Beloit Gets Fast Payback on Medium Voltage Drives

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April 18, 2012

Abstract: Municipal wastewater treatment plants use low pressure blowers to supply air to the biological process used to remove dissolved organic pollutants. The aeration blowers represent more than half of the total electric power used by most treatment plants. Recent advances in medium voltage drives have made them a cost effective way to dramatically reduce energy consumption for the aeration process.

Keywords: activated sludge, aeration, blowers, energy efficiency, variable frequency drives, medium voltage drives

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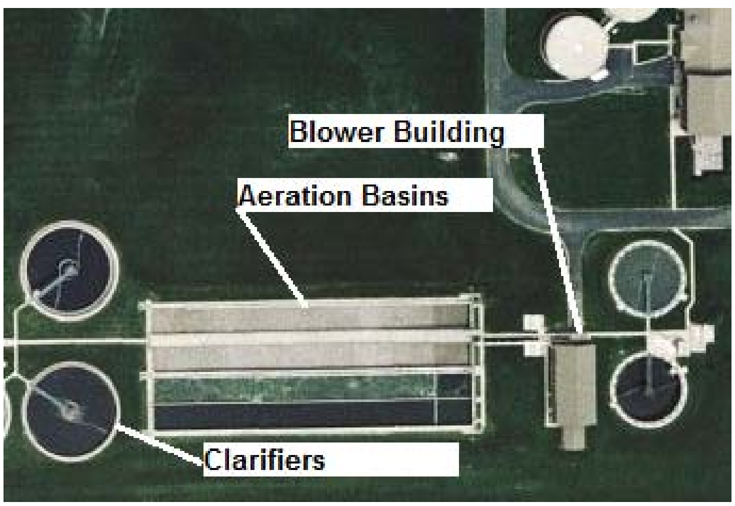
Introduction: The City of Beloit, Wisconsin, employs a conventional activated sludge process for treating wastewater. The aeration basins are a critical part of the biological treatment system. In these basins microorganisms metabolize the organic waste components in the influent wastewater. The oxygen required by the microorganisms for respiration is supplied by bubbling air through diffusers and into the bottom of the aeration basin. As the bubbles rise the oxygen in the air is dissolved into the wastewater.

The air for the aeration process at Beloit is provided by electric motor driven multistage centrifugal blowers. As is typical for most municipal wastewater treatment plants (WWTPs), the power for the aeration blowers accounts for almost half of the total electricity use at the plant[1]. There are two different sizes of blowers at the Beloit WWTP:

- Two 400 hp nominal blowers, with 480 VAC motors
- Three 600 hp nominal blowers, with 4160 VAC motors



Arial View of the Beloit WWTP Aeration System

Seasonal changes in wastewater temperature affect the metabolism of the microorganisms, the oxygen transfer efficiency of the diffusers, and the demand for oxygen. As with most municipal WWTPs, the Beloit plant also experiences fluctuations in wastewater flow and organic loads. Some of these occur on a daily basis, reflecting patterns of population activity. Some short term variations occur when rain flushes the sewer system. The Beloit facility also has a significant load contribution from food processing plants, causing a concentration of organic loads approximately double that of the typical municipal wastewater. Variations in loading from the food processors cause additional fluctuations in air demand.

The organic loading to the plant is quantified as biochemical oxygen demand (BOD) and expressed in units of mg/l. This is an indirect measurement of the pollutant concentration, which consists of complex and varied organic compounds. The wastewater BOD concentration indicates the demand for oxygen that will be exerted in the biological treatment process and the process air requirements.

There are two methods commonly used to modulate the air flow rate delivered by multistage centrifugal blowers. The first, and most common, is throttling the blowers with inlet butterfly valves. The second method is controlling blower speed by using a variable frequency drive (VFD). Although not all blower systems are suitable for VFD control, when it is feasible the power savings are typically 15% to 20% compared to inlet throttling.

