Energy Savings in Injection-Molded Plastic Manufacturing

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Abstract

The results of a joint project between the Wisconsin Focus on Energy program, the Milwaukee School of Engineering (MSOE), and Plastic Molded Concepts, Incorporated to improve the injection-molded plastic manufacturing process are described.

Medium range (10 - 100 HP) motors are used to pump hydraulic fluid in injection-molded plastic processes. Hydraulic power required during one cycle of manufacturing a single part varies greatly. With a single speed motor driving a fixed displacement hydraulic pump, the electric power consumed over one cycle is constant and equal to at least the maximum required hydraulic power plus losses.

Energy savings are realized by reducing the speed of the motor via a variable frequency drive (VFD) during those times of the part cycle when less than maximum hydraulic power is required. Another energy saving alternative is to replace the fixed displacement hydraulic pump with a pressure compensated variable volume hydraulic pump.

Variable frequency drives are installed on a number of presses at Plastic Molded Concepts (PMC) in Eagle, Wisconsin. One of these presses is used as a test bed for this study. The test bed system at PMC is used to compare several different process technologies. A multidisciplinary team of students and faculty (ME and EE) conducted baseline energy studies and redesigned the process to include variable displacement hydraulic pumps or VFD technology.

Verified energy savings of the redesigned system with VFD technology are presented. Projected energy savings of the redesigned system with a variable displacement hydraulic pump are also presented. This paper includes a description of the manufacturing process, information on the instrumentation used for the energy studies, and a description of the redesign. Feedback from the student team involved in the baseline studies, redesign, and verification are offered.

Student Design Involvement

The Wisconsin Focus on Energy is a program funded by Wisconsin electric rate-payers to encourage energy efficiency and the use of renewable energy, enhance the environment, and ensure the future supply of energy for Wisconsin. University involvement in the program is a deliberate decision intended to expose engineering students to energy conservation concepts and techniques.

As a result of this decision, students at Milwaukee School of Engineering (MSOE) are participating in a number of Focus on Energy projects. The faculty at MSOE view the projects as an opportunity for students to learn engineering methods, not just in the somewhat contrived and sterile academic laboratory, but in practical, industrial settings.

Student involvement in this particular project began after the proposal was awarded but before the design of the experiment started. Under direct faculty supervision, undergraduate engineering students coordinated testing efforts among the various constituencies on the project, designed the instrumentation system used to collect data, installed the instrumentation system at the plastic manufacturing facility, and finally collected data and assisted in data reduction and analysis. Hopefully this paper will provide a model for similar projects involving undergraduate engineering students in the energy conservation area.

Experimental Design

A simplified system diagram is shown in Fig. 1. Electric power was measured at the input to the variable frequency drive (VFD) using two separate instruments: a Load Controls, Inc. Portable Power Cell (PPC) and a Yokogawa WT1030M Digital Power Meter. The PPC had its own clip-on voltage probes and clamp-on Hall-effect current sensors. The PPC was configured as a three phase power meter using a three phase four wire configuration.

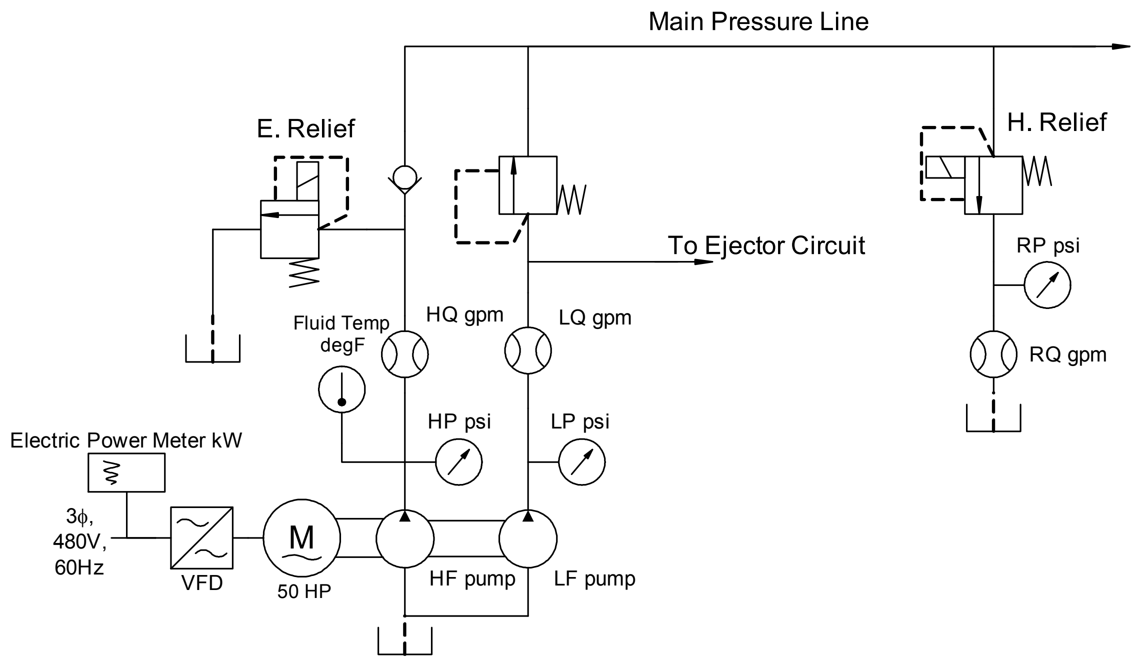

Fig. 1 Simplified hydraulic system diagram of PMC press #15.

