Investigation Of Electric Motors Energy Saving Potential In Industrial Applications

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Abstract: It is estimated that motor driven systems account for around 65% of the electricity consumed by European Union industry. It is further estimated that switching to energy efficient motor driven systems can save Europe around 202*TWh* in annual electricity consumption [1]. This excess energy consumption represents increased industrial operating costs and around 80 million tons of CO_{2eq} emissions per year. Reduction of CO_2 emissions shall aid abating today's problems regarding climate change. In the majority of the cases, energy efficient motor systems have reduced running and maintenance costs. This reduction can rise to 35%. The envisaged reduction in costs by introduction of energy saving measures would increase industry's competitiveness. This paper analyses the loading of the injection mould machine's electric motor where it is found that most of the time, the motor operates below the rated power. This introduces inefficiency and by applying several schemes such as replacing the standard motor with a premium efficient motor and/or installing a motor energy controller the efficiency is increased. Simulations will show that an injection mould machine can save up to 11.7%.

Keywords: Efficiency, Electric Motors, Energy Savings, Injection Mould Machine, Load Profile.

1. Introduction

This paper is concerned with conducting case studies in the Maltese manufacturing industry, in order to increase the efficiency of their motor driven systems. There are around 300 to 400 Injection Mould Machines (IMMs) in the major Maltese manufacturing plants; this paper will focus mainly on such machines. Two large plants were selected for a detailed energy analysis to obtain the motor's driven system's load profile. The measurements were carried out on the induction motor used to drive the hydraulic system of the electrohydraulic IMM. The detailed study of the electric motor point of operation vis-à-vis the load cycle of the IMM was carried out with the aim to investigate the possibility of energy savings. Different approaches for motor energy savings, such as replacing the standard motor with a high efficient motor and/or by introducing a motor energy controller will be considered.

From the analysis it will be shown that most of the time the motor driving the hydraulic pump operates at low load, thus at low efficiency [2]. Since the motor works at highest efficiency when operating at rated load, for the case of the hydraulic pump motor there is potential for increasing its efficiency during operation. The paper will present a number of simulations that provide an estimate of the potential energy savings.

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2. Background on injection mould machines

Injection moulding is a major part of the plastics industry and is a big business world-wide, consuming approximately 32% of all the energy used for plastics production. There exist many different types of IMMs, based on factors such as quantities, sizes, shapes, product performance, or economics [3]. An IMM has three basic components:

- The injection unit
- The mould
- The clamping system.

In general, there exist two types of IMMs, one type with a hydraulic accumulator and another type without. The accumulator 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. The one without the accumulator is known as the single-stage and the one with the accumulator is called the two-stage machine [3]. Further IMMs can be of one to more colours, generally not more than four. This allows for the production of plastic parts of different colours.

The basic process of an IMM is as follows. Granules of plastic powder are fed into a hopper and stored until needed. Then, a heater heats up the tube, called the plasticator, and when it reaches a certain temperature a hydraulic motor turns a screw thread which pushes the granules along the heater section which melts into a liquid (plastication). After that, a controlled-volume shot of melt is injected from the plasticator into a closed mould. The injected material is maintained under pressure for a specified time to prevent back flow of melt and to compensate for the decrease in volume of melt during solidification (afterfilling). Then, the thermoplastic moulded part is cooled until it is sufficiently rigid to be ejected, and finally, the mould opens and the part is ejected. This cycle is repeated.

The production whole process loads the induction motor which drives the hydraulic system pump motor. A typical motor loading cycle is shown in Figure 1 [4]. It shows the different loadings according to the stages described. 'Closing' and 'opening' refer to the position of the mould. 'Nozzle forward' means that the plasticator is moved forward to prepare for the injection stage. During injection, the peak power consumption is reached although the time is relatively short. 'Plastication', refers to the heating of the granules of plastic for the next cycle. Results will show that if the IMM has an accumulator the load profile will not follow the pattern of Figure 1.

