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INCREASING THE ELECTRIC MOTORS EFFICIENCY IN INDUSTRIAL APPLICATIONS

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ABSTRACT: Electric Motor Driven Systems (EMDS) account for around 65% of the electricity consumed by EU industry. Switching to energy efficient motor driven systems can save Europe 202TWh in annual electricity consumption [1]. EMDSs are the single largest end-use of electrical energy, consuming more than twice as much as lighting, the next largest end-use. This excess energy consumption represents an unnecessary 79 million t/yr of CO_{2eq} emissions. If CO_2 emissions are reduced, it will help in today's problems regarding climate change. By introducing several energy schemes, costs can be significantly reduced. The aim of this paper is that by conducting case studies on the Maltese manufacturing industry and carry out several experimental tests recommend certain measures to increase the electric motors' efficiency in industrial applications.

Keywords: Efficiency, Energy Savings, Electric Motors

1 INTRODUCTION

Electric motors convert electrical power into mechanical power within a motor-driven system. The majority of the electricity used by Electric Motor Driven System (EMDS) is consumed by the electric motor itself. A very small amount is used to power control functions or other ancillary circuits.

The idea of this paper is to analyse in detail the operation of the electric motor within the driven system and hence come up with several measures in order to increase the efficiency. This paper is concerned with conducting case studies in the Maltese manufacturing industry so as to increase the efficiency of their motor driven systems. Injection Mould Machines (IMMs) are machines which consume a lot of energy and hence they were considered for analysing in detail their operation. There are around 300 to 400 IMMs in the major Maltese manufacturing plants. Two large plants were selected for detailed energy analysis to obtain the motor driven system's load profile. The measurements were carried out on the induction motor used to drive the hydraulic system of the electrohydraulic IMM. Another plant was chosen for other EMDS such as conveyers, elevators, compressors, mixers, cubers etc. Having the load profiles, investigation of potential energy saving solutions could be carried out. It can be shown that the efficiency of an electric motor increases as the load is increased as is shown in Figure 1. Off the shelf solutions exist by replacing the standard motor with a high efficient motor and/or by introducing a motor energy controller. A review of the diverse motor standards was carried out and investigation of motor energy controller and energy efficient motor at local industry was performed. A number of motors have been targeted for monitoring based on the motor power rating, the number of the same machine types, operating hours per year, energy usage per year and age. The data captured is analysed to monitor the loading of the machines hence the potential for energy savings can be estimated. Furthermore, a lab test rig has been developed to be able to emulate the industrial load through testing of intelligent energy controllers.

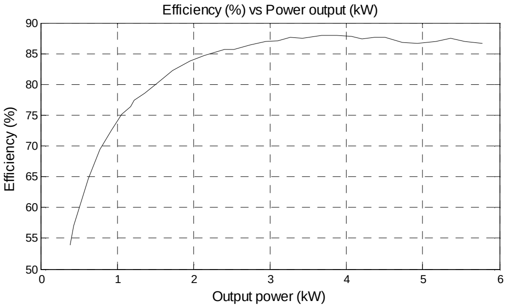

Figure 1: The efficiency vs power output of a 5.5kW motor. The efficiency is increased as the load increases. (Experimental result in laboratory)

2 BASICS OF INJECTION MOULD MACHINES

Injection moulding is a major part of the plastics industry and is a big business world-wide. Although there exists many different types of IMMs, based on factors such as quantities, sizes, shapes, product performance, an IMM has three basic components which are: *The injection unit, the* *mould* and *the clamping system*. There are IMMs which attached to them have a hydraulic accumulator. This is a mechanical device that acts as a pressure reservoir when high output capacity is needed for fast injection and thus it affects the load profile of the electric motor drive as can be seen later on [2]. The process of this particular machine is as follows. Granules of plastic powder are fed into a hopper and then, a heater, generally known as the plasticator, heats up the tube to a fixed temperature. After that, a hydraulic motor turns a screw thread which injects the material into the mould. The material remains there under pressure, cools down and then the mould opens and the object formed is ejected. This cycle is repeated all over again. The process loads the induction motor which drives the hydraulic system pump motor. According to the different stages of the process described, the motor is loaded accordingly. This can be verified by the plot shown in Figure 2.

