Preliminary Results about the Energy Saving Applied to the Decanter Centrifuge Used in Olive Oil Extraction

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Abstract
This paper illustrates the simulation, the experimental measurements and the analysis of the optimal coupling between a decanter centrifuge used for olive oil extraction in the olive oil mills and a the three-phase induction motor. The simulation offers the vantage of the reduction of the costs of purchasing various kind of motors to be tested. In this simulation different typologies of coupling between a driving electronic variable frequency driver, an alternating current electric induction motors and the decanter centrifuge were examined. Results show that the motor oversizing is necessary to improve the efficiency of the machine but the oversizing is limited by the asymptotic behaviour of the specific energy consumption with respect to the induction motor rated mechanical power. When comparing the "variable frequency" driving mode to the "field oriented control" driving mode, the gain in the overall energy consumption over the entire 40 days period of the campaign in the olive oil mill was between 7.7% and 8.2%, and when comparing the most common direct to electric line "STAR" connection driving mode to the "field oriented control", the gain was between 2.9% and 3.9% .

Keywords: induction three-phase asynchronous motor, variable frequency drive, simulink modelling, efficiency

Introduction
An important facet of sustainability is energy consumption. Sustainable process is therefore an efficient one, and the evaluation of energy efficiency is very important; once the energy efficiency of a process has been measured and benchmarked, control or design actions may be taken to improve the process.
Nowadays electric motors have broad applications in such areas as industry, business, public service and household electrical appliances, powering a variety of equipment including wind blowers, water pumps, compressors and machine tools (Saidur, 2010). Motor-driven systems account for approximately 65% of the electricity used by EU industry (Anon, 2004), but recently there has been a growing concern about energy use and its adverse impact on the environment.
It is very important to select an electric motor of suitable power to work efficiently. Motor oversize is one of the most frequently misapplication encountered and difficult to be fixed (Da Costa Bortoni, 2009). Oversizing accounts for a considerable share of the efficiency problems often found in motor applications. In general, motors are chosen in big capacities to meet extra load demands. Big capacities cause motors to work inefficiently at low load. Normally, motors are operated more efficiently at 75% of rated load and above. Correct sizing of electric motors is critical to their efficient operation, since oversized motors tend to exhibit poor power factors and lower efficiencies (Beggs, 2002). Depending on size and speed, a typical standard motor may have a full load efficiency between 55% and 95%. Generally, the lower the speed, the lower the efficiency, and the lower the power factor.

Energy can be saved in different ways for different industrial energy using machineries with different energy savings strategies. These strategies are broadly classified in three ways (Saidur, 2010):

- using regulations (voluntary, mandatory, mixed, standards, labels, education, soft loan, incentives);
- with the application of technology (variable speed drives (VSD), power factor improvement, new technology);
- by housekeeping (maintenance, switching of, reduce standby losses, auditing).

Switching to energy-efficient motor-driven systems can save Europe up to 202 billion kWh in electricity use, equivalent to a reduction ofs10 billion per year in operating costs for industries. It was reported that a reduction of 79 million ton of CO2 emissions (EU-15), or approximately a quarter of the EU's Kyoto target is achievable using energy-efficient motors.
Energy savings by technology includes use of VSDs to match the load requirements and capacitors to reduce losses thus improving motor power factor (Elliot, 2007).
In about 25% of the applications that induction motors are used, there is no need to operate the motor at full load (Leonard Abbott III, 2006). For example, in the water supply industry, constant speed drives will operate the pump at 100% of the motor rated speed, then the valves are placed in the pipeline and are adjusted to restrict the flow of water. In other industries, reduction gears are placed after the electric motor to reduce the speed or torque. The cost of valves, gears, and excess electric energy can be an additional unnecessary cost once output power is clamped down (Leonard Abbott III, 2006). Constant speed motor starters cannot adjust their speed, so that anytime there is need for the speed of a motor to operate.
Variable frequency drives provide continuous control, matching motor speed to the specific demands of the work being performed (APEC, 2008; Jayamaha, 2008). Variable-frequency drives are an excellent choice for adjustable speed drive users because they allow operators to fine tune processes while reducing costs for energy and equipment maintenance.
Adjustable speed motors conserve energy by operating motors at levels only necessary for the particular task at a given time and can provide significant savings in energy usage and costs.
Qureshi and Tassou, 1996, reviewed the VSD in refrigeration application to reduce energy uses. Variable-frequency drives (VFD) are routinely used to vary a pump and fan speed in heating, ventilating and air conditioning of buildings.
Another example of the use of VFDs was in the pumping of machine coolant at an engine plant. Pressure at the pumps was reduced from 64 psi to 45 psi, average flow cut in half, and power usage reduced by over 50% with no adverse effect on part quality or tool life (Price et al., 1989). Reducing the coolant system pressure also reduced the misting of the coolant, reducing the ventilation requirements and cleaning costs. VFDs can also be used in draft fans on coal fired boilers, instead of dampers. The average electricity savings depend on boiler load, but will typically exceed 60% annually (Price et al., 1989).
Almeida et al., 2003, estimated that energy savings for motors using VFDs for food, beverage and tobacco industries amounts to 8.0 TWh.
Cini et al., 2008, estimated the electric energy consumption at small and medium size olive oil mills placed in Tuscany Region (Italy), referring to the overall electric power employed in each process step, including submitted equipment (pumps and fans).
In a typical olive oil mill plant motors are used to drive process equipment (olive crushers, kneading machine, pumps, centrifugal extractors).
During an entire production campaign the electric consumption amount could be very important especially taking into account that the decanter centrifuges are run several hours in