Hydraulic flow and pressure were measured at three nodes: high flow (HQ), low flow (LQ), and return flow (RQ). Hydraulic fluid temperature was measured at the HQ node. The hydraulic instrumentation provided an analog voltage signals that were proportional to the physical quantity being measured. The Yokogawa WT1030M was configured as a three phase power meter using a three phase, three wire configuration. Hewlett Packard 34134A Hall-effect type clamp-on current probes were used to sense the current. Both power meters provided an analog voltage signal that was proportional to the three phase active power.

All of the proportional analog voltage signals were recorded using a National Instruments DAQCard 6062E data acquisition card installed on the PCMCIA bus of a Dell Latitude C840 laptop computer. A total of nine (9) channels of data were collected at 900 samples/second on each channel. At the time of the measurements, the hydraulic instrumentation had current NIST-traceable calibration certificates. The WT1030M and the NI DAQCard 6062E also had a current NIST-traceable calibration certificate. The PPC and the HP 34134A current probe did not have a current NIST-traceable calibration certificate.

Two tests were conducted. In one test the VFD was operated at 100% of its frequency rating (60Hz) during the entire part production cycle. In the other test the VFD was operated at 60% of its frequency rating during the entire part production cycle.

Results

All tests were performed after the injection press had reached steady state in its part production. Steady state was determined primarily by consistent part production and secondarily by examining hydraulic fluid temperature. Multiple part production cycles were recorded at a data sampling rate (per channel) of 900 samples/second. Two three phase active power meters, the PPC and the WT1030M, were used to measure the input to the VFD.

Results Test 1: VFD Output Frequency Operated Continuously at 60Hz

A comparison of the three phase active power input to the VFD measured by each power meter for the VFD output operating at 60Hz is shown in Fig. 3. The 54.5 seconds of data in Fig. 3 is for one part production cycle. The average active power input to the VFD per part production cycle (lasting approximately 54.5 seconds) for each meter is shown in Table 1. On the basis of the WT1030M a 3.6% difference is noted.

Table 1 (VFD @ 60Hz)

	WT1030M	PPC
Average active power per part production cycle (kW)	13.9 kW	14.4 kW

The part production cycle in Fig. 4 shows five main operating modes: eject/core pull, mold close, injection, screw rotate (part is cooling in the mold), and mold open. The opportunity to reduce the power input to the VFD is mainly during the screw rotate mode of the part production cycle.

Figure 5 shows the active power at each measurement node plotted for one part production cycle with the VFD output at 60 Hz. Hydraulic fluid temperature reached a steady state value of 111 ºF during this test. The power at the HQ node (approximately 4kWhydraulic) is being dumped across a pressure relief valve. The power at the LQ node (approximately 4.5kWhydraulic) is splitting between clamp hold and a pressure relief valve. The hydraulic pump only needs to rotate fast enough to maintain clamp holding pressure and to continuously eject hydraulic fluid. Continuous ejection of pump hydraulic fluid is necessary to prevent overheating the fluid and the pump.

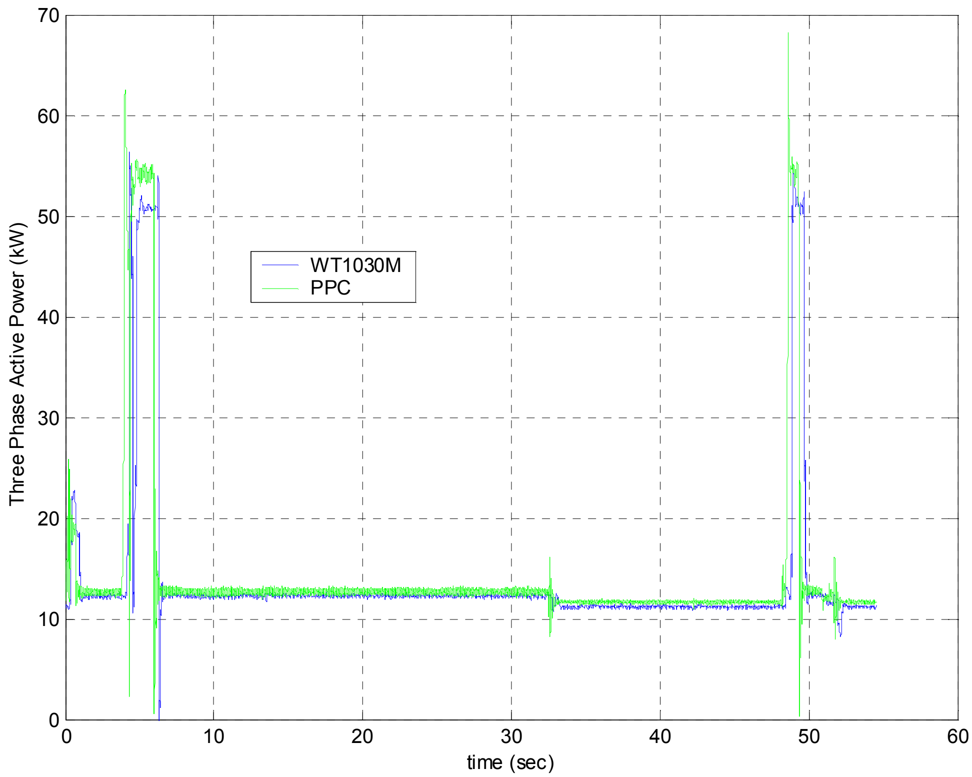

Fig. 3 Comparison of the three phase active power measured by each power meter for the VFD operating at 60Hz

