USE OF VARIABLE FREQUENCY DRIVES FOR EXTRUDER APPLICATION

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***Abstract*:** This paper describes a recent case study of replacing an Eddy Current Clutch (ECC) with modern medium voltage Variable Frequency Drive (VFD) for 2250 HP extruder application. It covers key issues, justification, factory and field measurements of torque-speed profile through 0.5-60 Hz as well power quality analysis. The paper reviews manufacturers' capability to build medium voltage VFDs that produce very high and stable torque at very low speed.

II. Introduction

Liquid cooled ECCs were a choice of variable speed control for large extruder applications in the 60's and 70's. These liquid cooled clutches offered high constant torque capability, smooth torque transmission and good first cost economics for a limited speed range requirements for large capacity extruder application.

As these ECCs approach about thirty years in service, they are becoming prone to breakdown requiring extensive repairs and causing downtime and loss of production. Also, ECC has very poor efficiency, which is linearly proportional to speed. There is a growing interest among the end users of extruders to retrofit their liquid cooled ECCs with VFDs to accomplish the following:

- Increase extruder availability and uptime
- Eliminate existing system components that potentially impact system reliability and performance
- Reduce repair works and costs
- Improve overall system efficiency
- Improve product quality

This paper describes a case study for replacing ECC with medium voltage VFD that was commissioned in November 1996. It is believed that at the time of implementation, this was the first application of its kind in North America for use of high-powered medium voltage VFD with induction motor for extruder application over extended low speed operation.

III. Background

NOVA Chemicals plant in Sarnia, Ontario has several extruders in operation. They are used to extrude the molten polymer into small polyethylene pellets. An extrusion is a process that involves forcing material through a die or opening under heat and pressure.

The original drive train is comprised of constant speed induction motor coupled to ECC and gear reducer to vary the speed of a screw type extruder to meet the process requirements. The largest extruder at this facility is designated #3RA and is rated 2250 HP. This extruder has been in service for over 20 years.

The ECC operates using the principle of slip between the driving and driven shaft. The input shaft is driven at a constant speed using an induction motor that provides a source of energy for the clutch. By controlling the excitation to the clutch, the amount of slip between the motor and the output shaft can be regulated and the output speed varied. The output speed, however, can never quite reach the input speed. If the excitation is high, the output speed increases towards the motor speed. If the excitation is lowered, the speed decreases towards zero speed. A given speed is maintained by balancing the excitation of the clutch to the load requirement. An ECC, when compared with modern VFD, is not an efficient device for speed control particularly for constant torque application load and requires substantial cooling to dissipate heat losses.

In 1994, an energy audit was conducted for this facility covering several pre-selected process drives including #3RA extruder. This study was sponsored by the local electrical utility and covered review of electrical demand profile, data collection, field measurements, establish load torque-speed characteristics and options available to reduce energy consumption. For this extruder application, the energy options considered were limited to the replacement of ECC speed control with DC or AC variable speed drive. The existing train for #3RA extruder is comprised of the following:

- Induction motor rated, 2250 HP, 4160V, 1785 rpm, design B, 1.15 SF, 274 A, class F insulation, 4 poles, 60 Hz and TEPV enclosure. This motor was

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purchased in 1990 to replace the original one and it was specified to be suitable for future inverter duty operation to accommodate harmonics losses and constant torque application. Also, the motor was specified to be forced ventilated from a single supply source located above the motor. The motor bearings were retrofitted with forced oil-lubrication to allow operating at very low speed

- ECC rated 1800-rpm maximum speed and water cooled
- Gear reducer having 2.6 service factor and 8.13 ratio
- Single screw extruder

The Load profile was established for several resin types covering HP versus speed requirements. It was desirable to establish the starting and running torque requirements for #3RA extruder under different resin conditions to properly specify a medium voltage VFD that would successfully start and accelerate the extruder load. This information was not readily available and due to the urgency of replacing the unreliable ECC it was not possible to conduct field torque measurements. However, it was pointed out by operation staff that for some specific resins the extruder is expected to run at very low speed (0.5 - 5 Hz) for extended period of time to ensure product consistency before accelerating the motor to the required speed. The normal operating speed range was 40 - 100 % at almost constant torque. Energy saving calculations were conducted for several operating points and it was determined that based on energy savings alone it was uneconomical to retrofit the extruder with medium voltage VFD. The simple payback period was calculated at 6 years based on average energy cost of 0.053 $/kWh (Canadian).