a day. Normally the electric motor is oversized with respect to the required power to run the decanter centrifuge, this is done to ensure a minimal delay of time to run the decanter at its nominal speed, but this also involves that the driving motor is run to one fraction of its nominal power with lesser efficiency. The aim of this work is to establish, by means of both a simulation and experimental measurements, the relationship existing between overall efficiency and coupling between an inverter driven asynchronous electric motor and the decanter centrifuge when operating at an olive oil mill. In fact it has shown (Zakharov, 2008) that the use of simulation programs for induction motors is relevant in engineering problems.

Materials and methods

The machine used was a decanter centrifuge BABY-1 from "Pieralisi", with an operating throughput of about 5000 kg/h, equipped with a 5.5 kW nominal mechanical power (M1) asynchronous electric three-phase induction motor (IM) from "ABB", the motor was driven by an electronic three-phase inverter, i.e. an electronic variable frequency driver (VFD), whose efficiency was about 0.95. The Matlab Simulink software (using the SimPowerSystems toolbox) from MathWorks was used to simulate the physical system. The use of other three induction motors (named as M2, M3 and M4) was supposed with respectively a 4.0 kW, 3.0 kW and 2.2 kW nominal mechanical power in order to investigate the optimal coupling between motor and decanter centrifuge. Several hypothesis were simulated, from the case of oversized IM to the case of overloaded IM; testing various couplings between the four motors and the decanter centrifuge and between the electric line and the four motors. The characteristics of the real motor (see tab.1) and of the decanter (see tab.2) were measured on field and entered into the model while for the induction motor M2, M3 and M4 characteristics were taken from the datasheet by ABB. Moreover a time table provided by a real olive oil mill was used to simulate the activity time of the motor coupled to the decanter (see fig.1); from data was observed that, considering the overall working time per day, for about 6% of this time the decanter was run unloaded while for the remaining 94% of working time the decanter was run loaded.

In order to evaluate the possible energy saving when the decanter is operated at the olive oil mill, different typologies of coupling between the driving electronic VFD, the alternating current (AC) electric induction motors (IM) and the decanter centrifuge (DEC) were examined. The examined coupling cases, for each of the four motors M1, M2, M3 and M4, were the following:

- C1. VFD (efficiency of 0.95) driving the IM at variable frequency and sinusoidal line voltage (VARF), speed variation with fixed gear ratio (efficiency of 0.97) but variable with the inverter frequency in order to attain the decanter nominal working speed, working decanter speed of about 4916+/-5% rotations per minute (RPM), in this case was calculated the overall IM efficiency and the active power sunk by the IM from the electric line;
- C2. IM directly connected to the electric line with a "star" connection (STAR), speed variation with fixed gear ratio of 1.7365 (efficiency of 0.97), even in this case was calculated the overall IM efficiency and the active power sunk by the IM from the electric line;
- C3. IM directly connected to the electric line with a "delta" connection (DELTA), speed variation with fixed gear ratio of 1.7365 (efficiency of 0.97), in this case was calculated the overall IM efficiency and the active power sunk by the IM from the electric line;

C4. VFD driving the IM with a direct torque control algorithm (DTC) with sensor feedback control of IM speed, speed variation with fixed gear ratio of 1.7365 (efficiency of 0.97), working IM speed set-point of 2831 RPM, in this case was calculated the overall VFD+IM efficiency and the active power sunk by the VFD+IM from the electric line;

C5. VFD driving the IM with a field oriented control algorithm (FOC) with sensor feedback control of IM speed, speed variation with fixed gear ratio of 1.7365 (efficiency of 0.97), working IM speed set-point of 2831 RPM, in this case was calculated the overall VFD+IM efficiency and the active power sunk by the VFD+IM from the electric line.