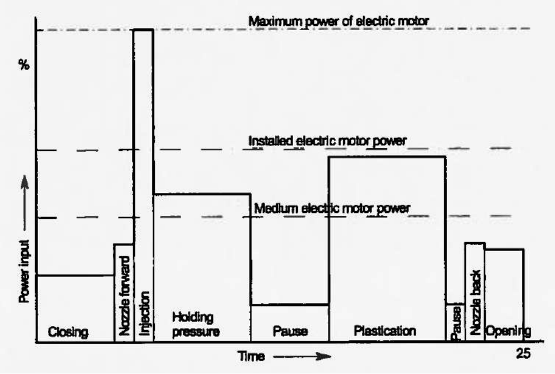

Figure 1: Typical load profile of an IMM, showing the different stages of the whole process [4]

3. Methodology

A detailed survey of the IMMs used at local manufacturing plants was carried out. The data collected included the IMM type; the quantity of the same machine types; operating hours per year; energy usage per year, age and the hydraulic pump motor rating. A sample of machines was selected for measurements. This involved the monitoring of the motor load of the IMMs using a power meter. The measurements obtained were used to analyse the loading pattern of the electric motors to establish the potential for energy savings.

Table 1 shows the list of the IMMs which were identified for power measurement of their electric motor. The main criteria for the selection of the machines to be monitored were: the quantity of the same types of machine in the respective plants; the motor ratings; and whether the IMMs were going to be retained in the future. The machines considered in this paper are labelled type A, B, C and D and were of maximum three-colour. Type A is a three-colour machine, type B is a two-colour machine and both have the same rated clamping force (600kN). Both machines have an accumulator. Due to the colour related difference they have motors of different ratings at 30kW and 22kW respectively. Type C and D are both one-colour machines and they have different clamping force capabilities of 1500kN and 2000kN respectively. The clamping force difference explains the different motor ratings of 22kW and 30kW for type C and D respectively. Both machines do not have an accumulator.

IMM type	Manuf. Yr (Average)	Motor rating (kW)	No. of Hrs /yr (Average)	Quantity of the same machine types	Accumulator
Type A	2005	30	4002	23	Yes
Type B	2003	22	4247	22	Yes
Type C	2000	22	6000	8	No
Type D	2001	30	6000	6	No

Table 1: List of the injection mould machines identified for measurement

For types A and B, twelve readings were carried out; six for each type so that different readings could be taken with moulds requiring different cycle times. For types C and D, six readings were carried out; three for each type. The cycle times considered varied from about 20 to 60 seconds.

All the IMMs were monitored during continuous normal operation for two hours at a sampling rate of one second. The variables monitored were: voltages, currents, active power, reactive power and apparent power of each phase, frequency and power factor.

4. Analysis of types A and B

This section considers the analysis following the measurements on type A and type B machines which include a hydraulic accumulator. The results also include a type B1 machine which is similar to type B but has a motor rated at 30kW since it can be upgraded to a type A machine. Table 2 shows a list of the measurements taken. This table shows the cycle time and the energy consumption in two hours.

Reading	Type	Cycle time (s)	Energy in 2 hours (kWh)
Reading 1	A	20.8	23.2446
Reading 2	A	23.7	23.5810
Reading 3	A	34.3	24.2945
Reading 4	A	31.1	25.2655
Reading 5	A	51.3	25.7860
Reading 6	A	53.2	23.5810
Reading 7	B	24.1	14.8004
Reading 8	B	24.6	18.7955
Reading 9	B	37.4	14.5305
Reading 10	B	32.6	15.4967
Reading 11	B1	62.1	19.3875
Reading 12	B1	52.3	20.6056

Table 2: List of types A and B machines measured with the power meter

Figure 2 shows a typical load profile over four minutes of operation for a type A machine. Since the load profile for the type B machine is similar to that of type A, it is not shown here. The use of an accumulator explains the lack of pattern as was evident in Figure 1. Despite this, it can be seen that when the motor is highly loaded, this lasts for only about one second. This occurs on average four to nine times during the total cycle time.