Notwithstanding the poor energy payback, it was decided to proceed with replacement of ECC mainly due to high rate of equipment breakdown, difficulty in locating parts and production loss. The ECC supplier base is rapidly shrinking and the manufacturer no longer supports this technology. The reliability of the ECC was becoming increasingly suspect. In 1995 the ECC for #3RA extruder suffered three serious failures each resulting in loss of production and considerable repair costs. These failures were major contributors to speed up a program for replacing the ECC with more reliable means of speed controls.

IV. Replacement of ECC

The project team investigated options to replace the ECC with more reliable, cost-effective speed control device. The selected drive had to meet the initial starting and running load that is specific for extruder application. These important drive features included.

- Field proven variable speed drive that is capable to produce starting torque of 150% rated torque for cold start
- Capability to produce rated and stable torque at very low speed range 0.5 - 5 Hz
- Good speed response with application and removal of load
- Low maintenance and high availability
- Good power factor and low line harmonics across the wide operating speed range
- Clean output waveform to avoid torsional vibration of the driven equipment and overheating

Both DC and AC drives were considered for replacing the ECC. DC drives are field proven and have been commonly used in the past for extruder application because of very good speed control and overall cost. For this retrofit application, DC drive was disregarded because of the following:

1. The existing 2250 HP induction motor would have to be replaced with a new DC motor that had to be purged to meet class1, division 2, group C and D hazardous location.
2. The use of standard DC motor was not readily compatible for this installation because of very low speed operation of the extruder. Alternatively, selecting a low speed DC motor requires possible elimination of the gearbox and encountering great difficulty in installing an oversized motor during a very short turn around time.
3. Increased brush maintenance.
4. Power factor is poor and proportional to speed.
5. High input harmonics.
6. Foundation modification to align the new motor with the extruder shaft.
7. The combined installed cost of DC drive and DC motor was higher than the medium voltage VFD.

Based on above, it was recommended to retrofit the ECC with medium voltage VFD. This decision was carefully evaluated, as there were no known field proven installations of Medium Voltage induction motor VFD for extruder application at the time of implementation in April 1996. This was evident from the survey results covering users' and manufacturers' experiences with medium voltage adjustable speed drives [1]. In addition, several vendors of medium voltage VFDs were visited and requested to demonstrate their capabilities to produce stable high torque at very low speed (0.5 - 5 Hz). Also, several large extruder users were contacted to draw on their experience for retrofitting extruders with VFDs.

V. VFD Selection For this Project

A request for information was sent to medium voltage VFD Vendors requesting pertinent technical data and pricing to supply 2500 HP medium voltage VFD capable to produce rated torque between 0 - 60 Hz. Delivery was very critical and it had to be within 12 weeks from receipt of order. The vendors were requested to provide supporting data reflecting their experiences in replacing ECC with medium voltage VFD for extruder application. The VFD was specified to be vector controlled, air cooled with dry type isolating transformer to be suitable for indoor installation. The VFD was required to undergo factory acceptance tests including torque - speed response test to demonstrate VFD capability to produce rated and stable torque at very low speed.

During the bidding and evaluation phase in April 1996 no vendor was able to provide installation experience on medium voltage VFD for extruder application. However, two VFD vendors, recognizing the potential for business opportunity, had already been conducting factory tests to simulate extruder starting and running requirements with vector control VFDs. One vendor had successfully completed a very comprehensive testing of torque - speed response utilizing vector control, 600 HP PWM regenerative drive as the load.

