

Improving the Efficiency of Die Casting Machine Hydraulic Systems With the Retrofit of Adjustable Frequency Drives

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ABSTRACT

Die casting is a common method of light metal processing which is used to produce accurately dimensioned, sharply defined metal parts. Most die casting machines in use today utilize a complex hydraulic system to perform the necessary work required for the process. The pressure and flow rate demands on the hydraulic system vary significantly throughout the cycle. Many older systems are greatly oversized so that they are able to meet the peak hydraulic demand at any point. These systems operate inefficiently because there is typically no way to limit the hydraulic capacity during periods of low demand. As a result, fluid is throttled to lower pressures and excess fluid flow is routed directly back to the system reservoir, wasting motor energy and increasing the thermal load on the cooling system.

One option for improving the efficiency of older die casting machines currently in use is the retrofit of an adjustable frequency drive, or AFD. An AFD allows the speed of the pump motor to be varied, changing the pump output to suit the cycle demands. This minimizes the amount of wasted energy without affecting other process parameters. This paper will discuss the die casting process and examine the energy savings potential of retrofitting die casting machines with adjustable frequency drives.

BACKGROUND

Die casting is one of the dominant processes in the metalworking industry. It produces a higher annual volume and has a greater number of applications than any other metalworking process. It is estimated that the die casting industry accounts for over two billion pounds of finished product annually, with revenues approaching eight billion dollars. Based on data provided by the North American Die Casting Association, NADCA, there are over 450 die casting plants in the United States operating over 6,800 total machines, which represents a connected electrical load of over 315 MW.

DIE CASTING PROCESS

The basic die casting process is very similar to the injection molding process used for forming plastic parts. Two hardened steel mold or die halves are moved together and a large force is exerted against them to keep the halves from separating upon injection. Molten metal is then forced, at high pressure (2-15 ksi) and velocity (100-200 fps) into the mold. The metal solidifies quickly as it comes into contact with the cooled die. The die halves are drawn apart and the casting is ejected. Unlike the plastic injection molding process, the raw material is melted previous to entering the injection chamber in an ancillary furnace.

DIE CASTING MACHINES

A typical die casting machine, DCM, consists of basically four fundamental systems. These are the casting mold or die, the clamping unit, the injection unit, and the hydraulic system.

Die casting molds perform two crucial functions; imparting the desired shape to the molten metal, and removing heat from the metal to solidify the part. The mold houses the impression into which the molten metal will be forced, creating the desired part dimensions. Typically, fluid passageways embedded in the back of the mold halves are used to cool the mold. A temperature-controlled fluid such as a water-glycol mixture or oil is pumped through the mold to maintain a desired mold temperature. This allows the heat rejected from the parts to be quickly transferred away from the mold, speeding the solidification process.

The clamping unit is responsible for opening and closing the mold halves, as well as exerting the force that holds the two halves of the mold together during injection. Most die casting machines use a type of clamping unit called a toggle clamp. This is a mechanical linkage that allows the use of a relatively small hydraulic cylinder to achieve the mold movement and high clamping force. In some cases, a single large diameter hydraulic cylinder is used instead of the toggle mechanism.

The injection unit is used to force the molten metal into the mold. It functions like a single cylinder piston pump for the molten metal. Its job is to push the metal into the mold at high velocity and pressure.

There are two classes of injection unit, the cold chamber machine and the hot chamber machine. In a hot chamber machine, the injection plunger and injection cylinder are continually immersed in the molten metal. Typically cold chamber machines are used with high melting point alloys that would attack the plunger and cylinder assemblies if left in constant contact, while the hot chamber machine would be used with low melting point alloys such as zinc and magnesium. A hot chamber machine is slightly faster than the cold chamber machine because there is no need to wait for the metal to be poured.

The hydraulic system generates and transmits power throughout the machine. A typical die casting machine hydraulic system uses a fixed displacement pump coupled with a constant speed, AC induction motor.