Blower Fundamentals: Throttling and VFD control are both routinely used for pump control, and conceptually the implementation for blower control is similar. However, because of the compressibility of air and because of the operating characteristics of centrifugal blowers, the implementation of these techniques for blower control is significantly more complex than for pump control.

Centrifugal blowers with variable speed control follow "affinity laws" similar to those for pumps. Varying the blower speed in essence shifts the blower characteristic curve, with speed reduction moving the curve down and to the left. For small changes in speed the change in blower performance characteristics can be approximated by the following equations[2]:

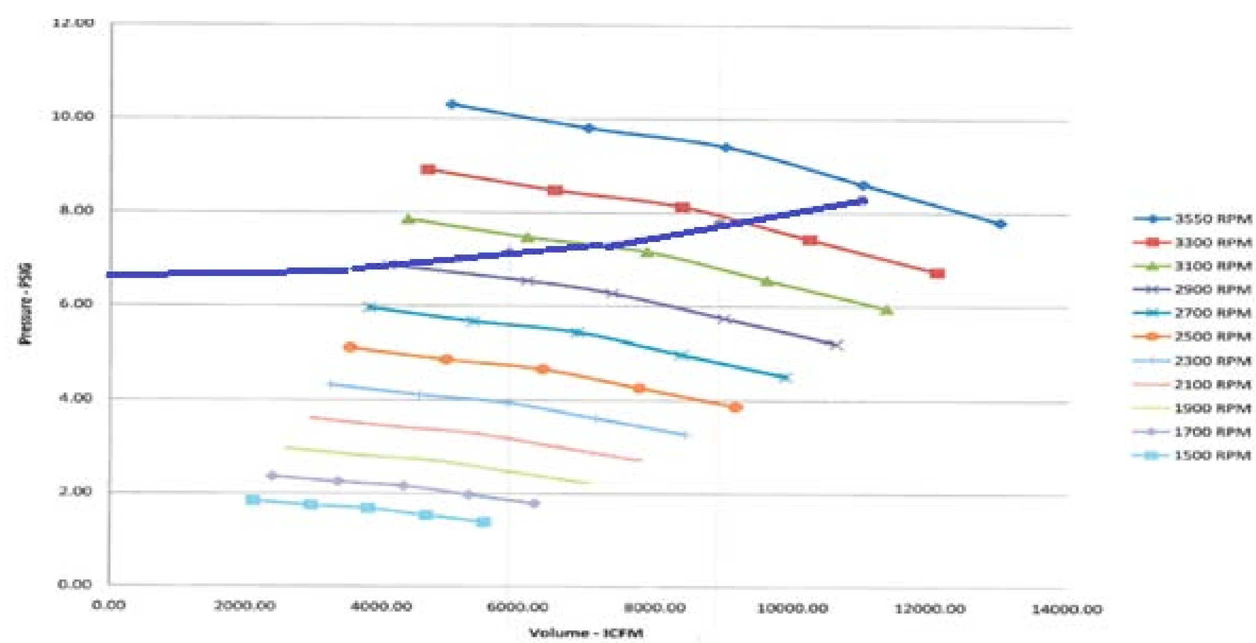
$$Q_2 = Q_1 \cdot \left(\frac{N_2}{N_1}\right)$$

$$P_2 = P_1 \cdot \left(\frac{N_2}{N_1}\right)^2$$

$$p_2 = p_1 \cdot \left(\frac{N_2}{N_1}\right)^3$$

Where:

Q_1 , Q_2 = air flow at original and new operating speed, ICFM
P_1 , P_2 =gauge pressure at original and new operating speed, psig
p_1 , p_2 = power at original and new operating speed, horsepower
N_1 , N_2 = original and new operating speed, rpm



Beloit Blower and System Curves

In addition to the impact of throttling and speed changes, the performance characteristics vary with air density. As the air density decreases with higher ambient temperature or lower barometric pressure the blower discharge pressure capability drops.