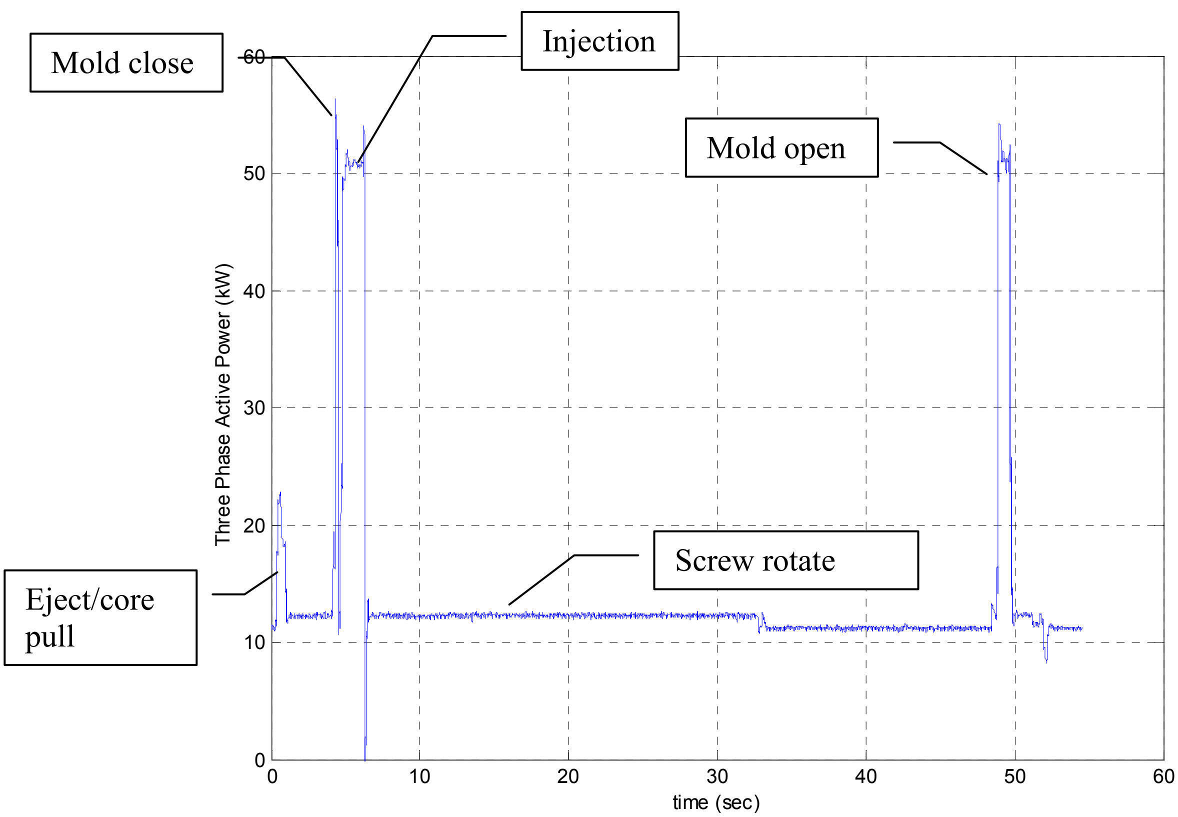

Fig. 4 Operating modes in part production cycle (VFD @ 60Hz)