DIE CASTING MOLDING CYCLE AND HYDRAULIC DEMANDS

The instantaneous demands on the hydraulic system of a die casting machine are determined by the set of actions occurring throughout the molding cycle. There are eight significant actions that occur in a typical die casting cycle in the following order. These are: mold close, toggle lock, idle1, slow shot, quick shot, hold (alt. intensify), mold open, and idle2. Die casting machines equipped with a hydraulic accumulator also would have an accumulator charge requirement that can occur at any time during the cycle. Other secondary hydraulic actions that occur but do not impose a large demand on the system are: injection plunger forward, injection plunger return, ejector plate forward, and ejector plate retract. The following discussion will explain the purpose of each machine action and outline what hydraulic requirements each action imposes on the hydraulic power pack.

Mold Close – During this stage the mold is being moved into the closed position by the clamping unit. In both toggle and straight hydraulic ram clamping units, this action requires a large amount of fluid at low pressure (~250 psi) as compared to other actions. Typically the ejector plate will also return during this phase. Time for this phase will ordinarily be in the range of 2-5 seconds.

Toggle Lock – During this stage the mold has closed and the clamp pressure is building as the

toggle mechanism approaches its locked position. This action requires little fluid flow, but the pressure will build close to the peak hydraulic pressure (~1200 psi). The duration of this phase will range between 2-5 seconds.

Idle1 – During this stage the main machine components are idle, waiting for the molten metal to either be ladled by hand or robot into the injection cylinder. The mold is still cooling from the previous casting. No flow is required for this phase, although pressure is held in the clamp cylinder to hold the mold closed. Duration of this stage varies widely, from 0-15 seconds.

Slow Shot – The injection plunger moves forward in the injection cylinder, sealing off the ladling slot and forcing molten metal into the now cooled mold. The primary objective of this phase is to get a good initial mold fill while forcing out the trapped air. Some DCMs utilize a vacuum system to evacuate the air from the mold just prior to the injection of metal. The flow requirement for this phase is small compared to mold close. The pressure requirement builds to the maximum system pressure (~1500 psi) as backpressure from the mold increases. Time ranges from 1-3 seconds.

Quick Shot – The injection plunger rapidly shoots forward until it reaches its preset stop limit. The higher injection velocity forces the molten metal into the entire mold, completing the mold fill. The flow requirement for this phase is high because of the rapid movement of the plunger. The pressure requirement is also high as the plunger meets tremendous backpressure from the mold. Duration is in the range of 0.25-0.5 seconds.

Hold – During this period, the injection plunger is maintaining pressure on the metal in the mold during its solidification. This compensates for shrinkage as the part solidifies. Flow requirements are low while pressure requirements are high. The duration of this phase is highly dependant on part characteristics such as maximum wall thickness and total shot size.

Alt. Intensify – Some machines will utilize an intensifier to apply a high pressure to the metal in the mold during part solidification (~6-15 ksi). Again, this is to achieve complete mold fill and acceptable part density. Flow requirements are low while pressure requirements are high.

Mold Open – After the part has solidified, the mold is opened by the clamping mechanism. As the

mold opens, the injection plunger moves forward pushing the biscuit out of the stationary mold half allowing the part to be carried with the ejector mold half. Once the mold is open, the ejector plate pushes forward kicking the part loose from the mold. Pressure requirements are initially high while flow requirements are low to release the toggle clamp from its locked position. Once the mold is unlocked the pressure will drop (~500 psi) and the flow requirement will increase as the mold opens. This phase typically occurs slightly faster than mold close, in the range of 1-4 seconds.

Idle2 – After the part has solidified and the mold is fully open, the machine stays idle waiting for the part to be removed manually or by a robot. Once the part has been removed, the mold is sprayed with a mixture of die lubricant and water. This is done to ensure easy part release from the mold, to limit the wear on the die halves, and to cool the surface temperature of the mold. This period has no flow and pressure requirements. Duration of this period can vary widely depending on process parameters and method of part removal.