Bids received were evaluated on technical information, VFD vendor experience, delivery and pricing. It was decided to select multi-pulse vector controlled voltage source drive for this extruder application. The purchased VFD (see Figure 3) consisted of a diode based rectifier bridge to convert AC to constant voltage DC power, DC link power circuit and an Insulated Gate Bi-Polar Transistor (IGBT) based multilevel PWM voltage source inverter bridge to convert the DC power to a variable voltage/variable frequency output power. The key VFD Components are:

- Load break incoming disconnect switch
- Indoor multi-winding input isolation transformer suitable for rectifier type load and constant torque application
- Rectifier bridge configured in 30 pulse arrangement and in conjunction with the multi-winding isolating transformer to meet IEEE 519 - 1992 [2] harmonic requirements across the operating speed range without the use of line harmonic filters
- Inverter bridge having 30 pulse voltage source PWM output to limit output current harmonics distortion factor to maximum of 5 % throughout the operating speed range and constant torque application
- Controller cubicle with vector control receiving a signal from an encoder mounted on the motor some 300 feet away for precise speed control and fast closed loop regulator response

The medium voltage VFD is rated to deliver 300 A continuous output current and 450 A for one minute. Torque output from the VFD is based on maximum current that can be delivered by the converter system. Based on the existing motor current rating of 274 A, the torque output capability of the VFD system, at the 1 minute overload rating of the converter, is expected to approach 165% of motor rated torque.

The medium voltage VFD was purchased with optional features including cell bypass for rectifier and inverter bridge, input and output power quality meters, redundant cooling fans with automatic switch over in the event of a blower failure, on-site service support and extended warranty. The torsional study was waived in this case because of the tight project schedule and the drive was designed to provide smooth torque output with less than 1% per unit electrically induced torque pulsation at the motor shaft throughout the specified speed range. However, arrangements were made to carry out vibration measurements during VFD start up and commissioning.

VI. VFD Topologies for Extruder Application

Advances in semiconductor switching devices over the past two decades have resulted in several practical, widely accepted, circuit configurations for medium voltage VFDs for induction motors. All VFDs share same power conversion principle by first converting AC power to DC and then converting back to AC to achieve constant volts/Hertz relationship in order not to compromise induction motor performance. The rectifier and inverter bridges configuration and switching components vary depending on the manufacturer experience and preference.

The input power quality is almost completely determined by the characteristic of line side converter (Rectifier Bridge) and output power quality to the motor by load side converter (inverter). Almost, all medium voltage induction motor VFD manufacturers, are now offering multi-pulse rectifier configurations (≥ 18 pulse) to suppress the lower order dominant harmonics and comply with IEEE 519-1992 without the need for line filters.

The VFD manufacturers are continuously reviewing their manufacturing processes and topology to improve reliability, availability and performance. A superior VFD topology and design is the one that include the following key features:

- Very clean input and output waveform
- Utilizing switching components that have very low internal losses, simple switching control, high switching frequency, high surge withstand, high current and voltage ratings
- Almost unity overall efficiency and power factor throughout the operating speed range
- Reduced number of components
- Smaller footprint
- Cost effective
- Simple maintenance and diagnostics

Medium voltage VFDs operating voltage is classified at 2300V, 3300 V, 4160V or 6000V or 6600 V. The North American market has historically been the leading users of medium voltage induction motor drives with the majority are designed at 4160V. The first medium voltage drive for induction motor was introduced to the market in 1983 and by end of 1999 it is believed that there are over 2000 medium voltage VFDs in service in North America. The medium voltage technology underwent a very rapid growth in 1997 - 1998 as four new manufacturers introduced their design/topology into the North American market.