The discharge pressure required at the blowers is dictated by the static pressure from the submergence of the diffusers and the friction losses of air moving through the diffusers, the air distribution piping and fittings. At most treatment facilities the largest portion of the total pressure is due to the diffuser submergence. At Beloit the static pressure accounts for approximately 7.0 psig of the total maximum rated blower discharge pressure of 8.5 psig.[3]

The intersection of the system curve with the blower curve at any given set of conditions determines the actual operating point of the blowers. The characteristics of the blowers are constantly changing from density and speed variations. The system curve also constantly shifts as flow control valves at the aeration basins are adjusted. The result is that control of variable speed blowers is more complicated than for pumps[4]. The evaluation of the energy savings is also more complex, and usually requires the efforts of a specialist for accurate savings predictions.

Beloit Energy Conservation Efforts: The Beloit WWTP has been heavily involved in energy conservation measures (ECMs) from its commissioning in 1991. Particular attention has been paid to the aeration system. The plant has an advanced dissolved oxygen (DO) control system[5] to control the blowers so the air flow supply is matched to the biological system's changing demand.

Beloit Blowers (Operator at a 600 hp Blower)

The initial DO control system was based on maintaining a constant discharge pressure, nominally 8.5 psig. The DO control system was modified to incorporate Most-Open-Valve (MOV) technology, which minimizes the friction losses in the air distribution by maintaining valves at their maximum possible position at all times. This eliminated the constant discharge pressure, and allowed the system pressure to float up and down as aeration demand fluctuated. After implementing MOV Beloit's typical system pressure dropped from 8.5 to 7.5 psig.

Because municipal treatment plants are designed for population growth over a twenty year period the capacity of the aeration system exceeds the requirements from current loads. For much of the year the air rate supplied by the blowers at Beloit was dictated by minimum mixing air flow requirements and not the biological treatment demand. The operations staff at Beloit determined that they could reliably meet treatment objectives by operating two of the four aeration basins. The plant further decreased energy consumption and improved reliability by changing from ceramic diffusers to membrane diffusers. This eliminated the need to maintain some air flow to offline basins, which was previously required to prevent fouling of the ceramic diffusers.

Inlet throttling control does not maximize the benefits of the MOV controls, since the inlet valve introduces parasitic pressure drop when throttling for flow control. Using a VFD for control, on the other hand, eliminates creation of unnecessary pressure and maximizes the energy savings. This is the basis for the energy advantage of variable speed control over throttling.

The plant began exploring VFDs for blower control in the mid 1990's. The initial investigation concluded that VFD control was not cost effective at that time, since the energy savings were not able to offset the cost of the VFD. This was particularly true for the larger 600 hp blowers, which required medium voltage (4160 VAC) VFDs. (Note: Although definitions vary, in general VFDs with line side power less than 1,000 VAC are considered low voltage, and VFDs with line side power greater than 1,000 VAC are considered medium voltage.)

Electric energy costs for the plant continued to increase, and as VFD technology improved the cost of low voltage VFDs decreased. The plant and their consulting engineer[6] revisited the evaluation, and in March 2010 ABB ACS 550 LV VFDs were installed on both 400 hp blowers, which have 480 VAC motors. The result was a 15% improvement in the kWh required per pound of BOD removed. The simple payback on energy savings with the 400 hp VFDs was three years.

Although the efficiency of the variable speed 400 hp blowers exceeded the efficiency of the throttled 600 hp blowers, the 400 hp units were not able to supply all of the air required throughout the year. In the summer time the demand of the aeration system increased and operation of a 600 hp blower was required. The expectation is that the 600 hp unit will be operated primarily in warm weather.