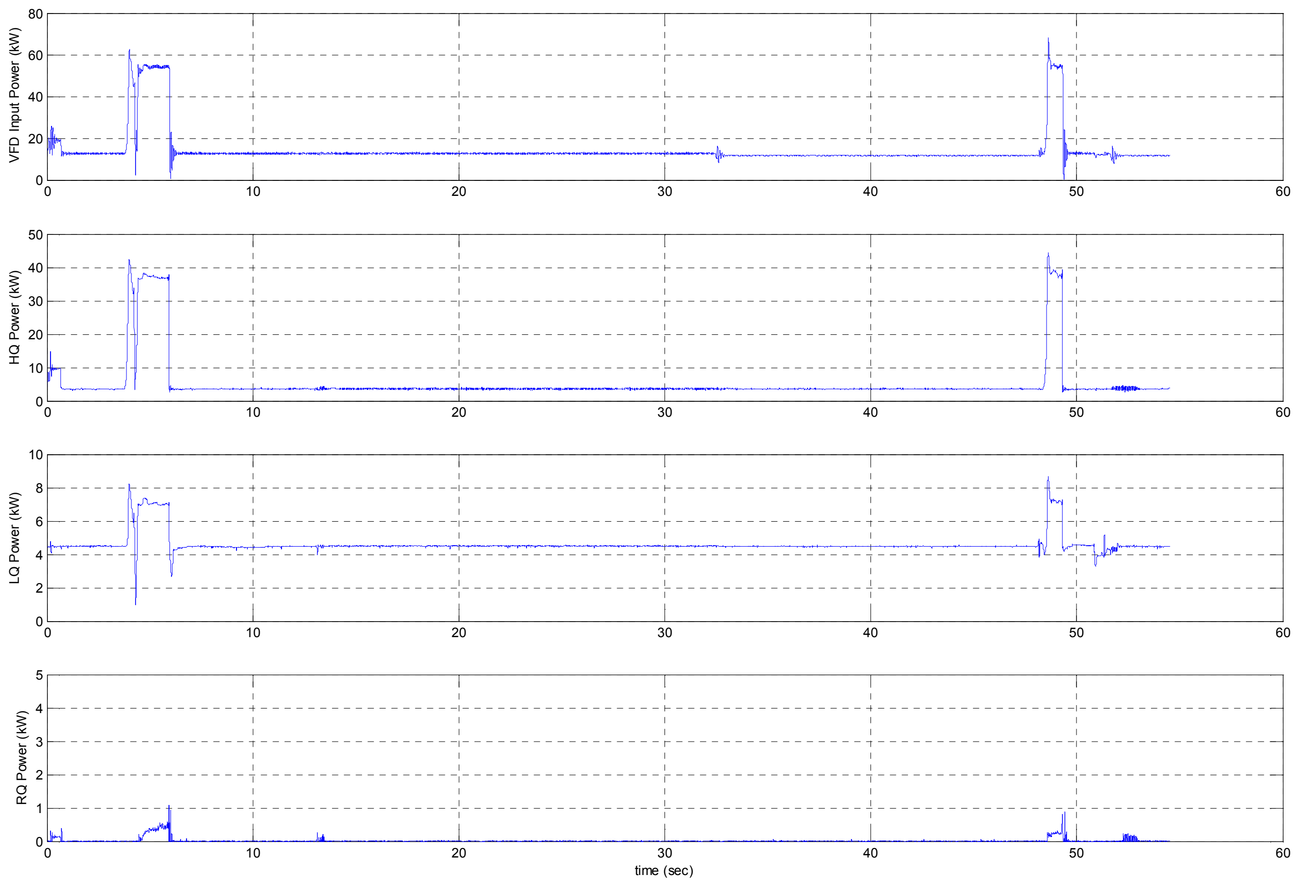

Fig. 5 Power at each system node (VFD @ 60Hz)

Results Test 2: VFD Output Frequency Reduced to 36 Hz During Screw Rotate Mode

Discussions with plant personnel at PMC indicated pump and/or motor failures when the pump speed was reduced by the VFD during screw rotate mode. This was observed for the "original settings" of the VFD after it was installed. Although no records were kept, it is believed that under the "original settings" the VFD was running the motor at 12 Hz (20% of 60Hz) during screw rotate. The 50HP motor is rated for 1200rpm when operated at 60Hz. A 12 Hz motor input would result in a hydraulic pump speed of less than 240rpm. Analysis of the hydraulic pump indicates that 240rpm is below the pump minimum eject speed. A decision was made with PMC personnel during testing that the system would not be operated at its "original settings" that caused component failures.

A conservative estimate of minimum pump speed for this system is 600rpm. The VFD was programmed to reduce motor frequency to 36Hz during the screw rotate mode. This results in a pump speed of approximately 720rpm. Hydraulic fluid temperature was continuously monitored to ensure safe operating temperatures. Figure 6 shows the active power at each measurement node (nodes as shown in Fig.1) plotted for one part production cycle for the reprogrammed VFD. The hydraulic fluid temperature reached a steady state of 109 ºF during this test.

A comparison of the electric power input to the VFD as measured by the two power meters is shown in Fig. 7. The average active power input to the VFD per part production cycle (lasting approximately 54.5 seconds) for each meter is shown in Table 2.

Table 2 (VFD @ 36Hz during screw rotate)

	WT1030M	PPC
Average active power per part production cycle (kW)	9.1 kW	9.7 kW

On the basis of the WT1030M a 6.6% difference is noted. The WT1030M consistently read lower active power input to the VFD than the PPC meter. One possible cause for the difference is the meter update rates. The WT1030M updated its output every 100ms. The PPC updated its output every 17ms. An undersampling of the active power could result in a lower average reading.

Comparative Analysis of Results

The input power to the VFD is compared in Fig. 8. The power savings by reducing the VFD during screw rotate mode is highlighted. On a per part production cycle basis, the average power savings indicated by the PPC is

$$P_{saved}\big|_{\text{PPC}} = 14.4 - 9.7 = 4.7\text{kW} \tag{1}$$

On a per part production cycle basis, the average power savings indicated by the WT1030M is