The basic topology used by the manufacturers to produce medium voltage VFDs for induction motor can be grouped into three categories. These are current source inverter – pulse width modulated (CSI-PWM), three level voltage source inverter – pulse width modulated (VSI – PWM) and multi-pulse VSI-PWM.

a) CSI – PWM Drives

This drive concept was introduced to the market in 1993 and since then there are several hundreds of drives in service for pumps, fans and compressors applications. Recently, this type of drive was used for a retrofit application for an extruder rated 2000 HP. The CSI – PWM drive, see Figure 1, consists of phase controlled rectifier (similar to a DC drive) circuit utilizing SCRs to convert 60 Hz input supply to variable DC supply, a large reactor in the DC link and PWM inverter using GTOs. An output filter is utilized for high order harmonic reduction. Based on the full PWM strategy in this case output capacitance requirement is reduced to approximately 0.3 per unit output. The PWM inverter uses Selective Harmonic Elimination (SHE) technique [3] [4] to eliminate lower order output harmonics mostly the dominant 5th and 7th components. Very recently, this concept is being adapted to the line converter by having PWM rectifier for harmonic reduction. The key features of CSI – PWM drives are:

- Power rating up to 12000 HP
- Suitable for variable torque and constant torque application
- Input isolating transformer is required for retrofit applications and is optional for new applications at smaller HP ratings
- Input converter (rectifier) can be configured in 6 pulse or 12 pulse for harmonic reduction. Recently, 18 pulse is also available for greater harmonic cancellation. (Alternative solution to reduce input harmonics is the recent introduction of PWM rectifier with GTOs)
- Input power factor reduces linearly with speed and input filter could be required for power factor correction and harmonic reduction
- Regeneration capability for motor braking
- Redundancy in switching components
- Vector control for high torque, low speed application (extruder)

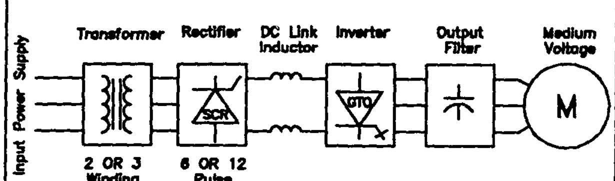

Fig.1: Medium Voltage CSI with PWM and Motor Filter Capacitors (CSI–PWM)

b) 3 - Levels Neutral Point Clamped Voltage Source – PWM Drives

This drive topology has been widely adopted by VFD manufacturers in Europe. In late 1997, a VFD manufacturer in North America began marketing this inverter technology but with considerable modification to address problems associated with the original design. The main components of the new VFD design, see Figure 2, include an isolating transformer with single primary winding and triple secondary windings, 18 pulse diode rectifier configuration, capacitor DC link and 3-level inverter utilizing IGBTs or IGCTs (Insulated Gate Commutated Thyristors) as switching devices. The key features of neutral point clamped voltage source inverter – PWM drives are:

- Power rating up to 7000 HP
- Suitable for variable torque and constant torque application
- Input isolating transformer suitable for indoor or outdoor having single primary winding and triple secondary winding
- Input converter (rectifier) having 12 pulse or 18 pulse or 24 pulse configuration to meet IEEE 519-1992 harmonic guidelines without input filters
- Output converter (inverter) using neutral point clamp topology and IGBTs or IGCTs depending on the drive voltage ratings
- Input power factor is greater than 0.95 throughout the speed range
- Utilize closed loop cooling system (heat pipe technology)
- Non-regenerative capability without modification

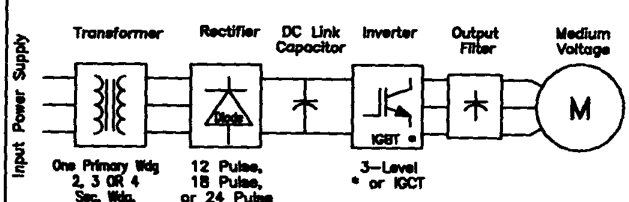

Fig.2: 3–Level Voltage Source Inverter VSI–PWM Drive

c) ***Multi- Level Voltage Source – PWM Drives***

This medium voltage drive technology was first introduced to the market in early 1995 for use with induction motors [5] [6]. This is the drive technology that was selected for this project for extruder application. The drive is characterized by the use of multi-winding indoor input isolating transformer, multi-pulse diode rectifier and multi-pulse IGBTs PWM inverter, see Figure 3. The drive converter consists of several series connected cells (each rated 480 V or 690 V) to produce the required motor voltage. Three 480 V cells in series (line to neutral) for 2300 V, 4 cells for 3300 V and five cells for 4160 V. Similarly, five 690 V series connected cells yields 6000 V output and 6 cells produce 7200 V. Each cell design is identical to low voltage 480V PWM circuit except that the inverter includes only 4 IGBTs switching devices that are connected in an H-bridge circuit. The main features of this drive is as follows:

- Up to 10000 HP rating built and capability up to 15000 HP
- Suitable for variable torque and constant torque application
- Input indoor isolating transformer is required for new and retrofit applications
- Input converter (rectifier) and load converter (inverter) is configured in 18 pulse, 24 pulse, 30 pulse or 36 pulse for harmonic reduction
- Input power factor remains above 0.95 across operating speed range
- Meet IEEE 519-1992 harmonic requirements for current and voltage total harmonic distortions at drive input and output without the use of harmonic filters
- Air cooled with optional redundant fans or liquid cooled with standard redundant pumps
- Bypass option with cold and hot synchronization
- Cell bypass
- Vector control for high torque, low speed application (ex: extruder)
- Non-regenerative capability

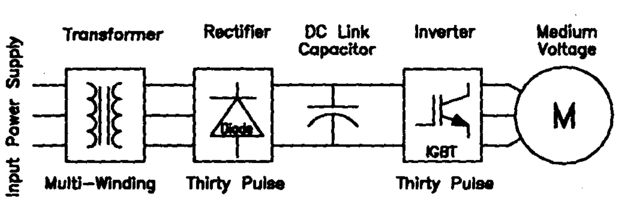

Fig.3: Medium Voltage Multi-Level VSI-PWM Drive

VII. Factory Acceptance Testing

The VFD system underwent a comprehensive factory acceptance testing to validate performance, features, selected options and torque/speed response. These included standard factory testing as well as the following additional testing:

1. Extended burn-in (12 hours) to reduce infant mortality failure rate of solid state devices.
2. Simulated loss of one power cell.
3. Simulated loss of speed signal from the encoder and observed drive tripping.
4. Verified the automatic transfer scheme for the two air blowers. Simulated high temperature to automatically restart the second blower.
5. Performed power quality measurements for input and output current and voltage Waveforms.
6. Performed torque/velocity performance test to verify stable operation of speed control at 0, 5, 18, 30, and 60 Hz while suddenly applying and removing the load. Figures 4 to 6 show a typical torque/speed response for a laboratory set up consisting of a 4160 V VFD connected to a 500 HP induction motor that was coupled to a 600 HP motor as part of a dynamometer test stand. The load consisted of a 600 HP CSI-PWM capable of operating in a regenerative mode. The torque feedback signal is from a torque transducer connected between the motor under test and the load motor. The scaling is 5 VDC = 2500 lb-ft. The torque limit is used to control the amount of torque on the load motor. In addition, to the speed and torque measurements taken, output current and voltage waveforms were captured at selected speeds. Figure 4 shows VFD speed response with motor running at 5 Hz and applying rated torque. Figure 6 show torque/speed response at 60 Hz when rated torque was applied. It can be seen that there was hardly any change in speed when the load was applied indicating a very good speed regulation.

VIII. Start Up and Field Results

In spite of the comprehensive testing that was conducted at the factory, the VFD start up was not as smooth as was anticipated. Some of these problems were due to component failure and other due to miscommunication. This VFD requires 3-phase 480 V for testing the individual power cells before applying 4160 V to the isolating transformer. At this facility, the available power supply is at 575 V. It was decided to proceed with start up by applying 4160 V to the transformer primary. A power cell experienced a failure and had to be replaced. The VFD also suffered a trip due to loss of encoder signal. The investigation revealed that the encoder supplied was suitable only for distances up to 50 feet and the encoder supplier was contacted to expedite an encoder that is suitable for 300 feet and comply with the area classification. The drive experienced other trips that were related to the logic control and these were corrected by adjusting the settings.