Accumulator Charge – During this phase, fluid is being pumped against an inert gas pre-charge into an accumulator. This allows pump work to be stored and released quickly, serving to reduce the peak load demanded from the pump. Fluid flow is initially moderate while pressure is also moderate (~1000 psi). As the inert gas is compressed the pressure increases. This phase has the highest hydraulic demand.

DIE CASTING MOLDING MACHINE HYDRAULIC SYSTEMS

As seen in the description above, the hydraulic requirements of a DCM vary significantly throughout the cycle. In contrast, a simple hydraulic system might only use a fixed displacement pump driven by a constant speed, AC, induction motor and a mechanical relief valve. This system will produce a constant flow rate and pressure. Since the instantaneous power requirement of the pump is the product of the flow rate and the pressure, this system will have a constant power draw, regardless of the external requirements. Another drawback of this simple system is that it must be sized to meet the peak external demand, even if that peak occurs only during a short part of the cycle. At other times this system wastes energy by returning fluid at high pressure over the relief valve directly back to the reservoir.

DCM manufacturers have addressed these problems by incorporating a number of efficiency improvements into their machines. These include: bypass valves, system pressure modulation, multiple pumps, hydraulic accumulators, and hydraulic intensifiers. These features are found on today's typical die casting machines. In fact, the simple hydraulic system described above would rarely be found in operation today. However, even with these improvements, the overall system efficiency is still quite low. Other efficiency improvements that are beginning to gain acceptance are variable displacement pumps, and adjustable frequency drives, AFDs. These additions can dramatically improve the overall system efficiency. Increasing energy costs have driven DCM manufacturers to include these features on new machines, and have prompted DCM users to look to retrofitting older machines.

ADJUSTABLE FREQUENCY DRIVES AS A RETROFIT

Variable displacement pumps and the use of an AFD are both methods of regulating a pump's volume output. While a variable displacement pump is mechanically altered to achieve a change in volume flow, an AFD changes the frequency of the power going to the AC pump motor, thereby changing the pump speed. Using both methods, bypass fluid and pressure throttling can be kept to a minimum by closely matching the output of the pump to the cycle requirements. However, a variable displacement pump only succeeds in changing the load on the pump motor. Unfortunately, as the load on an AC induction motor decreases, its efficiency and power factor also decrease. AFDs change the speed of the pump motor, keeping the motor near full-load efficiency and at a power factor of near unity all of the time.

The biggest advantage of an AFD as a retrofit over any of the other solutions used to improve the efficiency of a hydraulic system is its ease of installation. Any machine with a constant speed AC induction motor can be retrofit without making substantial changes to the hydraulic system. The vast majority of DCMs in operation today already utilize fixed displacement pumps. The AFD is ideally suited for controlling the volume output of a fixed displacement pump.

Installing an AFD on a DCM requires only two main interfaces to be established, the pump motor power input and the system signal processing. Most new DCMs and many of the more modern ones possess integrated control systems that can be

directly connected to an AFD. Older machines with multiple independent digital controls and even earlier machines with mechanical timer relay and solenoid control need the addition of a programmable logic controller, PLC, to interpret the system signals and relay them to the AFD. Installation of the physical apparatus and connections for an AFD typically takes only one to two shifts and can be done during times when the machine would already be down.

The goal of the retrofit system is to match the pump output to the requirements of the particular portion of the cycle that is occurring. The installer of the AFD determines exactly what process actions are significant in terms of hydraulic demand, and sets these up to be recognized by the AFD. For each action recognized, there will be an ideal motor speed set point. Optimizing the motor speed set points should be done for each individual part that will be produced on the machine. Typical AFDs allow settings to be customized for individual molds. This is because ideal motor speed set points will vary depending upon the process requirements, which in turn, are dictated by the properties of the part being produced.

