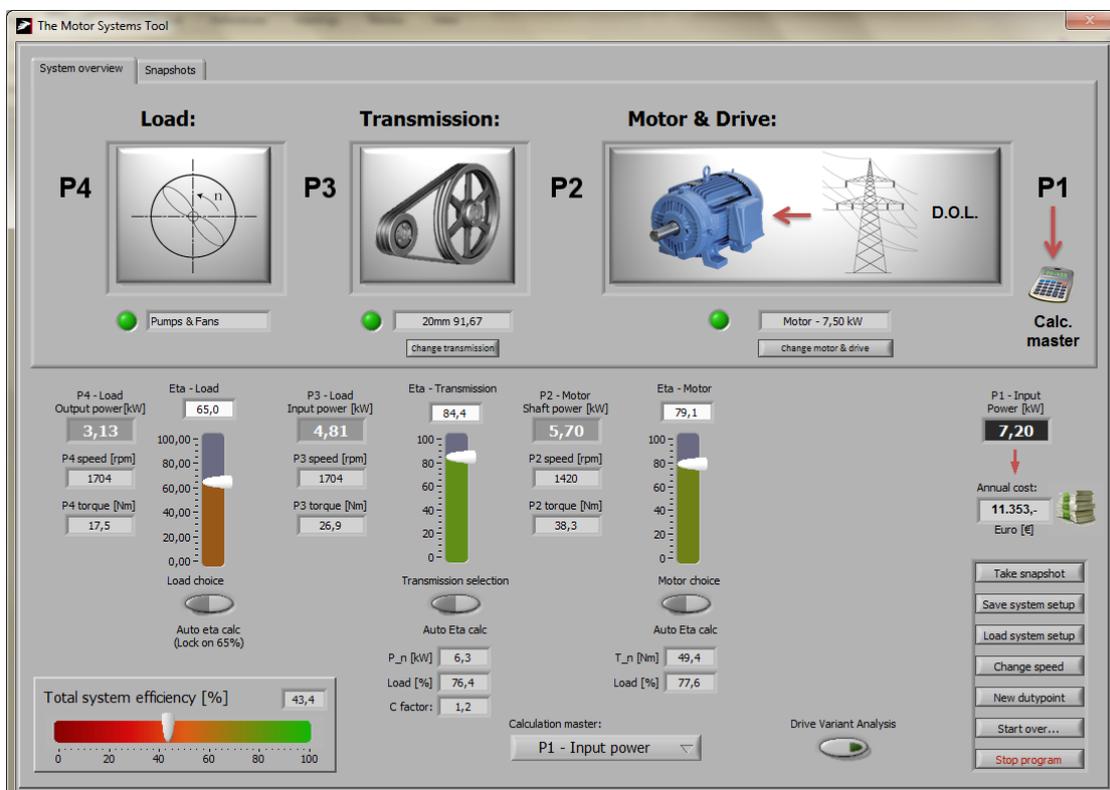

Figure 7 Main screen of The Motor Systems Tool

Stage 3 – The Main Screen

At first glance, a lot of information and numbers are provided, but looking closer, the upper half of the screen is simply a repetition of the user input data with only the lower half giving new information. In the above example the known duty point was P1 input power/wall outlet and for this reason the power field here is in a different color combined with an illustration above.
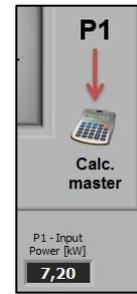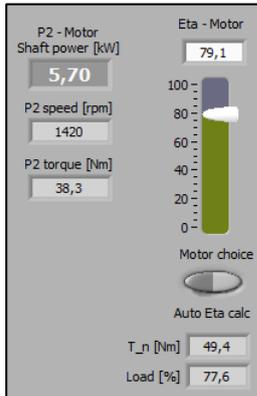

Figure 8

Figure 9

Going left from this point the user encounters a column of the calculated motor conditions at the actual duty point.

From the top the user see's the calculated efficiency as a precise number. Below this there's a slide for illustration. Background color of the slide changes dynamically if efficiency drops. This slide can be used for manual input of motor efficiency if selected below on the "motor choice" button.

Below this button the calculated nominal torque of the selected motor and the actual load of the motor at the actual duty point are stated.

The load here is calculated as: $T_{P2}/T_{mot-nom} \cdot 100\%$, where $T_{P2} = P_{P2}/\omega$

Left of the "motor column", P_2 (motor shaft) power, speed and torque are calculated and stated.

The next column is about the selected transmission. If no transmission is selected this section will be "grayed out".

In this case the calculated efficiency is stated as an exact number and shown on a dynamic slide. Below these, the nominal power, actual load and C-factor for the belt drive are visible. C-factor for belt drives is a type of load factor that is directly linked to the motor connection, number of running hours per day and the kind of machine being run by the belt. (For instance, D.O.L. motors have higher C-factor than motors started by soft starters as they treat the belt tougher).