Figure 2 shows that the induction motor always consumes a minimum constant amount of power which is being defined as the base load. The load on the motor never falls down below this value. This base load exists even when the IMM is idle (i.e. not producing any products); and when it experiences a production fault which requires manual resetting of the process. The average load of type A during the two hour measurement is $12.4kW$ which is 41.3% of the motor rating. Although it appears that the motor is overrated, there are certain instances where the motor is loaded up to twice its rating. This loading limits the choice of motor power.

During operation, the motor's average power factor is 0.54 lagging, and the lowest recorded is 0.25 at low load. It is desirable that the power factor is close to unity to minimize the I^2R losses in the power distribution cables. The power factor can be improved by installing Power Factor Correction (PFC) capacitors at the machine. The pattern of the power factor variation resembles that of the active power. This is because, when the motor is at low load, the current is mainly used for magnetisation of the motor's field, whilst when the motor is loaded closer to the rated power, the current is used for active power creation thus increasing the power factor towards unity.

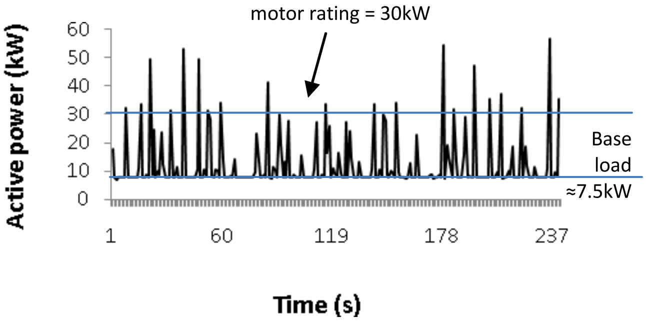

Figure 2: Typical load profile of type A machine

Table 3 shows the typical base load, average load, consumption, power factor and peak maximum load data for types A, B and B1. For type A machines the average consumption in one hour is $12.1kWh$ while that of types B and B1 are $8.1kWh$ and $10.0kWh$ respectively.

Type	Motor rating	Base load (kW)	Average load (kW)	Max load (kW)	Consumption (kWh / hour)	Average p.f.
A	30	7.5 (25%)	12.4 (41.3%)	74.2 (247.3%)	12.1	0.54
B	22	3.5 (15.9%)	8.1 (36.8%)	31.9 (145.0%)	8.1	0.49
B1	30	7 (23.3%)	10.0 (33.3%)	70.3 (234.3%)	10.0	0.50

Table 3: A table showing the motor ratings, typical base loads, average loads, consumption, power factor and peak maximum of types A, B and B1. The values in the brackets are the percentages of the motor ratings.

An analysis was carried out on the percentage time that the machine operates at different power levels. The results were arranged as shown in the histograms of Figure 3. Every point measured with the power meter was categorised into sections according to the instantaneous power. They were divided into bins of power of $0kW$ to $5kW$, $5kW$ to $10kW$, etc. Figure 3(a) shows that, for Reading 3 (Table2), 70.9% of the time during two-hour measurement consumed a power between $5kW$ and $10kW$, this corresponds to the base load power. Similar percentages were observed in the other readings. The same analysis was carried out on the distribution of the energy consumption with respect to the instantaneous power to construct the histogram of Figure 3(b). The figure shows that for Reading 3 energy is mostly consumed when the power is in the range of $5kW$ to $10kW$. This power corresponds to the base load operation where 11.2 units were consumed in two hours. As can be seen from Table 2, the energy measurements were carried out on the motors of same type of IMM for different production cycle times to determine if this effects the consumption. The table shows that the energy consumption is not affected by the cycle time since energy readings are similar for different cycle times.