Ideally, once the AFD has been installed, all of the major flow restriction valves such as those controlling the mold and injection speeds should be opened so that only the AFD is controlling the fluid flow rate. Then the motor speed set points should be established. This is typically done on a trial and error basis, where motor speed is reduced until either the cycle time starts to increase, or part quality is compromised.

SAVINGS

As with any business decision, the purchase and installation of an AFD will only be undertaken if it can be expected to recoup the initial investment in an acceptable period of time. While initial costs for purchase and installation are readily obtained from AFD distributors and installers, to quantify the savings is much more difficult. Due to the complexity of the hydraulic systems, the affinity laws usually used to predict AFD savings for centrifugal pumps and fans are not sufficient for DCM installations.

Rather than using this type of analytical means to develop a method of predicting savings, a combination of industry experience and experimental data will be investigated. This is likely to produce a more accurate and manageable estimation for savings. Unlike the plastic injection molding industry, where the use of AFDs is now a common practice, there are relatively few retrofit installations

on die casting machines. Consequently there is currently very limited data available concerning the energy savings achievable via an AFD retrofit on a DCM.

Discussions with an installer of AFDs who has retrofit several die casting machines provided several general rules of thumb that can be used to initially determine if a machine is a good candidate for retrofit. For a machine with constant displacement pumps, an estimate of 15-45% of pre-retrofit energy consumption savings is expected. Generally savings will increase (~10%) if multiple pump motors are employed. Increased cycle time also tends towards an increase in savings. Savings are not expected to differ significantly between toggle and straight hydraulic ram clamping units. Nor are percent savings expected to differ significantly between die casting presses in the range of 400 to 1500 tons. The use of multiple pumps driven by a single pump motor is expected to slightly decrease savings. If variable displacement pumps are used, overall savings will generally be below 20% of pre retrofit energy use, and installation is not recommended because the simple payback period will be extensive. Processes with cycles times less than 15 seconds should also not be considered for an AFD retrofit, due to the ramp up and ramp down time of the AFD. If the cycle time is too short, the AFD will not have enough time to accelerate and decelerate the motor to the ideal set points.

ANALYSIS OF AFD INSTALLATIONS

Some AFD installers offer to provide and install a trial AFD unit from which they will gather data on energy consumption to demonstrate savings. Some of this test data was obtained from an AFD installer. This data contained the pump motor horsepower, the machine tonnage and the pre and post retrofit average power draw for eight die casting machines. The average energy savings for these machines was 35%. The savings ranged from a high of 45% to a low of 22%, with no apparent correlation to any of the other reported parameters. It is important to note that this data was collected by a power meter, measuring only total kilowatt-hours, over a two-hour period and was not corrected for any change in cycle time or for long periods of idle time.

To verify the savings reported by the AFD installer and to try to identify key process and machine parameters affecting savings, an in-depth analysis was performed on four machines located at three separate manufacturing facilities. To collect data on pre and post retrofit energy consumption, a Rustrak Ranger IV data logger was used. Phase voltage, phase amperage, and phase angle were

measured with a sampling rate of four samples per second for all three phases. Using these inputs, instantaneous power, power factor, and total power were also calculated and recorded. Figure 1 shows a cycle taken from a post-retrofit machine with a time line indicating the actions taking place during the cycle. Because the AFD was not set up to recognize every machine action, there is also a time line indicating the speed settings of the AFD through the course of the cycle.

Interestingly, not all of the AFD installations investigated recognized the same number of machine actions. The AFD retrofit demonstrated in Figure 1 was setup to recognize four actions, while one of the other tested AFD installations was set up to recognize six machine actions. The explanation for this is that some cycles regularly have machine actions that overlap other actions having a higher hydraulic demand. The motor speed set point would necessarily be established to fulfill the higher demand action. For example, if there is regularly an accumulator charge requirement during mold close, the system demand will be dictated by the accumulator charge, and there is nothing to be gained by recognizing the mold close action.