The economics and technology of medium voltage VFDs continued to improve, and in 2011 the plant and their consulting engineer determined that medium voltage VFDs had become cost effective. An ABB ACS 2000 Voltage Source Inverter (VSI) Direct to Line (DTL) medium voltage drive was installed in July 2011. The DTL design eliminated the need for a dedicated transformer, and Beloit's existing three phase power supply distribution and grounding system was retained. The new VFD included an active front end for harmonics mitigation, so engineering studies on system resonances and available short circuit compatibility were not needed. Based on the installed cost and projected energy savings upgrading a 600 hp blower control with a medium voltage VFD would provide a three year payback.

ABB ACS 2000, 4160 Volt, Direct to Line, 600 hp VFD at Beloit

Both the 400 hp and 600 hp projects based the initial payback calculations and project justification on the assumption that the full cost of the project would be borne by the City. However, the City and their consulting engineers were able to significantly reduce the city's investment by taking advantage of available incentive programs from the electric utility. In the case of the two 400 hp VFDs a grant from Wisconsin Focus on Energy[7] reduced the payback by 1/3, to two years. A similar incentive from Wisconsin Focus on Energy[7] was provided for the medium voltage installation, and the net payback for Beloit was reduced to two years for the 600 hp VFD as well.

The incentive programs required that the City provide data for evaluation of the performance and energy improvements obtained. This data shows that in both blower revamp programs the energy savings exceeded initial projections.

Medium Voltage Upgrade Details: Installation of the 600 hp ABB medium voltage VFD was straightforward. No significant problems encountered in either construction or commissioning.

The existing 2-pole induction motors were retained. The motors were not inverter duty, but did have a 1.15 service factor. Based on recommendations from the VFD supplier Beloit had the motors rewound and the class F insulation upgraded to a higher voltage rating. This made them suitable for use with the new VFDs. The motors were fitted with new vibration sensors, but this was part of a routine instrumentation upgrade and was not related to the VFD installation.

In part because blower power is a significant portion of the total plant electrical load, harmonics are generally a concern in any wastewater treatment plant installation. This concern was particularly significant at the Beloit facility, since a standby generator is used for emergency power needs and harmonics can affect generator performance. The ABB ACS 2000 VFDs have an active front end (AFE), which provides real time dynamic control of line side harmonics. The line side harmonics with the AFE are comparable with typical 24-pulse VFDs, and exceeded the requirements of IEEE-519 specifications.

Load side dV/dt pulses are also a concern for retrofit applications. The Beloit system posed some unique challenges. In order to prevent interference of new conduit with the overhead crane and blower mechanical maintenance the amount of overhead conduit in the blower room had to be minimized. The 4160 Volt power was run from an existing breaker to the new VFD, which was installed in the blower room adjacent to an interior wall. The load cables were run back to the existing MCC and then to the motor using existing conduit buried in the blower building floor. This resulted in a long (200 ft.) cable run between the VFD and the motor, which often causes problems with motors. However, the ABB drive has a special output waveform filter that lengthens the PWM rise time and minimizes dV/dt transients. The result is reduced potential for load side problems.

Grounding is always a concern with VFD installations, since poor grounding can cause a variety of problems, including power quality issues and bearing fluting. The Beloit system grounding was tested and verified by the installing electrical contractor. Grounding brushes were installed on the motors. There have been no issues at Beloit related to 600 hp motor insulation or bearings.

The blower control system was upgraded to accommodate variable speed operation. Blower “surge” is a potentially damaging pulsating air flow that centrifugal blowers experience at low flow rates. The local blower control panels were upgraded to provide the surge protection algorithms required for variable speed operation. Throttled applications rely on motor amperage draw for monitoring flow and surge, but this is not adequate with VFD control. The actual flow rate must be monitored for control and surge protection and the surge point adjusted for inlet conditions and speed. Flow measurement may be accomplished either by calculating flow from power consumption and inlet and discharge conditions or by using air flow transmitters. Since the Beloit blowers had existing averaging pitot tubes and flow transmitters they were utilized for the surge control.