The C-factor is calculated automatically within the Motor Systems Tool.

$P_{belt\ nominal}$ and $Load_{belt}$ are calculated using the same method as with motors.
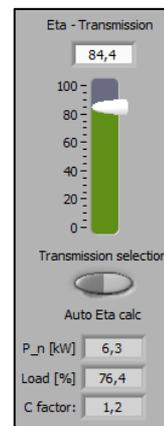

Figure 10

At the left of the main screen, P4 (output of the driven machine), machine efficiency and P3 (input to the driven machine) conditions are stated.
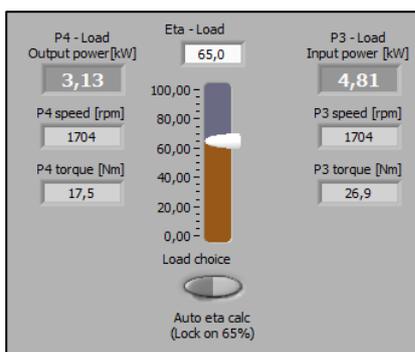
Figure 11

P3 is the output from the transmission calculation and at this point speed is known so torque is easily deducted from this information.

The efficiency of the load – the driven equipment – is at this point impossible to calculate. The current version of the Motor Systems Tool does not contain an algorithm for the driven equipment. For this reason, when the user selects "automatic", the program assumes an efficiency value of 65%. If the user knows better (from experience, real life measurements or maybe even curves or diagrams) it's possible to enter the true constant efficiency of the driven equipment.

In the example case 65% is chosen and the final output power from the driven machine is 3,13kW. (Which would be hydraulic power had it been a pump driven)

Compared to the input power which in this case was 7,2kW, the 3,13kW corresponds to a total calculated system efficiency of 43,4%. This number is calculated by The Motor Systems Tool dynamically and is shown at the lower left corner of the main screen:
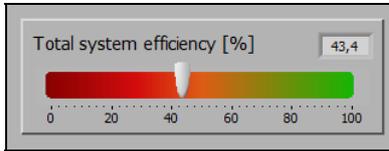

Figure 12

Whether this number is considered high is very individual and depends on the driven equipment type and size, system design and operating characteristics and surrounding conditions. As a rule of thumb, system efficiency's below 50% should be revisited as cost-effective efficiency improvements are most likely available.

Room for improvement?

One of the features in the Motor Systems Tool is an "on the fly" drive analysis.
Pushing this button launches a pop-up screen which shows the current duty point (calculated from current shaft conditions, speed & power) but with drive variants. The Motor Systems Tool automatically selects three standard motors nearest in kW size for comparison. The user even select frequency converter included for comparison. This gives the user an idea of drive variants in this one duty point. If more duty points are desirable the user has to use "energy analysis" including curve of duration etc. elsewhere in the program.
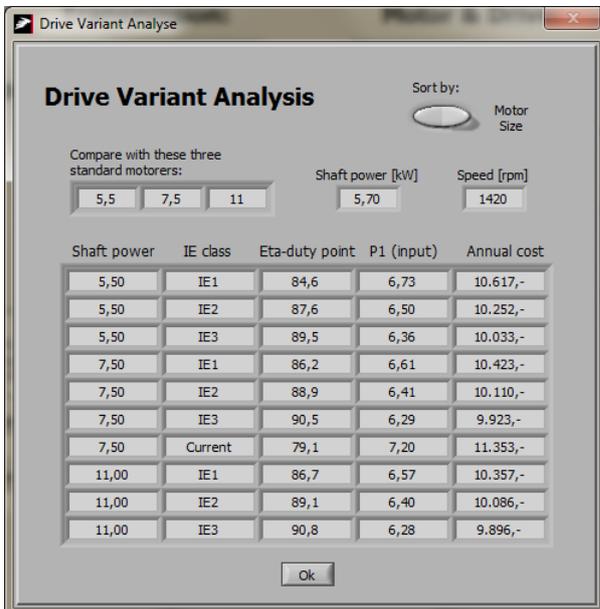

Figure 13

In the above example – selecting an IE2 7,5kW standard motor instead of the current motor would bring annual energy costs down by approximately 1.243,- €

The currency calculus for this is input by pushing the "money stack" icon at the right side of the main screen which brings up the following screen:
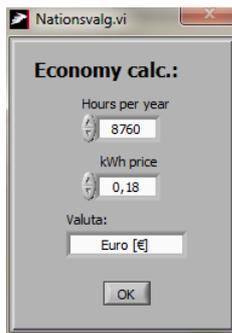

Figure 14

In this screen it is possible to define your own custom assumptions regarding annual running hours, price per kWh and currency.