The following table, Table 1, shows the average motor speed set points for the four machine actions that were recognized in all of the test installations.

Table 1. Average AFD Settings
Percentage of Rated Motor Speed

Accumulator Charge	85%
Mold Open	73%
Injection	70%
Idle	28%

These settings are as expected, with the actions having a lower hydraulic demand showing the most reduction in motor speed. Although the hydraulic demand at idle is very small, AFDs will typically not be run below 25% of rated speed due to concerns of motor overheating and excessive ramp up time.

Data was also collected on many process and machine parameters. Several parameters were investigated that seemed to lack any strong correlation to savings. These were, clamp tonnage, pre-retrofit average motor load, motor horsepower, total cycle time, mold size, shot size, and number of machine actions recognized by the AFD. In fact, the only process or machine parameter which provided a consistent positive correlation was the ratio of idle time to total cycle time.

The average savings for the four machines when including all data was 35.2%, with a high of 38.4% and a low of 33.2%. This data seems to agree with the findings of the AFD installer. However, it was found that there were significant changes in cycle time most likely caused by the addition of the AFD. The average change in cycle time was an increase of 2.9%, with a maximum increase of 7.5% and a minimum that was actually a decrease of 4.5%. The machines that exhibited an increase in cycle time likely were set-up incorrectly, or were not adjusted properly when the mold was changed. An AFD is capable of running the motor at speeds higher than rated, so should not inherently generate any change in cycle time. In fact, because the motor may be run faster than the rated speed, certain machine actions may be made faster than previously possible. It was found with most of the examined installations that the method of optimization for the AFD was less than sufficient. Flow control valve settings were not changed and no individual mold optimization was performed. Settings were established which were aimed at satisfying the requirements for any of the molds run on the machine. This was an attempt to generate some savings all of the time without having to optimize for each mold and train employees to operate and adjust the AFD. This method must be avoided, because with the high overhead and operational costs for these machines, the increase in cycle time significantly outweighs any decrease in energy consumption.

Also, it was found that there were several periods of time during the tests where the machines were idle. These idle periods were due to operators either going on break, or changing the process set-up. Because an AFD will generate significant savings when the machine is idle, these periods inflate the average savings.

In order to predict an accurate per cycle savings based on cycle parameters, the idle periods were neglected and the data was examined on a power consumption per cycle basis to negate the changes in cycle times. With these corrections, the average energy savings for the four installations was 24.4%, with a high of 28.2% and a low of 19.7%. Figures 2 and 3 show comparison graphs of the pre and post retrofit cycle energy usage for two of the machines.

A PROTOCOL FOR ASSESSING THE EFFICACY OF AN AFD RETROFIT

It is not possible with the size of this data set to develop a complete mathematical model to predict savings based on several machine and process parameters. However, it is possible to say that little

correlation existed between most of these parameters and the measured savings. It is apparent from this data that the dominant factor in determining savings is the ratio of idle time to total cycle time. All of the collected data correlates well to this factor. To determine whether a DCM is a good candidate for a AFD retrofit and what the expected savings might be, the following steps should be taken.

Data Collection

As in any situation, the more information that can be collected about the DCM and its process, the more informed the estimate of savings. At least three pieces of information are needed to make a prediction of AFD savings. These include the number and size of electric hydraulic pump motors, whether or not variable displacement pumps are used, and the cycle time breakdown of the process.

The most important piece of information collected is the breakdown of the total cycle time into its separate actions as defined previously. This can be done through visual means using an instrument no more complex than a handheld stopwatch.