The air flow control logic and data logging needed to interface the blowers with existing DO control and SCADA systems were upgraded by the original control system supplier[5]. The rework of the local control panel and installation and wiring of upgraded PLC components was done by the plant’s instrumentation technicians.

The only failure that occurred with the medium voltage VFD system was the loss of an I/O card resulting from a utility power disturbance. ABB had a technician on site the next day and had the drive back up and running within 24 hours.

The performance of the system and the reduction in blower power has exceeded the plant staff’s expectations.

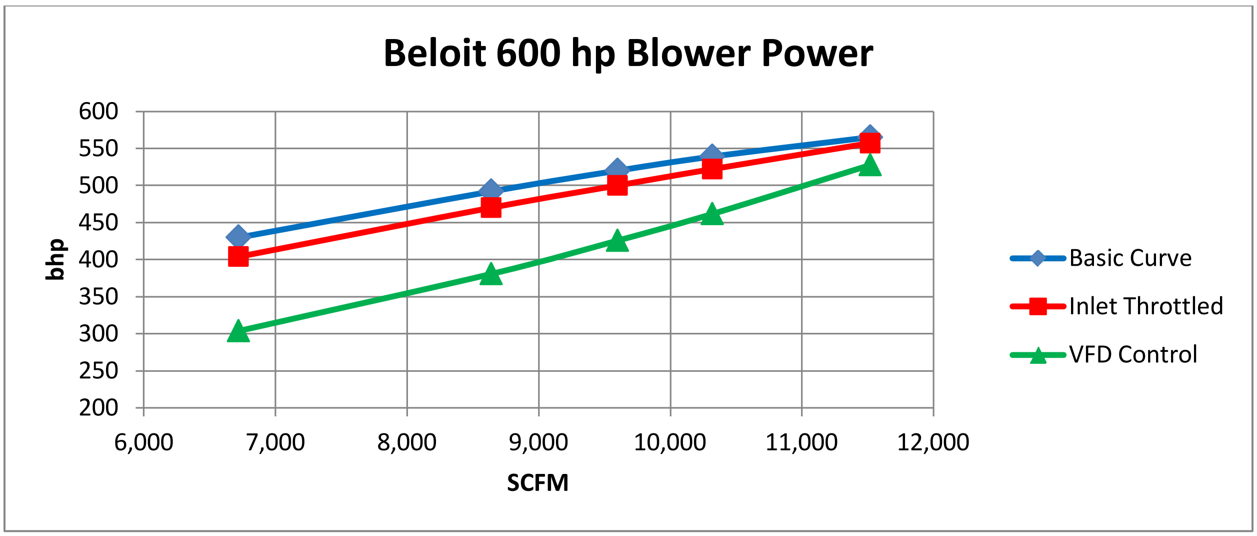
Energy Conservation Results: The determination of energy savings with aeration blowers is a complex prospect. The blower air delivery varies depending on the process demand, which in turn varies with organic loading, water temperature, and diffuser oxygen transfer efficiency. To further complicate the analysis the blower power varies with inlet temperature, pressure and relative humidity.