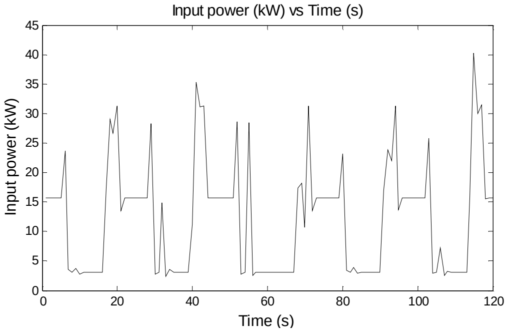

Figure 2: Typical load profile of an IMM showing the different loadings according to the process of the machine.

As can be clearly seen from Figure 2, a pattern is formed. Note that if the hydraulic accumulator is connected to the IMM, the load profile will not follow any pattern as can be verified in Section 4.

3 METHODOLOGY

A collection of data at the three plants selected has been carried out in order to obtain a general idea of the motors used in industry. The data collected included the type of drive, the quantity of the same machine types, operating hours per year, energy usage per year, age and the motor rating.

Several EMDSs were identified for power measurement of their electric motors. The main criteria for the selection of the machines to be monitored were: the quantity of the same machine types in the respective plants; the motor ratings; and whether the machines were going to be used more in the future. The list of the EMDS identified for monitoring with a power meter is in Table 1. IMMs A and B are from one plant, IMMs C and D are from another plant; both from the plastics industry, and the elevator is from a plant which manufactures animal feeds. The latter has several systems to transport food from one location to another within the premises. The elevator is a simple EMDS which is used for transportation. The load profile is much simpler than the IMM since the motor is either at *high load* or at *low load*.

Table 1: List of the EMDS selected for further measurements

EMDS	*Motor rating (kW)*	*Operating hrs. / yr*	*Quantity*	*Acc.*
IMM A	22	6000	8	No
IMM B	30	6000	6	No
IMM C	30	4000	23	Yes
IMM D	22	4200	22	Yes
Elevator	7.5	N/A	11	--

IMM A and B are both one-colour machines but they have different clamping force capabilities of 1500kN and 2000kN respectively. The difference in the clamping force explains the difference in the motor rating. These types of IMMs work almost 24 hours a day all year long and do not have the presence of the accumulator. The ‘quantity’ column represents the amount of the same EMDS type within the same plant. On the other hand IMM C and IMM D have the same rated clamping force of 600kN, however, they are both capable of producing more than one colour. IMM A is a three-colour machine while IMM B is a two-colour machine. This clarifies the difference in the motor ratings. Both machines have the accumulator.

4 ANALYSIS

4.1 Injection Mould Machines

This part of the paper analyses the monitoring of the IMMs (A, B, C and D) and studies the possible measures which can be done to improve the efficiency on such machines. Load profiles which resulted from the machines’ monitoring are available in this paper.

A sample for all the types was selected to monitor the power by a specialised power meter. The sample varies according to the quantity of the machines at the respective plant. Every measurement of the IMMs was of two hours and the cycle times considered vary between 20 and 60 seconds. The results show that different cycle times do not affect the energy consumption.

A typical load profile of IMM A is shown in Figure 3 which is very similar to Figure 2. Figure 3 illustrates that the induction motor always consumes a minimum constant amount of power which is being defined as the base load. This load exists even when the IMM is not producing any products and it never falls below a particular value. Moreover, when the IMM produces a fault the motor keeps on operating at this base load. The profile shown in Figure 3 is of IMM A, however the profile of IMM B is similar since both do not have the accumulator.

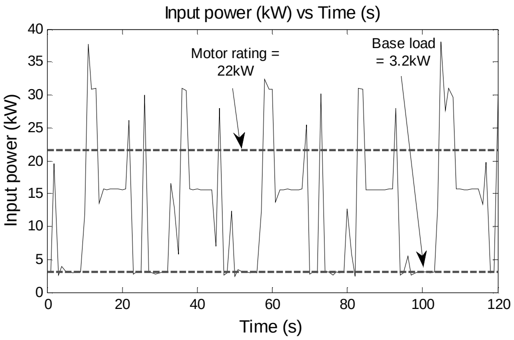

Figure 3: Typical load profile of IMM A showing the base load and the motor rating

Note that the motor operates most of the time at the base load which is not close to the motor rating. This introduces inefficiencies as was concluded from Figure 1.