Determination of Pre-Retrofit Motor Energy Use

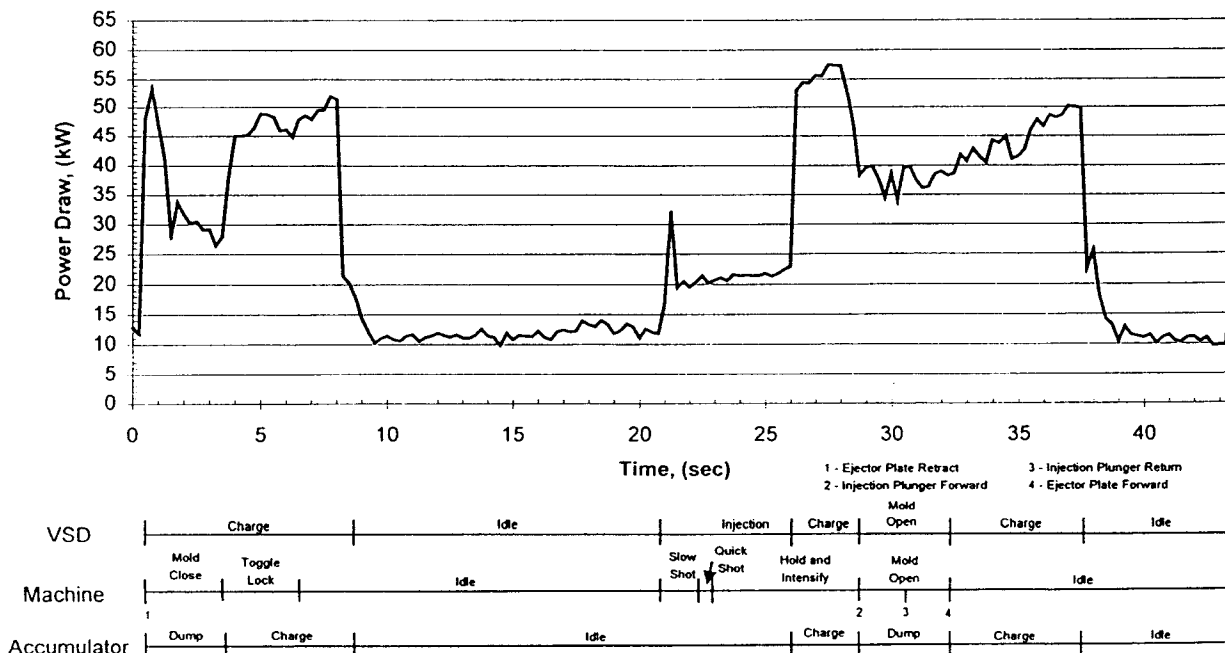
The pre-retrofit motor energy use must be obtained to get an accurate prediction of savings. This is because the generated savings are a percentage of the pre-retrofit energy use, not the rated

power of the motor. In data collected from a combination of sources, totaling 20 DCMs, the average pre-retrofit motor load was 64%. However, the range was from a high of 99% to a low of 35%. Clearly the pre-retrofit motor load can vary significantly. This is mostly due to the fact that DCMs rarely operate at their rated clamp tonnage. If a machine is producing a part that is either using a lower injection pressure, a slower injection speed, or which has a projected area that does not require a high clamp tonnage, the machine is adjusted for the specific mold by adjusting the relief and flow restriction valves. Based on this information, the ideal and only really accurate method of finding the pre-retrofit motor energy use is to use some type of measuring equipment. A power meter may be used which calculates the total kilowatt-hours consumed over a certain period of time, an amp clamp may be used with a stop watch to estimate an average power draw, or as in this case, a data logger may be set up to record instantaneous power draw over time.

Determination of AFD Energy Savings

All of the collected data falls within the expected die casting industry guideline for savings of 15-45%. Our estimation of AFD savings is based on a simple mathematical model that very accurately predicts the actual savings measured in the test cases. Generally, during portions of the cycle where the machine is loaded, a 6% savings will be realized. During idle

Figure 1
Cycle Power Draw with VSD



portions of the cycle, such as the period of time the mold is open, and the period of time between the toggle lock and the slow shot, savings will approach 46%. Table 2 shows the proposed method for predicting AFD savings.

Any additional idle time, such as worker breaks, or even unexpected breaks such as a process problem will introduce additional savings. For any period of time the machine is left running at idle, 46% savings may be expected.