$$P_{saved}\big|_{\text{WT1030M}} = 13.9 - 9.1 = 4.8\text{kW} \tag{2}$$

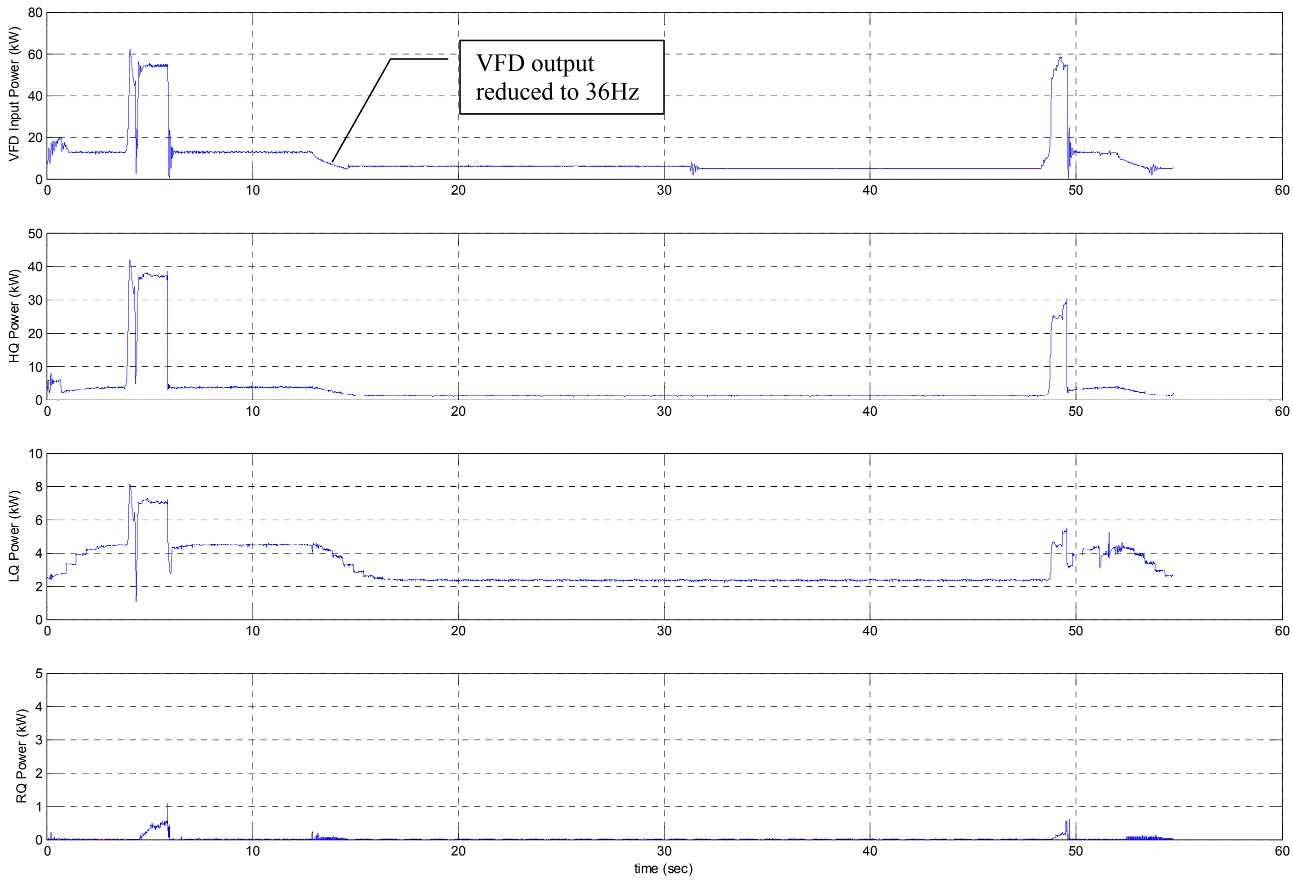

Fig. 6 Power at each system node (VFD @ 36Hz during screw rotate)

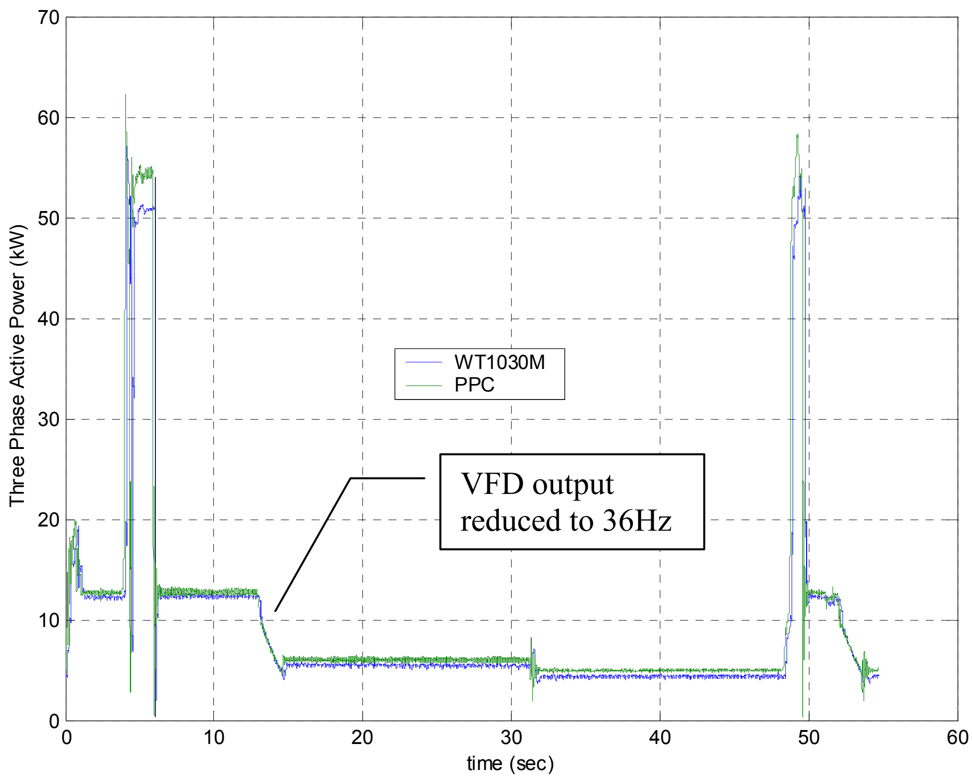

Fig. 7 Comparison of the three phase active power measured by each power meter (VFD @ 36Hz during screw rotate)