The DTC algorithm is one of the methods used in VFD to control the torque (and directly the speed) of three-phase IM. This involves an estimate of the motor's magnetic flux and torque based on the measured voltage and current of the motor. It is one form of on-off feedback control system. (Lai and Chen, 2001; Casadei et al., 2002).

The FOC algorithm, based on the control of the fed current to the machine, is very common in IM control due to both its low cost and ability to control the motor speed more efficiently if compared to other control systems. Although the vector control algorithm is more complicated than the DTC, the algorithm is not needed to be calculated as frequently as required by the DTC algorithm. In a typical industrial application, the improved dynamic behaviour enabled by FOC also enables designers to size the motors optimally, rather than oversize the motor to meet the transient requirements. A smaller motor also runs at a higher fraction of its power rating, meaning that the resulting operating point is suited to provide a better efficiency. (Casadei et al., 2002).

Finally the simulated results at steady state for each case from C1 to C5, with decanter centrifuge loaded and unloaded were analysed, using the Matlab software. Results of analysis were applied to the time table, conjecturing a 40 days campaign time. Assumption were made about the dilution ratio (mass of added process water related to the mass of olive oil paste) considered 0.3 and about the decanter full throughput capacity considered equal to 5000 kg/h; the final results were the energy consumptions per olive oil unit mass.

Table 1. Electric induction motors M1, M2 M3 and M4, measured and calculated characteristics to be computed by the Matlab’s “simulink” model.

	M1 (5.5 kW)	M2 (4.0 kW)	M3 (3.0 kW)	M4 (2.2 kW)
Electrical Active Power (kW)	6.4	4.66	3.5	2.66
Line Voltage (Vrms)	400	400	400	400
Line Current (Arms)	10.6	7.9	6.2	4.6
Frequency (Hz)	50	50	50	50
CosPhi	0.871	0.851	0.815	0.835
Poles Pairs	1	1	1	1
Efficiency	0.859	0.858	0.857	0.827
Mechanical Power (kW)	5.5	4.0	3.0	2.2
Torque (N.m)	18.454	13.24	9.855	7.269
Shaft RPM	2846	2885	2907	2890
Slip (%)	5.133	3.833	3.100	3.667
F (friction factor)	0.0005	0.0005	0.0005	0.0005
J (Inertia) (kg.m^2)	0.01241	0.00671	0.0042	0.00163
Motor Type	Squirrel-cage	Squirrel-cage	Squirrel-cage	Squirrel-cage

Table 2. Decanter centrifuge "Baby-1" measured and calculated mechanical characteristics to be computed by the Matlab's "simulink" model.

Drum Operating RPM	Speed Variation	Speed Variation Ratio	Speed Variation Efficiency	Motor Shaft Operating RPM	Differential Scroll RPM	F (friction factor) (N.m.s)	J (Inertia) (kg.m^2)	Additional Torque when Loaded (N.m)
4916	Pulley with two toothed drive belts	1.7365	0.97	2831	12	0.009714	2.3410	1.8025

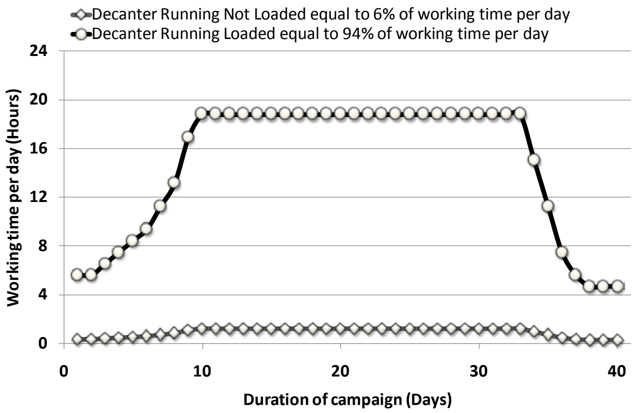

Figure 1. Time table recorded from a real olive oil mill to simulate the activity of the motor coupled to the decanter when used for the olive oil extraction at a real mill over a 40 days campaign.