Additional Benefits

In addition to the savings generated by reducing the energy consumption of the hydraulic pump motor, there are several other benefits that occur as a result of the addition of an AFD. Less wasted hydraulic energy will decrease the rejection of waste heat into the plant's cooling system. Although uninvestigated in this study, from injection molding guidelines this has the potential of increasing savings 5-20% over the hydraulic pump motor energy savings.

AFDs inherently produce an improvement in the motor's power factor. In all AFD installations investigated in this paper, the average power factor for the hydraulic pump motor was increased from a pre-retrofit range of 0.5-0.75 to 0.97. This would reduce any applicable power factor penalties as well as increasing the load capacity of the plant's transformers and transmission lines.

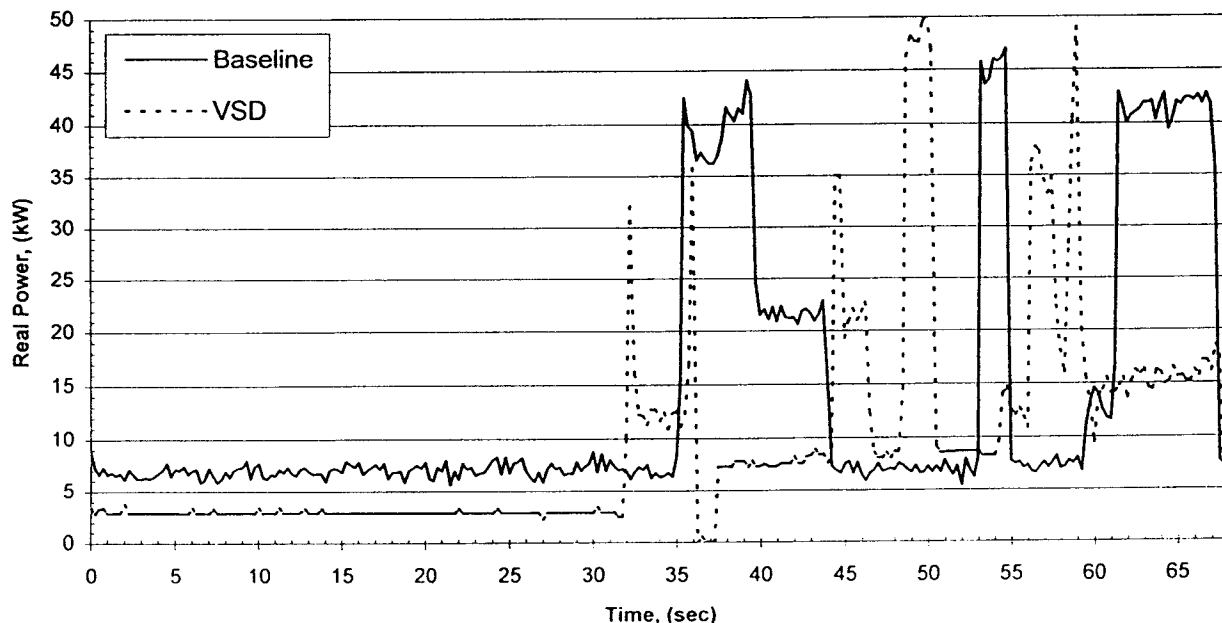
Another benefit of AFDs is their true soft start capabilities. Using an AFD to start a motor drastically reduces inrush current at start-up and during severe load fluctuations, extending motor life. Indeed, even motor operating temperatures can be reduced, extending the life of bearings and motor windings.

CONCLUSIONS

This paper examines the energy savings potential of retrofitting die casting machine hydraulic systems with adjustable frequency drives. It is found that the pre-retrofit motor energy usage may be reduced from 15-45%. It was also found that the most dominant parameter in determining the actual amount of savings was the ratio of idle time to total cycle time. All AFD installations investigated in this paper had simple payback periods in the range of 2-4 years when neglecting utility rebates. All of the machines examined in this project used fixed displacement hydraulic pumps, had toggle clamps and had cold chamber injection units.