The energy savings per part produced is the product of the power saved and the time to produce one part:

$$E_{saved} = \left(P_{saved}\right)\left(t_{part}\right) = \left(4.7\text{kW}\right)\left(54.5\frac{\text{sec}}{\text{part}}\right)\left(\frac{1\text{hour}}{3600\text{sec}}\right) = 0.0710\frac{\text{kWh}}{\text{part}} \quad (3)$$

Assuming the press is producing *this* part continuously on two 40 hour weekly shifts for 40 weeks per year, an extrapolated yearly energy savings is

$$E_{saved}\Big|_{\text{per year}} = \left(4.7\text{kW}\right)\left(80\frac{\text{hours}}{\text{week}}\right)\left(40\frac{\text{weeks}}{\text{year}}\right) = 15{,}040\frac{\text{kWh}}{\text{year}} \quad (4)$$

Energy cost savings per year based on an electric rate charge of $0.045\frac{\$}{\text{kWh}}$

$$C_{saved}\Big|_{\text{year}} = \left(15{,}040\frac{\text{kWh}}{\text{year}}\right)\left(0.045\frac{\$}{\text{kWh}}\right) = \$677/\text{year} \quad (5)$$

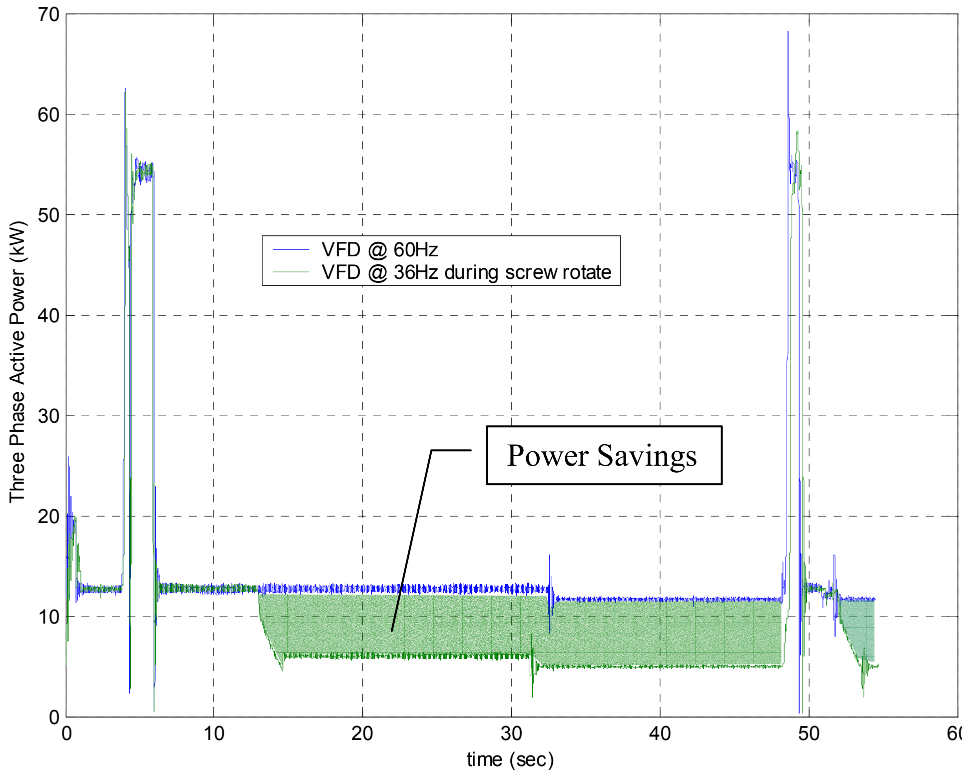

Fig. 8 Comparison of the three phase active power for the two different VFD settings

Reviewing the assumptions in (3)-(5):

- Power saved per part is based on the *particular part* being produced primarily because part cooling times vary
- Energy saved per part is also based on the particular part being produced because part cycle times vary
- Energy and cost savings per year are based on press utilization rate, the part being produced, and electric energy cost
- Other factors include press hydraulic settings such as pressure set-point

Hydraulic System Analysis: Variable Displacement Pump

An engineering analysis of the hydraulic system was performed to determine the potential energy savings if a pressure compensated, variable displacement hydraulic pump replaced the both the high flow and low flow fixed displacement pumps presently installed as shown in Fig. 1. A modified system diagram is shown in Fig. 9.

Specifications for the variable displacement pump were based on system operation with the VFD output at 60Hz as shown in Fig. 6(a). The pump size is based on a maximum flow rate of 70gpm at a pressure of 1500psi (46 HP(hyd)). This pump would be capable of delivering the same maximum power as the existing pump. A Rexroth pump that meets these specifications was chosen for the analysis.

A variable displacement pump will reduce its power consumption based on the demand of the hydraulic system. The Rexroth pump consumes approximately 4.5kW(hyd) during times of minimal hydraulic system demand. Based on a motor efficiency of 90%, the active power input to the system during times of minimal hydraulic system demand would be 5kWe. The difference between the existing system active power input and the variable displacement pump system active power input is shown graphically in Fig. 10.