The load profile of IMM C is illustrated in Figure 4, where it can be clearly seen that the pattern discussed earlier is not followed. This is due to the presence of the accumulator. Note again here the values of the base load and of the motor rating. It is concluded that, here again, the motor operates most of the time at low load.

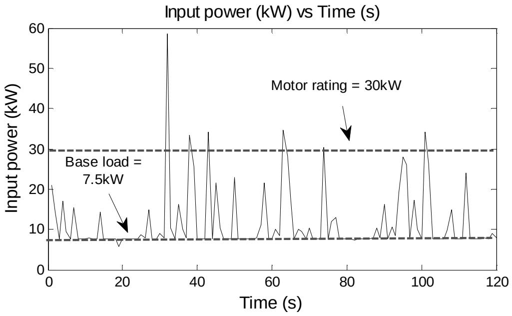

Figure 4: Typical load profile of IMM C showing the base load and the motor rating

The operation of the base loads of IMMs A and B are similar since the load factors are close (14.5% and 15.7%) however when considering the average load, IMM B is operating more efficient than IMM A since the load factor is higher. The results are summarized in Table 2. Both machines are equipped with individual capacitors and so the average power factor is close to unity, especially IMM A.

Table 2: A table showing the typical base loads, average loads, maximum loads and power factor of the IMMs. The values in the brackets are the percentages of the motor ratings

IMM	*Base load (kW)*	*Average load (kW)*	*Max load (kW)*	*Ave. p.f.*
IMM A	3.2 *(14.5%)*	9.9 *(45.0%)*	43.9 *(199.5%)*	0.99
IMM B	4.7 *(15.7%)*	15.9 *(53.0%)*	62.8 *(209.3%)*	0.85
IMM C	7.5 *(25%)*	12.4 *(41.3%)*	74.2 *(247.3%)*	0.54
IMM D	3.5 *(15.9%)*	8.1 *(36.8%)*	31.9 *(145.0%)*	0.50

The base load factors of IMMs C and D are 25% and 15.9% respectively. Although they differ between each other, they are still low. Even when considering the average load, it can be concluded that the electric motor is operating most of the time at low loads. These machines are not equipped with Power Factor Correction (PFC) capacitors as one can see from the values of the power factors. Although it appears that the motors are overrated, there are certain instances where the motor is loaded up to twice their rating. This loading limits the choice of the motor power.

A study was carried out on the on the machine's timings when the machine operated at different power levels. Every second was categorised into sections according to the instantaneous power. An example is given in Figure 5 where it can be shown that, for IMM C, 71% of the time the electric motor's load is between 5kW and 10kW (motor rating is 30kW). This power corresponds to the base load and concludes that the motor is operating inefficiently. Similar charts were obtained for IMM D. For IMMs A and B (Figure 6), although the base load percentage time is high, the time during clamping (holding pressure) is significant as well which is 24%.

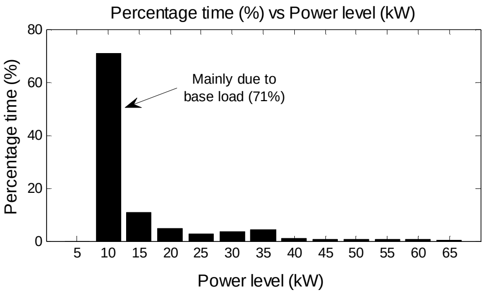

Figure 5: Chart showing the electric's motor percentage time against the operating power levels of IMM C

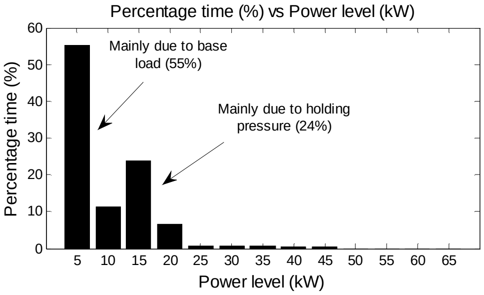

Figure 6: Chart showing the electric's motor percentage time against the operating power levels of IMM A

Figure 5 and Figure 6 show that electric motors of the IMMs are spending most of the time at low loads as can be seen from the percentage timing in the charts. This means that inefficiencies exist and measures need to be taken in order to optimise the efficiency.