A simple protocol was developed in this paper to assist in the determination of whether a die casting machine is a good candidate for an AFD retrofit and in determining expected energy savings.

Figure 2
Baseline Versus VSD Cycle Power Draw - Example 1



It is felt that this study has solidified the claim that many die casting machines are good candidates for an AFD retrofit. Investigation of more installations is ongoing, and is necessary to provide a more comprehensive estimate of energy savings. While this study has provided data that shows AFD retrofits to die casting machines can save energy, it has also brought forth some concerns. Foremost of these is the lack of optimization observed in the investigated installations. Improper set up of an AFD can lead to increased cycle times, thereby offsetting

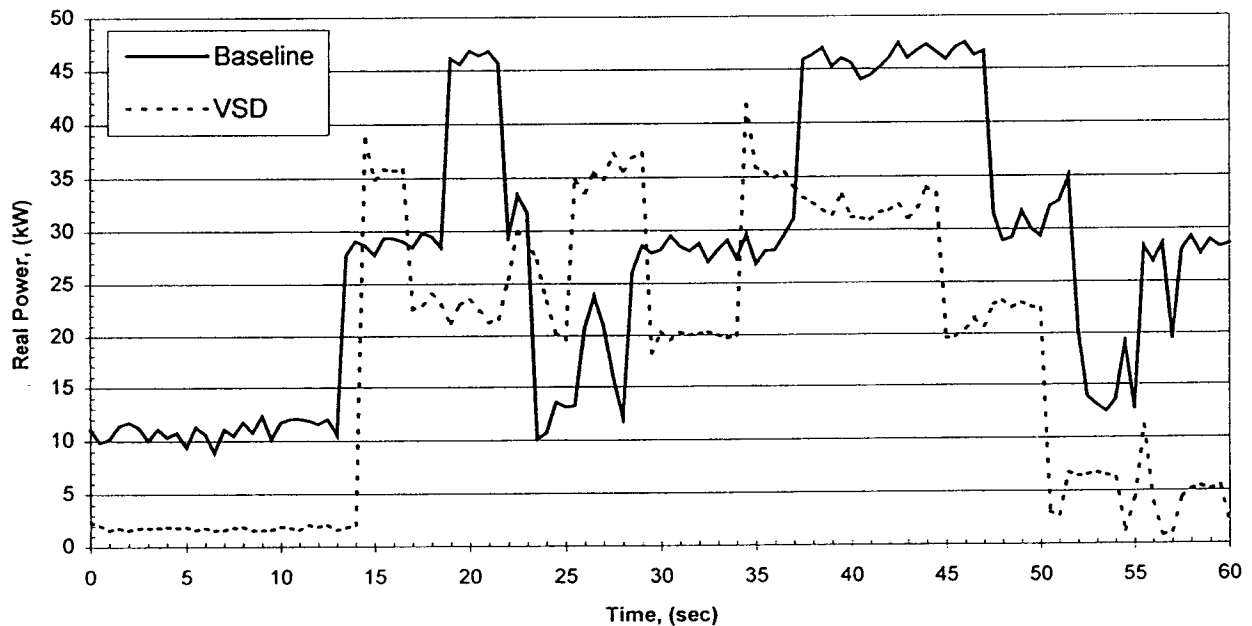
any beneficial effects. The installation of an AFD must be supplemented with support in the areas of management and operation to achieve the optimal results.

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Table 2. Proposed Method for Determining AFD Savings

$$\text{Savings} = \left[0.06 + 0.40 \times \left(\frac{\text{Total Idle Time in Cycle}}{\text{Total Cycle Time}} \right) \right] \times \text{Pre - Retrofit Motor Energy Use}$$

Figure 3
Baseline Versus VSD Cycle Power Draw - Example 2



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