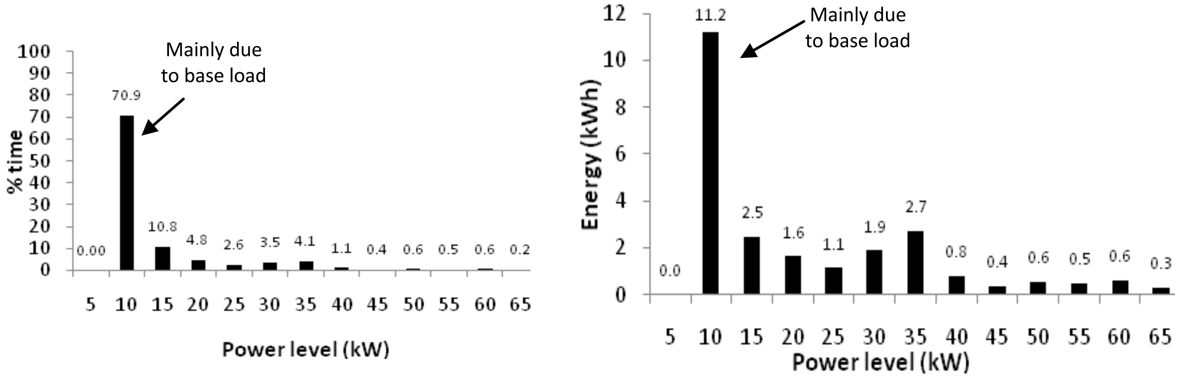

Figure 3: Histograms showing electric motor's percentage time and the energy against the operating power levels of Reading 3

5. Analysis of types C and D

A similar analysis was carried out on type C and D machines. The list of the monitoring carried out is shown in Table 4 where there are three readings of type C machine and another three readings of type D machine.

Reading	Type	Cycle time (s)	Energy in 2 hours (kWh)
Reading 13	Type C	22.8	15.5767
Reading 14	Type C	24.0	18.3590
Reading 15	Type C	22.8	23.0413
Reading 16	Type D	22.0	31.4524
Reading 17	Type D	22.4	29.4875
Reading 18	Type D	30.0	12.1521[1]

Table 4: List of types C and D measured with the power meter

Figure 4 shows the typical motor power load profile of type C and D machines over four minutes operation. Unlike in the case of machine types A and B, a pattern similar to that of Figure 1 can be clearly seen. The difference is due to the fact that types A and B have an accumulator and types C and D do not. The results of the detailed power analysis are shown in Table 5. The base load for type C is around $3.2kW$ which is 14.5% of the rated power while for type D it is around $4.7kW$ which is 15.7% of the rated power. When operating at the base load both type C and D have practically the same load factor. When considering the average load, type D is better than type C since the load factors are 45.0% and 53.0% respectively. Practically the maximum percentage loads are the same. As expected the energy consumption per hour of type D will be greater than that of type C. This is because the machine has a higher clamping force rating. As can be seen from Table 5, the power factor of the electric motors is close to unity, this is because the machines were equipped with individual PFC capacitors.

The analysis regarding the percentage time and energy consumption related to different power levels, carried out on types A and B, was repeated for types C and D. In the analysis of the percentage time a similar scenario to that of types A and B can be observed, that is, the larger percentage time is spent at base load operation. However in the case of the energy consumption distribution there exist some differences. The histograms shown in Figure 5 are for the data of Reading 13. Figure 5(a) shows that for 55.3% of the time the motor's power is in the range between $0kW$ and $5kW$, which corresponds to the base load. Since these types of machines do not have an accumulator, the loading during the holding pressure stage is significant as well. In this case 23.8% of the time is used for holding pressure. Figure 5(b) shows that in the case of these machines, even though most of the time is spent at base load, the higher energy consumption is for production of the holding pressure. Figure 5(b) also shows that amount of energy used for the base load and other stages such as injection and plastication. Table 5 also shows that for type C machines, the average consumption in one hour is $9.5kWh$ while that of type D is $15.3kWh$.