4.2 Other EMDSs

In the previous section IMMs from two different plants were studied to see the efficiency of operation. Studies on other types of EMDSs were carried out at a different manufacturing plant.

In one particular plant which produces animal feeds, monitoring on various motors inside various systems was carried out in order to study their operation. EMDSs measured include *conveyers*, *elevators* and *cubers*. The operation of these motors is similar and the elevator was chosen for further analysis. Generally the motors at this location operate either at low load or at high load. For example the elevator, which transports the material from one point to another higher point, the motor operates at high load but when the elevator does not have any material on it, the motor continues operating at low load. Figure 7 verifies that two states exist which are called *low load* and *high load*. Note that when the motor operates at low load the load factor is very low which is around 17%. The rating of the motor is 7.5kW so even when the motor operates at high load it is not loaded significantly. The average power at low load is 1.3kW while at high load is 4.3kW.

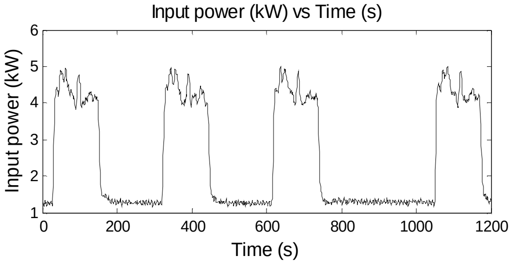

Figure 7: Load profile of an elevator

The load profile shown in Figure 7 is of a particular EMDS in this particular plant. However, other motors were monitored and similar profiles were obtained. From Figure 8, it can be proved that at low load the motor works around 75% of the time which is significant. This means that the elevator is left running a lot of time without the material on it although it has a function that after some time idle it switches off automatically.

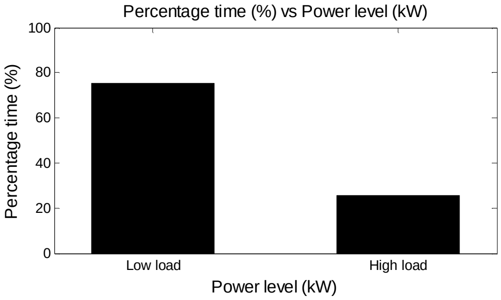

Figure 8: Chart showing the different percentage timings between low load and high load of an elevator

4.3 Conclusion

From the analysis of the three plants selected for monitoring, it can be concluded that the motors installed in industries are probably operating most of the time at low load which means that they are introducing a lot of inefficiencies. Apart from this, all the motors from the plants chosen were of standard efficiency. This means that apart from the inefficient operation of the motor they are naturally less inefficient than the latest High Efficient Motors (HEM). Therefore measures need to be taken in order to increase the efficiency in industrial applications.

Hence, one way to increase the efficiency is by simply replacing the old standard motor with a HEM [3]. Further it is recommended that when a standard motor becomes faulty it is replaced by a HEM instead of being repaired. It is important to note that when a motor is rewound, the efficiency is decreased.

Another measure is by the reduction of the supply voltage on the motor at low loads [4]. This causes the reduction of the motor flux thus decreases the losses in the motor and so the efficiency is increased. Simulations [5] and experiments confirm that by installing a Motor Energy Controller (MEC) this can be achieved. When this apparatus senses low loads on the motor it controls the supply voltage accordingly.

5 EXPERIMENTAL SET-UP

A lab test rig has been built in order to make tests on available standard motors and emulate loads on them which are similar to the ones found in industry. A detailed schematic of the equipment can be seen in Figure 9.