Other features of The Motor Systems Tool

Another feature of The Motor Systems Tool is the possibility to vary the speed at P4 based on the load curve input at the beginning of the program.

Current example:
According to general theory on pumps and fans (the laws of affinity) torque variation is equal to speed variation squared. This basically means that reducing speed to one half requires only one eighth of the power consumption.

In the example to the right speed is reduced to 1080 rpm from 1704 rpm which leads to a power reduction from 3,13kW to 0,8kW given by the following formulae:

$$T_{new} = \left(\frac{n_{new}}{n_{old}}\right)^2 \cdot T_{old} = \left(\frac{1080\ rpm}{1704\ rpm}\right)^2 \cdot 17,5\ Nm = 7,03\ Nm$$

$$P_{new} = T_{new} \cdot \omega = \frac{7,03\ Nm \cdot 1080\ rpm \cdot \pi}{30} = 795\ Watt$$
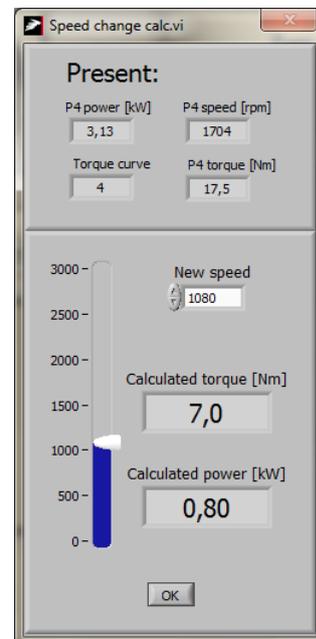
Figure 15

At any given time it's possible to save a "snapshot" of the current duty point. When doing so all of the relevant data (P4 → eta load → P3 → eta trans. → etc.) are put into a table. This table can later on be used as the basis for an energy analysis (with another motor for instance). The table can be saved and loaded as a normal tab separated file which can be handled by any external program as well.

The user can, when using this table, build up a collection of duty point's describing a system in different situations during a day, a month or even a whole year and from this deduce a curve of duration that very quickly will reveal unnecessary stand-by power, excessively long periods of running at specific duty points and other problems.

This is a quite efficient tool for analyzing existing systems.

Figure 16 Energy analysis screen – same duty points, better motor

Within the screenshot:

The Motor Systems Tool

System overview | Snapshots

Snapshots from user: Open file | Save file | Clear table | Sort table   Recalc new motor type

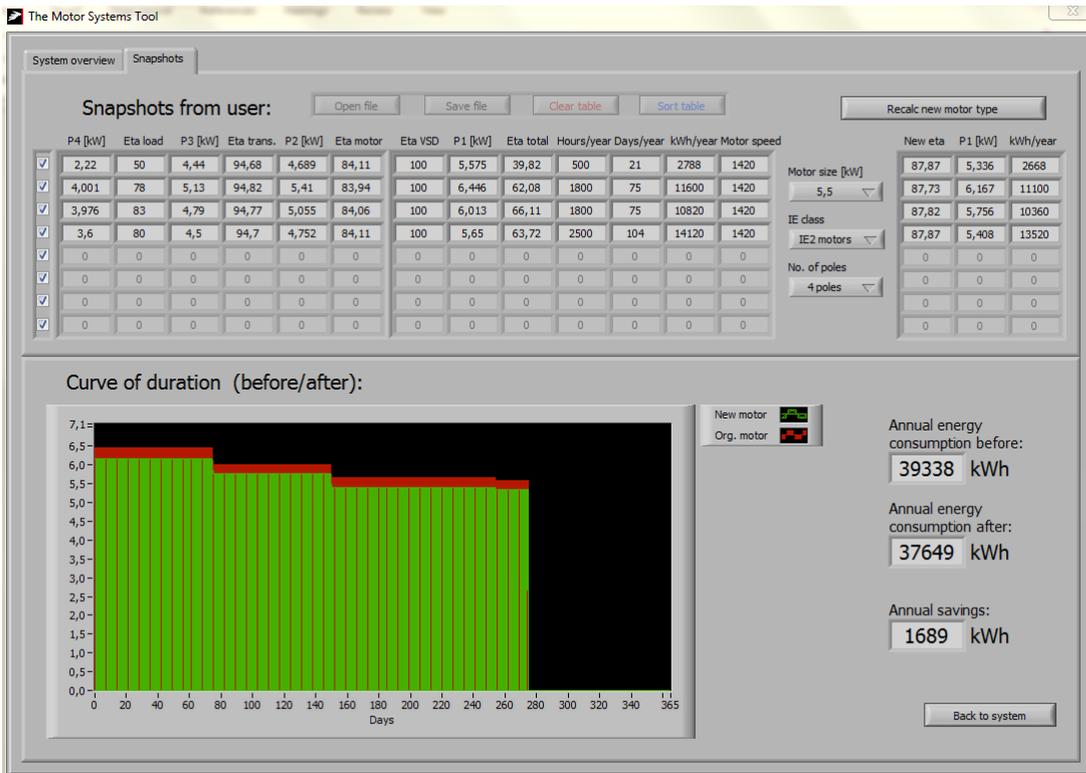| P4 [kW]	Eta load	P3 [kW]	Eta trans.	P2 [kW]	Eta motor	Eta VSD	P1 [kW]	Eta total	Hours/year	Days/year	kWh/year	Motor speed	New eta	P1 [kW]	kWh/year
2,22	50	4,44	94,68	4,689	84,11	100	5,575	39,82	500	21	2788	1420	87,87	5,336	2668
4,001	78	5,13	94,82	5,41	83,94	100	6,446	62,08	1800	75	11600	1420	87,73	6,167	11100
3,976	83	4,79	94,77	5,055	84,06	100	6,013	66,11	1800	75	10820	1420	87,82	5,756	10360
3,6	80	4,5	94,7	4,752	84,11	100	5,65	63,72	2500	104	14120	1420	87,87	5,408	13520
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Motor size [kW]: 5,5
IE class: IE2 motors
No. of poles: 4 poles