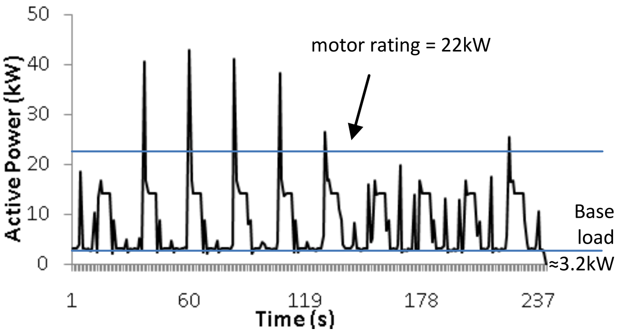

Figure 4: A typical load profile of type C

Type	Motor rating	Base load (kW)	Average load (kW)	Max load (kW)	Consumption (kWh / hour)	Average p.f.
E	22	3.2 (14.5%)	9.9 (45.0%)	43.9 (199.5%)	9.5	≈ 0.99
F	30	4.7 (15.7%)	15.9 (53.0%)	62.8 (209.3%)	15.3	≈ 0.85

Table 5: A table showing the motor ratings, typical base loads, average loads, consumption, power factor and peak maximum of types C and D. The values in the brackets are the percentages of the motor ratings.

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[1] Machine suffered interruptions

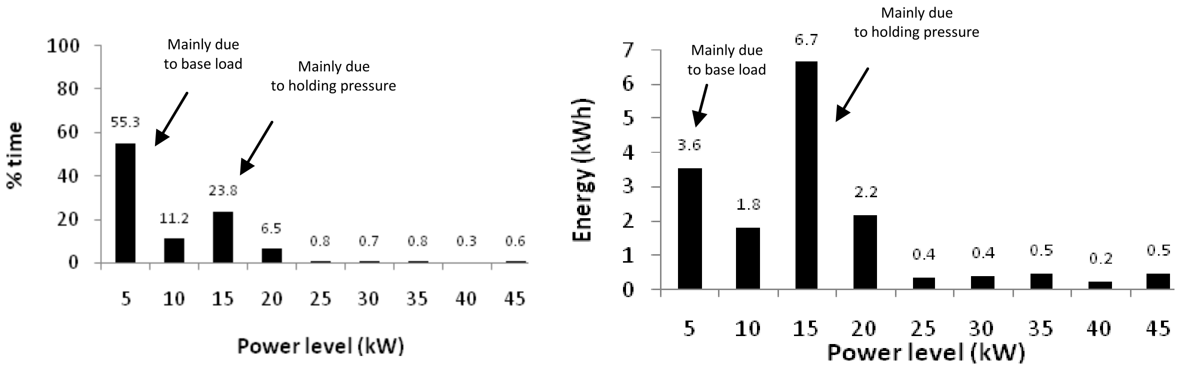

Figure 5: Histograms showing electric motor's percentage time and the energy against the operating power levels of Reading 13

6. Potential energy savings and simulations

The results presented in this paper show that energy savings opportunities exist for IMMs. The main potential for energy savings is due to the fact that the motor is lightly loaded for a substantial percentage of the cycle time. The rating of the IMM is selected to be of a high power to allow for operation of short duration at circa twice the rated during the injection process without exceeding the motor's pull-out torque.

One measure to achieve energy savings is by replacing the standard induction motor of the IMM with a premium efficiency motor. For example, $22kW$ and $30kW$ motors, rated at EFF3, have an efficiency of 90.5% and 91.4% respectively, at the rated load. On the other hand, if premium efficient motors (IE3) are used, the efficiencies at rated load of the $22kW$ and $30kW$ motors increase to 93% and 93.6% respectively [5].