The motor under test is the AC induction motor which is being coupled to a DC motor through a torque meter. The DC motor, which is being driven by a DC drive, serves as the load on the motor under test. The DC drive can be controlled manually by increasing the torque using a potentiometer from a ‘manual I/O control box’ built especially for the DC drive. Moreover, instead of manually controlling the torque, the PC can be pre-programmed so as to load the motor like the loads shown in the analysis. The presence of the torque meter is to monitor directly the output power of the induction motor. It is connected as well to the PC so as to take real-time readings of the *torque*, *rotational speed* and *output power*.

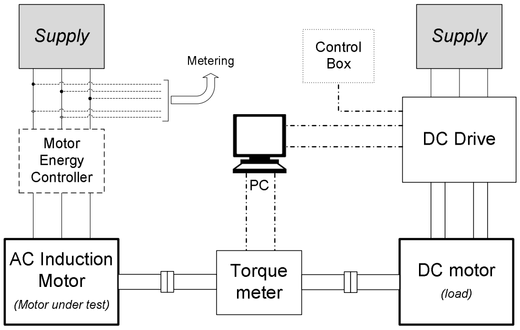

Figure 9: A schematic of a test rig in the lab to emulate loads found in industry

The experimental set-up allows for a standard AC motor with a MEC to be tested. Figure 9 shows how the AC motor is supplied via a MEC. Other measurement equipment is connected to the input of the MEC so as to monitor directly the voltages, currents and input power. The energy saving mode of the MEC can be disabled so as to see the effect of the equipment. The rating of the AC motor under test is 5.5kW

6 RESULTS & ENERGY SAVINGS

Several tests were carried out in order to verify the measures that need to be taken in order to increase the efficiencies in the motors of the EMDSs mentioned in the previous sections.

One simple test involved the motor under test running without a load attached to it; first with the energy saving mode *off* and then *on*. At no load, the active power of the 5.5kW motor is around 500W. However when the MEC is switched *on* the power is reduced to around 400W as can be verified from Figure 10. This means that at no load 20% energy savings can be achieved.

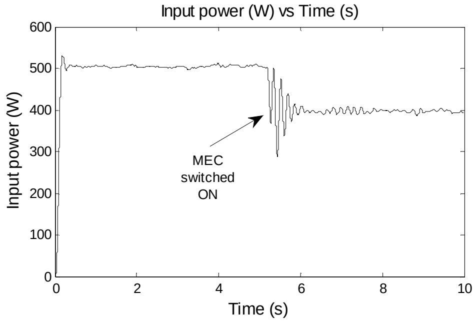

Figure 10: The variation in active power with the MEC

This result is very promising since as was seen in Section 4, motors installed in industries operate for significant amount of the time at low loads. Saying this, the 20% obtained has to be taken into perspective because still, in reality, there are times when the motor operates at high loads.

The same 5.5kW motor was used to test the efficiency in the output power range between 380W to 5.8kW. Two tests were carried out to monitor the difference in efficiency between the motor with and without the MEC. The results are plotted in Figure 11. Note that the dotted line is above the solid line meaning that the efficiency has actually increased. The difference in efficiency between MEC *off* and *on* decreases as the load increases since at no load the voltage on the motor can obtain the least possible value. But when the motor is being loaded, the voltage starts to increase thus the rate of increase in efficiency decreases. The efficiency is calculated by using the direct method which means taking the ratio of the input power and output power. The input active power is monitored by measuring the voltages and currents at the input of the MEC while the output power is read from the torque meter.

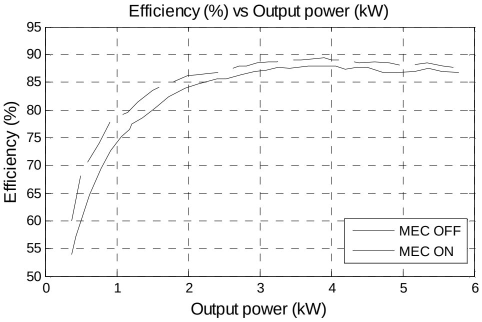

Figure 11: The difference in efficiency between the MEC *off* and *on*

Since the loading on the motor under test can be varied in a very flexible manner, a load profile similar to that of the elevator discussed in Section 4 was applied on the motor to see how much the MEC is capable to save energy with this load profile. The load profile was set with 75% of the time at low load and 25% at high load. Figure 12 shows the input active power monitored with the load profile programmed with the PC. Two tests were carried out; one with the MEC *off* and one with the MEC *on*. The difference in the average power will be the energy savings achieved with the MEC.