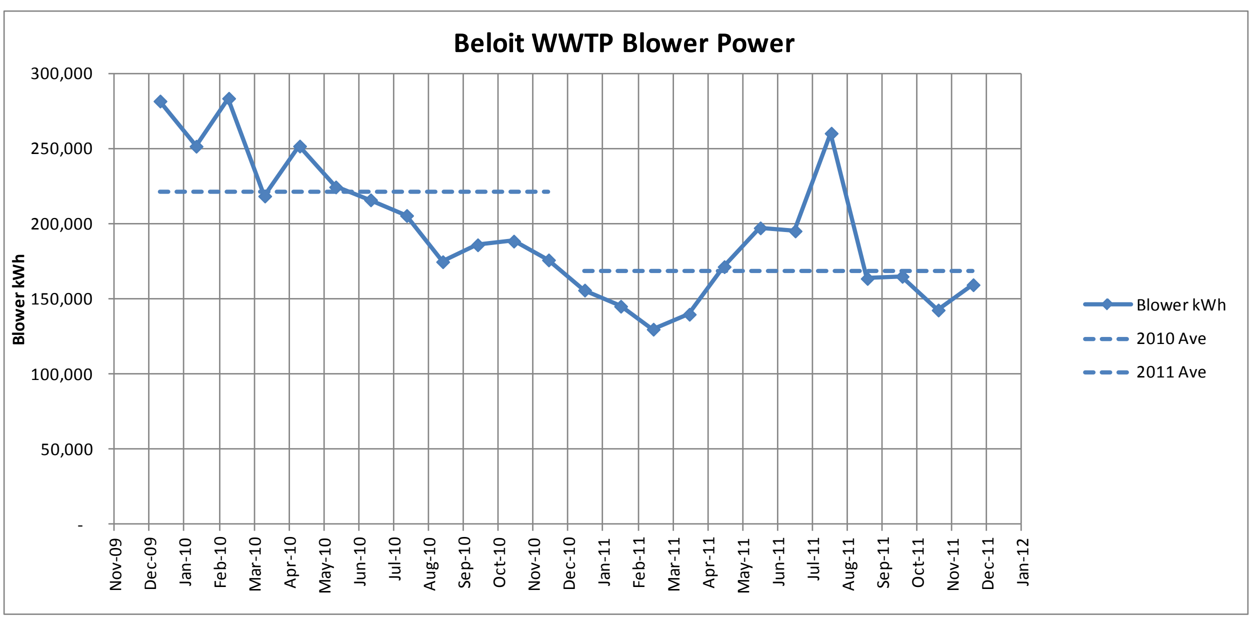
In the project design stage the blower performance was evaluated at annual average conditions for the City of Beloit. These are 55°F, 36% RH, and 14.25 psia barometric pressure. The power consumption vs. air flow (SCFM) at these conditions was calculated for the uncontrolled blower characteristic curve, the existing inlet throttling control, and variable speed control. The resulting average improvement in energy consumption was 15%, which is consistent with typical aeration blower system savings with VFD control.

	Basic Curve	Inlet Throttled		VFD Control		Savings	
SCFM	bhp	Hz	bhp	Hz	bhp	bhp	%
6,720	430	60.0	404	52.1	304	100	25%
8,640	492	60.0	470	54.1	381	89	19%
9,600	520	60.0	500	55.4	426	74	15%
10,320	539	60.0	522	56.5	462	60	11%
11,520	565	60.0	557	58.5	528	29	5%
Data at 55°F, 36% RH, 14.25 psia barometer					**Average**	**70.4**	**15%**

After the medium voltage VFDs were installed the power consumption of the aeration blowers dropped by over 30%. This dropped the aeration blower power from approximately 50% of total plant electric power to approximately 30% of total plant electric power.