Power quality measurements and vibration readings were carried out during start up in November 1996 for the entire train of VFD, induction motor, gearbox and extruder. The measured total harmonic distortion factor for output current and voltage was less than 2% throughout the operating speed range.

IX. Conclusions

Recent advancements in the VFD technology and flux vector control have made it practical technically and economically to replace ECC with more efficient and reliable medium voltage VFD for extruder application. This was demonstrated by the successful operating experience of #3RA extruder with medium voltage VFD since November 1996. Based on the success of the initial installation, the second ECC designated #2RA rated 2000 HP is being replaced with same type of VFD used for #3RA. The second VFD with a new induction motor was delivered in March 1999 and is to be installed in 1999. In addition, a 7000 HP medium voltage VFD, liquid cooled, has been ordered and delivered for another plant as part of a major capital project. This is an entirely a new installation that consists of 7000 HP VFD, 4160 V induction motor, gearbox and an extruder. The VFD technology is identical to that used for #3RA and #2RA applications. There are presently several vendors that are capable of providing medium voltage VFDs to meet an extruder load requirement of high starting torque at a very low speed (.05 - 5 Hz).

X. References

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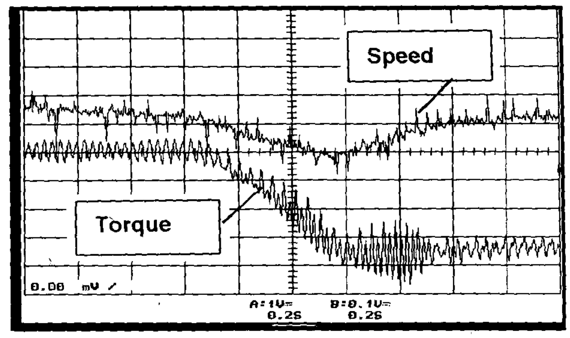

Figure 4: VFD Test at 5 Hz with 100% torque step load. Trace A = Torque scaled 5 VDC = 30,000 in/lb. Trace B = Speed scaled 6 VDC = 60 Hz. Trace A common at center. Trace B common at bottom.

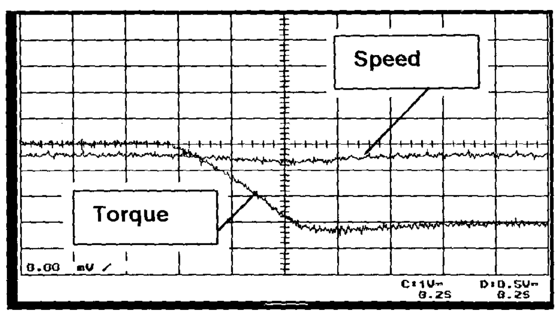

Figure 5: VFD Test at 18 Hz with 100% torque step load. Trace C = Torque scaled 5 VDC = 30,000 in/lb. Trace D = Speed scaled 6 VDC = 60 Hz. Trace C common at center. Trace D common at bottom.

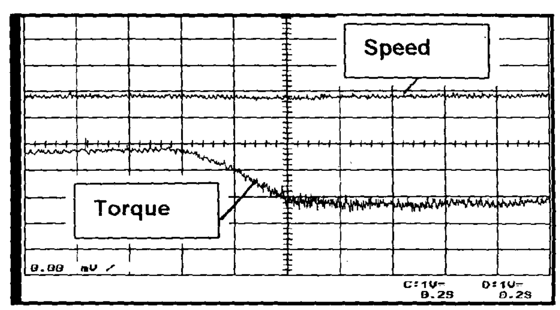

Figure 6: VFD Test at 60 Hz with 100% torque step load. Trace C = Torque scaled 5 VDC = 30,000 in/lb. Trace D = Speed scaled 6 VDC = 60 Hz. Trace C common at center. Trace D common at bottom.