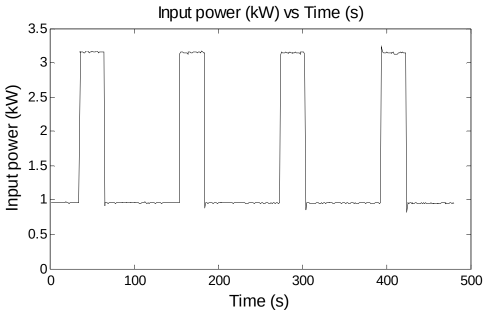

Figure 12: The load profile monitored at the test rig when the load profile was programmed similar to the elevator

Table 3 confirms that with this load profile the MEC is saving energy with 5.3% since the average active power has reduced by 80W from 1.50kW. For energy savings one should look at the active power (W) not the apparent power (VA). Although it is always beneficial to improve the apparent power this can be achieved by just installing a PFC. With the MEC the power factor is improved slightly as shown in Table 3, however still PFC is needed to increase the power factor significantly, say to 0.95. It is important to note that actually the PFC does not improve the active power. When it is installed the power factor is increased hence reducing the apparent power accordingly.

Table 3: Table of results

	MEC off	*MEC on*	*Energy Savings*
Average active power	1.50kW	1.42kW	**5.3%**
Average apparent power	3.63kVA	3.13kVA	13.8%
Current (A)	5.23	4.54	--
Power factor	0.3880	0.4161	--

This concept has to be kept in mind when analysing power energy savings. Care must be taken when quoting the current from the meter during monitoring because the current can be reduced but the power factor improves for the same real power, as proved from the following equation:

$$P = \sqrt{3} I_L V_L \cos\varphi$$

where,

$I_L = \text{line current}$
$V_L = \text{line voltage}$
$\cos\varphi = \text{power factor}$

Therefore when analysing energy savings the true power has to be quoted. But still it is always recommended to install the PFC to ensure almost unity power factor.

The 5.3% energy savings obtained from the experiments are very encouraging since in industry there are a lot of EMDSs which operate most of the time at low load. The figure of energy savings just mentioned is very significant especially when implemented in large industries.

The experimental set-up can also be used to program the load profile similar to that of an IMM. This is shown in Figure 13 and studies of this system are still on going.

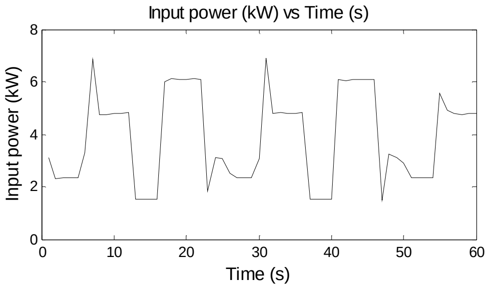

Figure 13: The load profile monitored at the test rig when the load profile was programmed similar to an IMM

7 CONCLUSION

From the analysis of the monitoring carried out in industry, it was found out that motors are operating most of the time at low load hence inefficient. Several measures can be taken in order to increase the efficiency by replacing the motor with a HEM of using a MEC. Experimental results show that a MEC lowers the supply voltage on the motor at low loads thus minimising the losses of the motor. Although this system has only been studied in detail with a standard industrial load such as an elevator, it is envisaged that it could achieve savings even with an IMM.

8 REFERENCES

[1] Leonardo Energy: The Global Community of Sustainable Energy Professionals, Energy Efficient Motor Systems, (2009).

[2] F. Johannaber, Injection Molding Machines, 4th Edition, Hanser, (2007).

[3] Rotating electrical machines: Efficiency classes of single-speed, three phase, cage-induction motors, Std. IEC 60034-30, (2008).

[4] C. D. Pitis, Power Savings Obtained from Supply Voltage Variation on Squirrel Cage Induction Motors, IEEE, (2008).

[5] P. Spiteri, C. Spiteri Staines, C. Caruana, Investigation of Electric Motors Energy Savings Potential in Industrial Applications, World Engineers Convention, (2010).

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