Results and discussion

The characterising results, in order of importance, for each examined case are:

- the active power in kW (APOW) absorbed by the electric line;
- the overall efficiency (EFF);
- the decanter running speed (DSPD) in RPM.

The obtained simulation's results are reported in tab.3, the energetic results are reported in tab.4 .

The first consideration is that the IM M4 in case C3 doesn't start under a loaded decanter because the required torque is greater than the breakdown motor torque. The use of the VFD enhances the starting capability of the IM and also permits the control of the decanter centrifuge running speed (see DSPD into tab.2).

In fig.2 are reported the specific energy consumption with regard to the overall processed product vs. the IM rated mechanical power (IMRMP).

From fig.2 arises that the DELTA driving mode brings a linear correlation between ESPEC and IMRMP in the tested range of power; moreover for IMRMP values lower than about 4.750 kW the figure 2 shows an ESPEC value greater than other tested cases.

The VARF driving mode (see fig.2) shows an asymptotic trend at high IMRMP, but also in this case the ESPEC values are greater than the other tested cases.

The STAR and DTC driving mode are quite similar (see fig.2) and again show the asymptotic trend at high IMRMP, however for the IMRMP of 2.2 kW their difference in ESPEC is remarkable. The FOC driving mode shows the minimal ESPEC values and therefore represents the best driving mode for the IM in our tested cases (see fig.2). Again we can see the asymptotic trend of the ESPEC value at high values of the IMRMP.

Table 3. Obtained results from simulation of various couplings between decanter centrifuge and IM and between IM and electric line: for each of the four IM and for the cases previously depicted are only shown the characterising results as the active power (APOW) in kW absorbed by the electric line, the overall efficiency (EFF) and the decanter running speed (DSPD) in RPM.

	M1 (5.5 kW)			M2 (4.0 kW)			M3 (3.0 kW)			M4 (2.2 kW)		
	APOW (kW)	EFF	DSPD (RPM)	APOW (kW)	EFF	DSPD (RPM)	APOW (kW)	EFF	DSPD (RPM)	APOW (kW)	EFF	DSPD (RPM)
UNLOADED												
C1 (VARF) (max EFF)	2.034	0.845	5136	2.041	0.841	5134	2.088	0.818	5123	2.118	0.791	5073
C1 (VARF) (min APOW)	1.999	0.819	5014	1.574	0.072	1321	2.086	0.81	5094	2.118	0.791	5073
C2 (STAR)	1.941	0.885	5137	1.944	0.883	5135	1.999	0.855	5124	2.012	0.833	5073
C3 (DELTA)	1.900	0.862	5013	1.964	0.826	4991	2.025	0.79	4955	2.374	0.555	4498
C4 (DTC)	1.853	0.849	4916	1.867	0.843	4917	1.924	0.817	4914	2.004	0.787	4921
C5 (FOC)	1.844	0.854	4917	1.837	0.857	4918	1.902	0.827	4914	1.924	0.817	4913
LOADED												
C1 (VARF) (max EFF)	3.149	0.851	5092	3.201	0.835	5086	3.28	0.81	5066	3.461	0.743	4966
C1 (VARF) (min APOW)	3.149	0.846	5074	3.201	0.835	5086	3.28	0.81	5066	3.461	0.743	4966
C2 (STAR)	3.001	0.893	5093	3.042	0.879	5087	3.126	0.851	5068	3.29	0.78	4960
C3 (DELTA)	3.047	0.819	4874	3.306	0.728	4768	3.483	0.673	4687	Doesn't start	Doesn't start	Doesn't start
C4 (DTC)	2.986	0.848	4916	3.025	0.837	4916	3.122	0.81	4915	3.425	0.739	4917
C5 (FOC)	2.894	0.874	4916	2.924	0.866	4919	3.025	0.836	4915	3.198	0.793	4924

Table 4. Obtained results from simulation of various coupling between decanter centrifuge and IM and between IM and electric line: for each of the four IM and for the cases previously depicted are shown the specific energy consumption (ESPEC) whit regard to the overall processed product, the overall energy consumption (ETOT) with regard to the entire campaign of 40 days, the variation percent (VAR) of the overall energy consumption with regard to the minimum energy consumption case (for witch VAR=0.0) as calculated by the Matlab's "simulink" model.