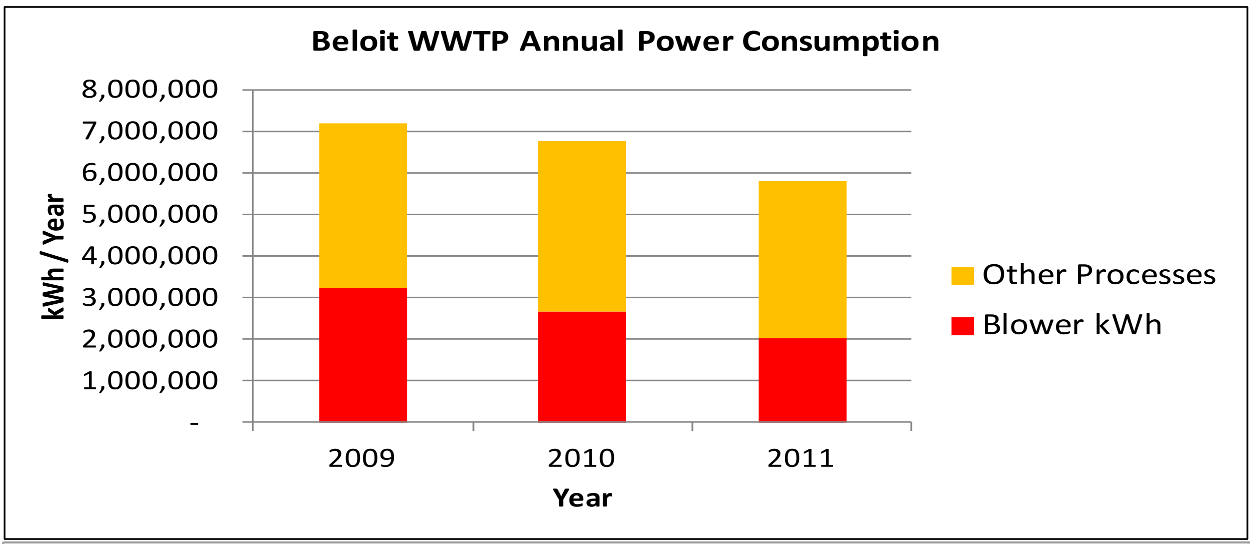
The total plant power decreased by over a million kilowatt-hours compared to 2008 and 2009. At an average composite electric rate of $0.062/kWh the annual savings of $75,000 per year were significantly better than the original projection of $48,000 per year. And, of course, as power costs continue to rise the economics of the VFD retrofit are improved further.

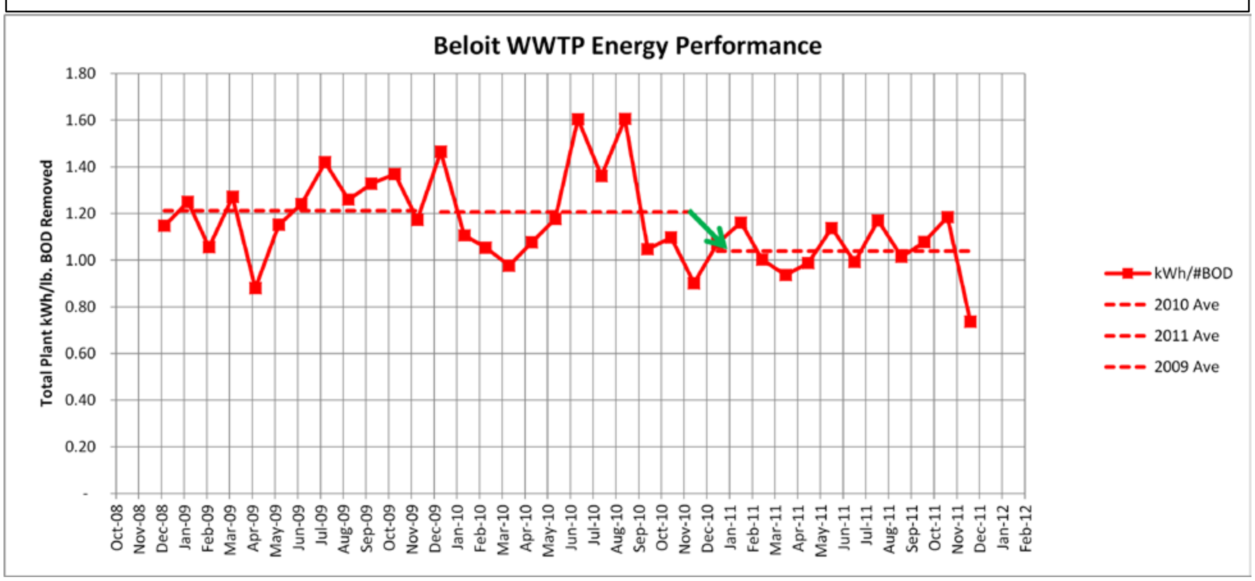




Year	Total WWTP Power kWh	Savings from 2008		
		kWh Saved	$ (6.2¢/kWh)	
2008	7,005,600	0		
2009	7,168,000	-162,400	$ (10,069)	-2%
2010	6,765,221	240,379	$ 14,903	3%
2011	5,786,400	1,219,200	$ 75,590	17%