Another measure to increase the motor's efficiency is by reducing the supply voltage of the lightly loaded motor [2]. Recalling Figure 3 and Figure 5 most of the time the motor load does not exceed $10kW$ for motor ratings of 22kW and 30kW. For type A, 46.1% of the energy consumption is due to the base load, while for type B almost 30% is consumed by the base load. For type C and D, the base load consumes 22% and 10% of the total consumption. These percentages are significant, thus if an energy saving technique is applied during the time when the motor is operating at low load, the efficiency can be increased. This can be achieved by introducing a Motor Energy Controller (MEC) which decreases the motor flux at low load by reduction of the supply voltage. There also exist Variable Speed Drives (VSD) however these will change the flow rate which will require significant modifications to the IMM and thus shall not be considered here. Simulations using MATLAB's SIMULINK were carried out to see the potential energy savings of IMM, resulting from lowering the supply voltage. Built-in blocks of an induction machine were used to analyse the motor dynamics, and the energy consumption and several other essential parameters such as the power factor were studied as well. The motor ratings for the simulations were $37kW$ and $15kW$. For every motor the core losses were estimated and included in the simulations. The base load for the type A machine is around 25%, and so, analysis was carried out on a $37kW$ machine with a 25% load. The analysis shall show the effect when the supply voltage is reduced when the induction motor is lightly loaded. The results are shown in Table 6. P_{in} is the input power supplied to the motor, P_{out} is the mechanical output power and *'rpm change'* is the change in the speed of the motor when the supplied voltage is reduced to the percentage shown. Three different scenarios are being presented with the same torque applied on the motor to give the 25% loading. Each scenario has different supply voltage so as to see the effect on efficiency during base load. As one can conclude from Table 6 the efficiency, which is the ratio P_{out} on P_{in}, is increased when the supply voltage is reduced to 45%, without altering much the speed of the motor.

% Voltage	P_{in} (kW)	P_{out} (kW)	Eff (%)	rpm	rpm change	Power factor
100	14.2	9.3	65.3	1495	-	0.6129
75	12.4	9.2	74.4	1491	0.27	0.7613
45	11.1	9.1	82.1	1473	1.47	0.9098

Table 6: A table showing simulation results with supply voltage reduced from 100% to 45% with a load factor of 25%. The motor rating is 37kW.

In the case shown in Table 6, the efficiency is increased by 16.8% since the input power (P_{in}) is decreased. The decrease in the input power from $14.2kW$ to $11.1kW$ implies an energy saving of 21.8%.

This result is very promising since the IMM's motor operates at the base load for a significant percentage of the time. For example, in the case of type A machine, it operates at the base load for 70.9% of the time. Thus there exists a potential for energy savings in this regard. The average consumption of the base load only of type A machine is 5.19kWh/hr. If the supply voltage is reduced during base load operation the overall potential energy savings become **9.4%**.

Table 7 shows similar analysis with a $15kW$ motor. The load factor remains at 25%. This time the maximum reduction possible applicable to the supply voltage is up to 50%. This was limited due to the resulting unacceptable speed change. The increase in efficiency is 15.7% which is 1.1% less than the $37kW$ motor. Table 7 shows that also the power factor is improved significantly. The results are summarized in Table 8. The lowest value of percentage energy saving obtained is 20.7%. Also in this case the results are very encouraging as concerns application of this energy saving technique on IMMs.

% Voltage	P_{in} (kW)	P_{out} (kW)	Eff (%)	rpm	rpm change	Power factor
100%	5.7	3.8	65.9	1491	-	0.5937
75%	5.0	3.7	74.9	1484	0.47	0.7507
50%	4.5	3.7	81.6	1464	1.81	0.9051

Table 7: A table showing simulation results with supply voltage reduced from 100% to 50% with a load factor of 25%. The motor rating is $15kW$.