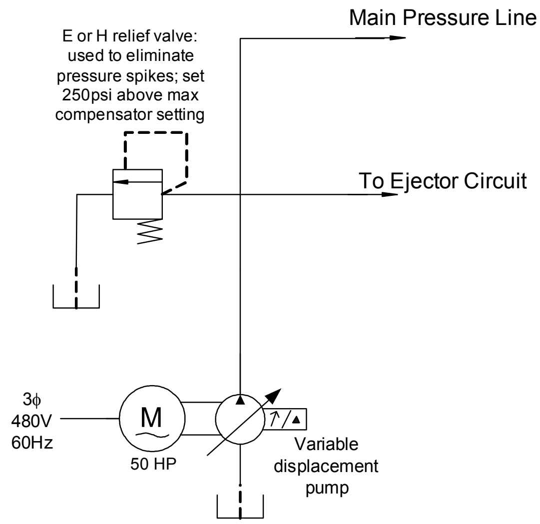

Fig. 9 Modified simplified hydraulic system diagram of PMC press #15

The power reduction is calculated using the data shown in Fig. 10(b)

$$P_{saved}\Big|_{\text{var-vol}} = \left(\frac{2.8}{55}\right)(12.6-5)+\left(\frac{26.6}{55}\right)(12.6-5)+\left(\frac{15.3}{55}\right)(11.7-5)+\left(\frac{2.3}{55}\right)(11.7-5) \tag{6}$$
$$= 6.2\text{kW}$$

The energy savings per part produced is the product of the power saved and the time to produce one part:

$$E_{saved}\Big|_{\text{var-vol}} = (P_{saved})(t_{part}) = (6.2\text{kW})\left(54.5\frac{\text{sec}}{\text{part}}\right)\left(\frac{1\text{hour}}{3600\text{sec}}\right) = 0.094\frac{\text{kWh}}{\text{part}} \tag{7}$$

Assuming the press is producing *this* part continuously on two 40 hour weekly shifts for 40 weeks per year, an extrapolated yearly energy savings is

$$E_{saved}\Big|_{\text{var-vol, per year}} = (6.2\text{kW})\left(80\frac{\text{hours}}{\text{week}}\right)\left(40\frac{\text{weeks}}{\text{year}}\right) = 19{,}840\frac{\text{kWh}}{\text{year}} \tag{8}$$

Energy cost savings per year based on an electric rate charge of $0.045\frac{\$}{\text{kWh}}$

$$C_{saved}\Big|_{\text{var-vol, year}} = \left(19{,}840\frac{\text{kWh}}{\text{year}}\right)\left(0.045\frac{\$}{\text{kWh}}\right) = \$893/\text{year} \tag{9}$$