Hours Loaded	589.38			Hours Unloaded			37.62					
Overall processed product (kg)				226685								
	M1 (5.5 kW)			M2 (4.0 kW)			M3 (3.0 kW)			M4 (2.2 kW)		
	ESPEC (Wh/kg)	ETOT (kWh)	VAR (%)	ESPEC (Wh/kg)	ETOT (kWh)	VAR (%)	ESPEC (Wh/kg)	ETOT (kWh)	VAR (%)	ESPEC (Wh/kg)	ETOT (kWh)	VAR (%)
C1 (VARF) (max EFF)	8.526	1933	8.2	8.661	1963	8.7	8.875	2012	7.8	9.350	2120	7.7
C1 (VARF) (min APOW)	8.520	1931	8.1	8.584	1946	7.9	8.874	2012	7.8	9.350	2120	7.7
C2 (STAR)	8.125	1842	3.6	8.232	1866	3.9	8.459	1918	3.3	8.888	2015	2.9
C3 (DELTA)	8.238	1867	4.9	8.922	2022	11.4	9.392	2129	12.9	-	-	-
C4 (DTC)	8.071	1830	3.0	8.175	1853	3.3	8.437	1912	3.0	9.238	2094	6.5
C5 (FOC)	7.830	1775	0.0	7.907	1792	0.0	8.181	1854	0.0	8.634	1957	0.0
Percent mechanical loading with decanter loaded with regard to full rated load of IM (%)	46.02			63.28			84.37			115.05		

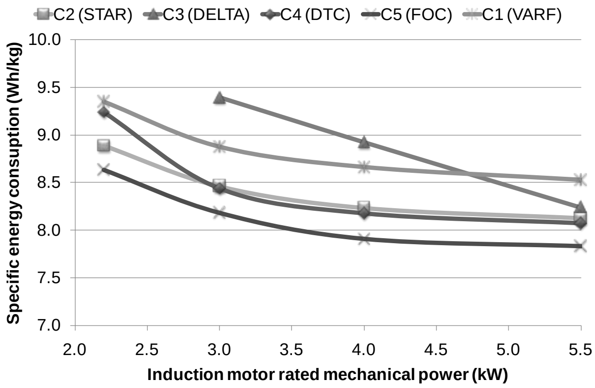

Figure 2. Specific energy consumption with regard to the overall processed product vs. the IM rated mechanical power, as obtained from simulation of various coupling between decanter centrifuge and IM and between IM and electric line for each of the four IM and for the cases previously depicted.

Tab.4 shows that the asymptotic trend of the ESPEC at high values of the IMRMP is also related to the mechanical motor loading percent (MMLP); in fact low values of MMLP bring to low ESPEC values and thus to a best overall process efficiency in terms of power consumption. This can enforce the opinion that heavily oversizing the IM leads to improve the energy saving of the process but this should be compared with the asymptotic behaviour of the ESPEC. At higher IMRMP values an increase of the IMRMP itself brings to a decrease of the ESPEC that can be negligible when compared with the biggest costs for purchasing the IM and VFD, so further investigations are required to correctly asses a method for the induction motor oversizing. From tab. 4 arises that comparing the VARF driving mode to the FOC, the gain in the overall energy consumption over the entire 40 days period of the campaign was between 7.7% and 8.2%, while comparing the most common direct to electric line STAR driving mode to the FOC, the gain was between 2.9% and 3.9% .

Conclusion

In this simulation different typologies of coupling between a driving electronic variable frequency driver, an alternating current electric induction motors and the decanter centrifuge were examined. From the trials arises that the motor oversizing is a need in order to improve the efficiency of the process but the oversizing is limited by the asymptotic behaviour of the specific energy consumption with respect to the induction motor rated mechanical power. In fact increasing the induction motor rated mechanical power brings to a decrease of the specific energy consumption that can be negligible if compared with the biggest costs necessary to purchase both a powerful induction motor and the variable frequency driver. When comparing the VARF driving mode to the FOC, the gain in the overall energy consumption over the entire 40 days period of the campaign in the olive oil mill was between 7.7% and 8.2%, and when comparing the most common STAR driving mode to the FOC, the gain was between 2.9% and 3.9% . Further investigations are required to correctly asses a method for the induction motor oversizing.

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