Motor rating (kW)	% Voltage	Efficiency increase	Energy savings (%)	Power factor
37	45	16.8	21.6	0.9098
15	50	15.7	20.7	0.9051

Table 8: Summary of the energy savings simulation results with 25% load factor

The overall potential energy savings of all types of machines monitored was estimated and the results are summarised in Table 9. Several considerations had to be done in order to keep the calculations more accurate. First of all, the base load factor measured had to be recorded so as to simulate the energy savings at the base load only. The simulations were carried out on the two asynchronous machines mentioned earlier and the lowest energy saving figure was used to calculate the overall potential energy savings of the actual machines. For example, for a 25% load factor, the least energy savings obtained in simulations was 20.7% and this was used to find the overall potential energy savings where there was a load factor of 25% at the base load. For the other machine types the same calculations were carried out and are shown in Table 8. The machine type which has the most overall potential energy savings is type B1. This was expected since, as explained earlier, it has an overrated motor to allow the machine to be upgraded to type A. The other types of machines also have significant overall potential for energy savings especially in the case of types A and B. Types C and D, have the lower potential for energy savings. This can be confusing since one should expect that the IMMs which have accumulators (types A, B and B1) would result in less energy savings. However, measurement results have shown that these machines consume more energy in the range of the base load compared to the other types of machines. Since the energy saving technique is targeted at operation at low loads, the outcome shown in Table 9 is justified. Machine types C and D have significant consumption of energy during other ranges of operation (about 60% of rated) such as operation for holding pressure and plastication.

Machine	Load factor (%)	Base load only energy savings (%)	Overall potential energy savings (%)
Type A	25	20.7	8.8
Type B	16	30.0	8.1
Type B1	25	20.7	11.7
Type C	15	31.1	5.3
Type D	16	30.0	3.5

Table 9: A table showing the overall potential energy savings of all the types monitored

7. Challenges

To apply the energy saving technique based on the reduction of the supply voltage, there exist several challenges in order to achieve the estimated energy savings. One of the main challenges is due to the short times at which the motor operates at the base loads, especially in the case of machine types A, B and B1. The results show that the occurrences of operation at base load are a lot however the timing of these occurrences is very critical and sometimes the duration is as little as two seconds. For proper implementation of the voltage reduction method, the motor controller needs to rapidly response to the point of operation and regulate the supply voltage on the motor accordingly. This could be facilitated by the introduction of a trigger signal which would be based on the point of operation following a well know pattern during the cycle of the IMM process. However in the case of load profiles of machine types A, B and B1, which do not follow any particular pattern , it is difficult to program when the controller is required to adjust the supply voltage. For the other machines, this is not an issue due to the regularity in their process load pattern.

8. Conclusions

The result present a detailed power analysis of the power usage in the electrical motor used in IMMs. The results show that the induction motor operates for a significant amount of the time at light load. Since the motor's efficiency is low at light loads, there exists the possibility to achieve energy savings by means of intelligent control of the motor. The possible savings using voltage reduction techniques have been simulated and it has resulted that base load operation savings of over 20% are possible. When analysing the application of such a method to the IMM's motor's ,the highest estimated overall energy savings reached was 11.7% on type B1 and the lowest was 3.5% on type D. This means that the potential for energy savings depends on the make and model of the machine and its respective load profile. The IMMs monitored for the purpose of analysis were machines which are the most commonly found in both industrial plants and which are going to continue to be used in the future. Therefore, application of proper energy saving measures on these machines will surely have an effect on their electricity consumption. Furthermore, there also exist other types of machines in local industry which have not been monitored which possibly still offer the potential for energy saving and thus can further reduce the electrical energy usage in the local industries. Moreover, there may be other companies which have similar types of IMMs to the ones discussed here one which the energy saving technique discussed here can be applied. A widespread application of energy savings techniques on IMMs in local industry would increase the total energy efficiency in manufacturing industry and making it more competitive by decreasing the overall energy consumption.

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