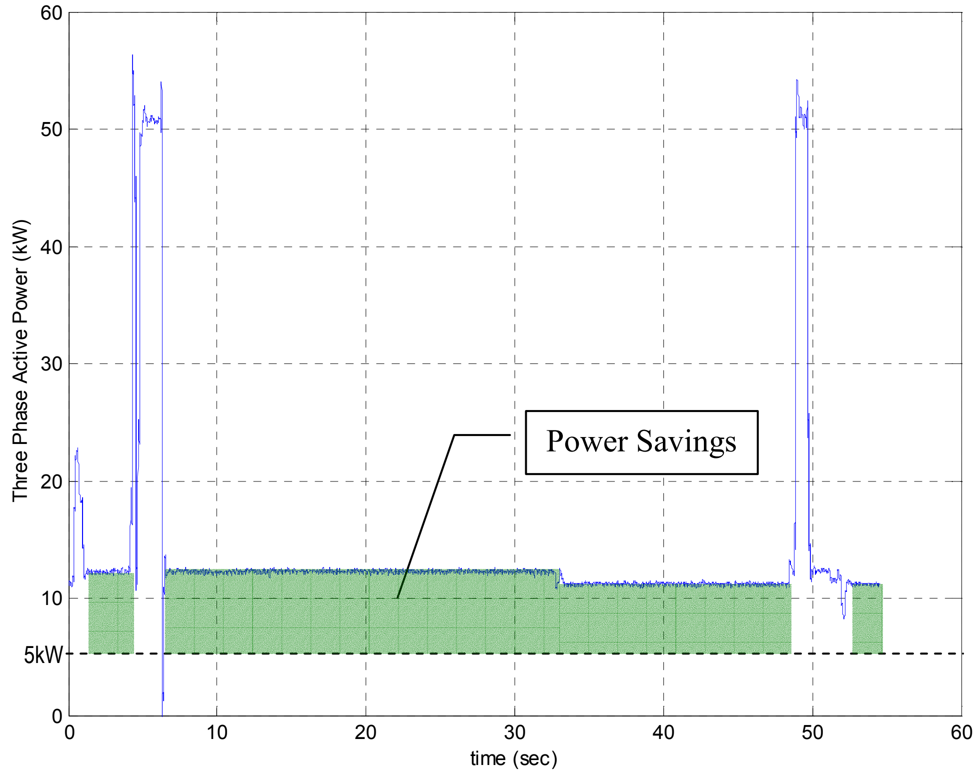

Fig. 10(a) Estimated power savings with a variable displacement pump

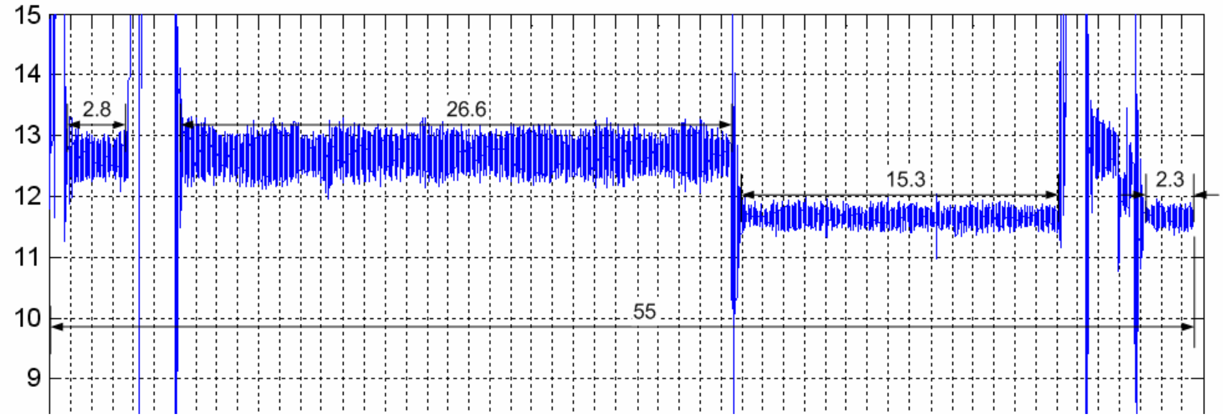

Fig. 10(b) Estimating power savings with a variable displacement pump

The acquisition and installation cost for the variable displacement pump is shown in Table 3. The motor replacement is included because the existing 50HP motor is a 1200rpm model. The variable displacement pump requires an 1800rpm motor.

Table 3

Variable displacement pump (70gpm)	$4,150
50HP, 1800rpm high efficiency motor	$2,350
Miscellaneous parts	$1,000
Installation labor	$2,000
Total	**$9,500**

Conclusions

Baseline electric energy use of an injection-molded plastic part press has been measured. The measured power savings for operating the press with a variable frequency drive is 4.7kWe. Yearly energy savings for operating the press with a variable frequency drive were extrapolated.

Projections of system energy use if the fixed displacement pump is replaced with a variable displacement pump were calculated. The projected power savings for operating the press with a variable displacement pump is 6.2kWe. The total acquisition and installation cost of variable displacement pump is estimated as $9,500. Yearly energy savings for operating the press with a variable displacement pump were extrapolated.

These results are predicated on a baseline data set for a particular part being produced by a particular press. Other parts will have different savings based on the proportion of their production cycle for which hydraulic demand is minimal. Likewise, extrapolated energy savings are based on a particular press duty cycle over one year. The energy savings will differ proportionally to the press duty cycle.

Three undergraduate students were directly involved in the execution of this project. Their contributions included specifying, ordering, and installing all hydraulic instrumentation. They designed the hydraulic manifold interface and the cabling and data acquisition support hardware. They tested the instrumentation system before installation at MSOE's Fluid Power Institute. The students assisted in developing a LabVIEW data acquisition program for synchronizing electric power data to hydraulic data.

Feedback from the undergraduates was uniformly positive. They appreciated working in an industrial environment and getting paid to perform work directly related to their studies. Of particular benefit were the times students were in a class taught by one of the authors that was related to their work on this project. The students were able to relate energy conversion principles from this project to their classmates during class.

References

1. Wrate, G, "Focus on Energy – Wisconsin's Initiative to Reduce Industrial Energy Consumption," *Proceedings of the 2002 American Society for Engineering Education Annual Conference & Exposition.*
2. Wisconsin Division of Energy, Department of Energy, "Public Benefits in Wisconsin: The Focus on Energy Plan" Request for Proposals, October 2000.

3. Neun, J.A., “Improving the Efficiency of Plastic Injection Molding Machines: A Case History,” Kadant-AES white paper, September, 2002, Queensbury NY.
4. Schaufelberger, W., “Engineering Education for Innovation, A Control Engineer’s Perspective,” SEFI Annual Conference 1995, Compiègne.
5. Reynolds, M.C., Meckl, P.H., Yao, B., “The Educational Impact of A Gantry Crane Project in an Undergraduate Controls Class,” *Proceedings of IMECE,* International Mechanical Engineering Congress and Exposition, Nov. 17-22, 2002, New Orleans, LA.
6. Walworth, M., Mahajan, A., McDonald, D., “An Innovative Integrated Learning Laboratory Environment,” Unknown.
7. Zywno, M.S., Kennedy, D.C., “Integrating the Internet, Multimedia Components, and
8. Hands-On Experimentation into Problem-Based Control Education,” 2000 ASEE/IEEE Frontiers in Education Conference, Kansas City, MO.
9. Knight, C., “Modern Engineering Laboratories That Deliver,” *Proceedings of the 2002 American Society for Engineering Education Annual Conference & Exposition*.

Biographical Information

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THOMAS WANKE is the director of MSOE’s Fluid Power Institute. He has more than 35 years of experience in fluid power technology, 25 of which have been at MSOE. Wanke has a bachelor’s degree in mechanical engineering technology and a master’s degree in engineering with a fluid power specialty option, both from MSOE. He has worked on projects in component and system design; development and evaluation; field troubleshooting and failure analysis; and fluids, filtration, and contamination control. He is a certified fluid power engineer and is active in the Fluid Power Society on several committees. Wanke is chairman of the NFPA T2.12 Testing Technology Committee.

MICHAEL SCHEUERELL is a senior at MSOE as well as an undergraduate research assistant at MSOE’s Fluid Power Institute. He expects to graduate with a BSEE and a minor in Physics in November of 2004.