There are several metrics used for wastewater treatment power consumption. The kWh of electricity consumed per million gallons treated is one of the most common. However, the influent load to the Beloit plant is significantly influenced by the industrial waste from the food processing facilities. The concentration of BOD is roughly twice the concentration in normal domestic wastewater. This load is independent of flow rate. Therefore, kWh per pound of BOD removed is a more appropriate metric for Beloit's power comparison.





Conclusions and Recommendations: The Beloit WWTP shows a successful application of VFDs to aeration blower control. The strategy isn't new, and aeration blowers have been provided with VFD control for some time. (An early installation in Pennsylvania dates to 1989.) However, the introduction of cost effective medium voltage VFDs represents a new class of potential applications for this technology.

It is common practice to use medium voltage motors for aeration blowers with motors larger than 500 hp. The reduced wiring expense and installation costs makes 4160 VAC more cost effective in the larger horsepower range. This is true for both multi-stage centrifugal blowers, like those at the Beloit WWTP, and single stage centrifugal blowers found in larger treatment facilities. In the past the high cost of VFDs made their application uneconomical. The introduction of cost effective medium voltage VFDs like the ABB units installed at Beloit has dramatically changed this situation.

The Beloit installation proves that the technology is cost effective for retrofit applications. The availability of utility incentive programs enhances the payback. In new blower installations, where the cost of starters is eliminated, the economics are even more favorable.

Because the aeration blowers are such a large portion of the operating cost they are among the first process equipment examined in a WWTP energy conservation program. Often replacement of existing units with new higher efficiency turbo blowers is the only option considered. Most manufacturers' turbo blowers only extend to 300 or 400 hp and are limited to 480 VAC. In larger facilities several blowers will be required to replace each existing unit, requiring extensive refurbishment of both piping and electrical systems. Using medium voltage VFDs with existing blowers is not only cost effective, but in most cases results in comparable or greater improvement in energy consumption.

In large wastewater treatment plants aeration is supplied by single stage blowers with inlet guide vanes (IGVs). Because IGVs are a more efficient control mechanism than inlet throttling it wasn't cost effective to replace the constant speed motor and IGV control with VFDs in the past. However, variable speed is even more efficient than IGV control, particularly at reduced air flow. With more cost effective drive technology replacing IGV control with variable speed control can provide an excellent payback through energy cost savings.

The economics of using VFDs for large blowers are even more favorable if controls are provided to use a single VFD for multiple blowers. If capacity is needed beyond the range of a single blower the operating blower can be synchronized with the utility power, switched to across the line operation, and the additional blowers started and controlled with the VFD. This system optimizes both equipment cost and energy consumption.

Aeration blowers are part of a sophisticated and complex system. In the application of ABB medium voltage drives to centrifugal aeration blowers expert engineering is essential. Thorough analysis in the design stage is required to verify the cost effectiveness. Controls and automation need to be revised as part of the upgrade. Grounding and harmonics need to be addressed.

The advent of cost effective medium voltage VFDs opens up a new range of applications for variable speed control of aeration blowers. The Beloit system demonstrates clearly that a properly designed system application is reliable, energy efficient, and cost effective.

Acknowledgements: The author appreciates the assistance of the following individuals in the preparation of this paper:

Paul Nolden, ABB
H.J. Dewes, ABB
Pat Carnahan, Symbiont
Scot Varney, City of Beloit WWTP

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