Curve of duration (before/after):

New motor / Org. motor

Annual energy consumption before: 39338 kWh

Annual energy consumption after: 37649 kWh

Annual savings: 1689 kWh

Back to system

Conclusion

The above mentioned features along with many more are only a part of the Motor Systems Tool – One of the outcomes of the EMSA work in task B: Technical Guide for Motor Systems.

The Motor Systems Tool is maybe the first tool ever to analyze entire motor systems as a whole, dynamically calculating efficiency changes in a user friendly windows-based environment.

The Motor Systems Tool allows "on the fly" changes and shows results, good or bad, instantly, and it handles both new and retrofit systems and even accepts partial inputs.

The Motor Systems Tool is impartial using "self – made" standardized models for all implemented components, thereby helping to ensure that no specific products or manufactures are being favored over others. This also means that results are general rather than exact.

The Motor Systems Tool is the obvious choice to use to inform and train not only engineers working in industrial plants but also energy consultants, original equipment manufacturers, trainers and teachers at schools and university's as well as government officials responsible for creating policy instruments.

Finally – best of all – The Motor Systems Tool is free of charge and it can be downloaded from the EMSA web-page http://motorsystems.org

The software comes in a self-extracting zip file and installs itself with a just a few clicks.
The only thing required is a registration on the EMSA page – for statistical purposes only

Summary of calculation models:

The present version of The Motor Systems Tool includes the following calculation models below. The tool can handle any combinations of these.

Load:
4 variations of torque vs. speed: $T(n) \sim n^{-1}$, $T(n) \sim n^{0}$, $T(n) \sim n^{1}$ and $T(n) \sim n^{2}$

Transmission:
Direct coupled, belt drives and gear motors.

Motor & Drive:
AC squirrel cage asynchronous motors 50 Hz models, D.O.L., connected through soft starters, VSD constant flux and VSD with automatic flux optimization.

For more detailed information regarding algorithms within the calculation models of the Motor Systems Tool please consult the manual of the program.

References

[1] Hvenegaard, Claus M. *Small changes – Big savings!* In: Proceedings of the 6th International Conference EEMODS '09: Energy Efficiency in Motor Driven Systems, Nantes, FRANCE, 14-17 September 2009, EUR 24142 EN/1 - 2010. Can be downloaded from: http://re.jrc.ec.europa.eu/energyefficiency/events.htm

[2] The Motor Systems Tool manual – available at the EMSA webpage, also a part of the package when installing The Motor Systems Tool

[3] EMSA webpage: http://motorsystems.org

[4] *Tool for optimization motor driven systems*, research project report (PSO 341-014). Carried out by Danish Technological Institute in cooperation with Lokalenergi, Danfoss, Lemvigh-Müller and Arla foods, 2010-11.

[5] *System Optimization of Machine Systems Driven by Electrical Motors*, research project report (PSO 338-009). Carried out by Danish Technological Institute in cooperation with Lokalenergi, Danfoss, Lemvigh-Müller, A-Vent and Arla foods, 2008.

[6] *Den lille blå om Systemoptimering [The Small Blue Book on System Optimization]*, ELFOR [The Association of Danish Energy Companies], Jørn Borup Jensen (ELFOR). Henrik Lykke Lilleholt (Lemvigh Mühler). Claus M. Hvenegaard, Hans Andersen (Danish Technological Institute). 2005.

[7] IEC 60034-30: Rotating electrical machines: Efficiency classes of single-speed, three-phase, cage-induction motors

Acknowledgement