Medium-Voltage Adjustable-Speed-Drive Retrofit of an Existing Eddy-Current Clutch Extruder Application

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***Abstract*—This paper describes a recent case study of replacing an eddy-current clutch with a modern medium-voltage adjustable-speed drive (ASD) for a 2250-hp extruder application. It covers key issues, justification, factory and field measurements of torque–speed profile from 0.5 to 60 Hz, as well power quality analysis. The paper reviews manufacturers' capability to build medium-voltage ASDs that produce very high and stable torque at very low speed.**

***Index Terms*—Adjustable-speed drives, drive topologies, extruder.**

I. Introduction

LIQUID-COOLED eddy-current clutches (ECCs) were a choice of variable-speed control for large extruder applications in the 1960s and 1970s. These liquid-cooled clutches offered high constant torque capability, smooth torque transmission, and good first-cost economics for limited speed range requirements for large-capacity extruder application.

As these ECCs approach about 30 years in service, they are becoming prone to breakdown, requiring extensive repairs and causing downtime and loss of production. Also, an 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 adjustable-speed drives (ASDs) to accomplish the following:

- increase extruder availability and uptime;
- eliminate existing system components that potentially impact system reliability and performance;
- reduce repair work and cost;
- improve overall system efficiency;
- improve product quality.

This paper describes a case study for replacing an ECC with a medium-voltage ASD 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 the use of a high-powered medium-voltage ASD with an induction motor for extruder application over extended low-speed operation.

II. Background

The NOVA Chemicals Corporation plant in Sarnia, ON, Canada, 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 a constant-speed induction motor coupled to an ECC and a gear reducer to vary the speed of a screw-type extruder to meet the process requirements. The largest extruder at this facility is designated #3 RA and is rated 2250 hp. This extruder has been in service for more than 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 to 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 toward the motor speed. If the excitation is low, the speed decreases toward zero speed. A given speed is maintained by balancing the excitation of the clutch to the load requirement. An ECC, when compared with a modern ASD, 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 preselected process drives including a #3 RA extruder. This study was sponsored by the local electrical utility and covered review of electrical demand profile, data collection, field measurements, establishment of 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 a dc or ac ASD. The existing train for the #3 RA extruder is comprised of the following.

- The induction motor was rated 2250 hp, 4160 V, 1785 r/min, design B, 1.15 SF, 274 A, class F insulation, four poles, 60 Hz, and TEPV enclosure. This replacement motor was purchased in 1990 and it was specified to be suitable for future inverter duty operation to accommodate

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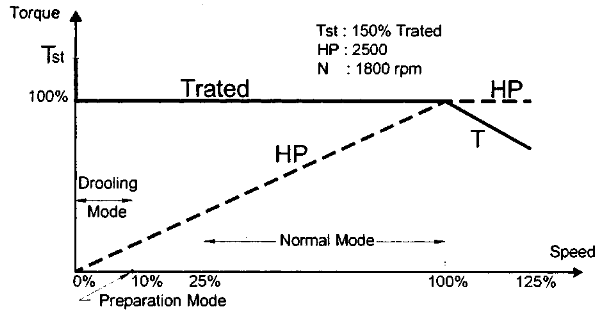

Fig. 1. Extruder torque/speed characteristic.

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.

- The ECC was rated 1800-r/min maximum speed and was water cooled.
- The gear reducer had a 2.6 service factor and 8.13 ratio.
- There was also a single-screw extruder

The load profile was established for several resin types covering horsepower versus speed requirements. It was desirable to establish the starting and running torque requirements for the #3 RA extruder under different resin conditions to properly specify a medium-voltage ASD that would successfully start and accelerate the extruder load. Typical extruder torque versus speed characteristic is shown in Fig. 1. The extruder mode of operation could be divided into the following main categories.

A. Starting Mode

The extruder starting torque is 150% of full-load torque,

B. Preparation Mode

Preparation mode covers the case where the extruder is required to run for up to 30 min at 10% speed to establish product quality before accelerating the extruder to the selected speed. The ASD shall be cable of producing rated stable torque at this very low speed.

C. Drooling Mode

Drooling mode covers the case of extruder operation just prior to when it is taken out for maintenance. The extruder is required to run below 10% speed rating at rated torque. Duration is estimated to be the same as the preparation mode, namely, 30 min.

D. Normal Mode

The normal operating mode for the extruder is between 25%–125% speed range. The load is constant torque between 25%–100% speed and constant horsepower between 100%–125% speed.

Energy-saving calculations were conducted for several operating points and it was determined tha, t based on energy savings alone, it was uneconomical to retrofit the extruder with a medium-voltage ASD. The simple payback period was calculated at six years based on an average energy cost of $0.053 (Canadian)/kWh.

Notwithstanding the poor energy payback, it was decided to proceed with replacement of the ECC, mainly due to the high rate of equipment breakdown, difficulty in locating parts, and production loss. The ECC supplier base is rapidly shrinking, and the manufacturers are no longer supporting this technology. The reliability of the ECC was becoming increasingly suspect. In 1995, the ECC for the #3 RA 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 a more reliable means of speed control.

III. Replacement of ECC

The project team investigated options to replace the ECC with a 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 the following:

- field-proven ASD capable of producing starting torque of 150% rated torque for cold start;
- capability to produce rated and stable torque at very low speed range of 0.5–5.0 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 initially 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, a dc drive was disregarded for the following reasons.

1) The existing 2250-hp induction motor would have to be replaced with a new dc motor. The dc motor would have to be purged to meet class 1, division 2, group C and D hazardous location.
2) The use of a 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 turnaround time.
3) There is increased brush maintenance.
4) There is poor input power factor and it is proportional to speed.
5) There are high-input line harmonics.
6) Foundation modification to align the new motor with the extruder shaft would be necessary.
7) The combined installed cost of the dc drive and dc motor was higher than the medium-voltage ASD.

Based on the above evaluation, it was recommended to retrofit the ECC with a medium-voltage ASD. This decision was carefully assessed, as there were no known field-proven installations of medium-voltage induction motor ASDs for extruder applications at the time of implementation in April 1996. This was evident from the survey results covering users' and manufacturers' experiences with medium-voltage ASDs [1]. In addition, several vendors of medium-voltage ASDs were visited and requested to demonstrate their capabilities to produce stable high torque at very low speed (0.5–5.0 Hz). Also, several large extruder users were contacted to draw on their experience for retrofitting ECC extruder applications with ASDs.

IV. ASD Selection for This Project

A request for information was sent to medium-voltage ASD vendors, requesting pertinent technical data and pricing to supply a 2500-hp medium-voltage ASD capable of producing rated torque between 0–60 Hz. Delivery was very critical and it had to be within 12 weeks from receipt of the purchase order. The vendors were requested to provide supporting data reflecting their experiences in replacing an ECC with a medium-voltage ASD for an extruder application. The ASD was specified to be vector controlled, air cooled, with dry-type isolating transformer to be suitable for indoor installation. The ASD was required to undergo factory acceptance tests, including a torque–speed response test to demonstrate the ASD 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 a medium-voltage ASD for extruder application. However, two ASD vendors, recognizing the potential for a business opportunity, had already been conducting factory tests to simulate extruder starting and running requirements with vector-controlled ASDs. One vendor had successfully completed a very comprehensive testing of torque—speed response utilizing vector control, 600-hp pulsewidth modulation (PWM) regenerative drive as load.

Received bids were evaluated on technical information, ASD vendor experience, delivery, and pricing. It was decided to select a multipulse vector-controlled voltage-source inverter drive for this extruder application. The selected ASD (see Fig. 3) was comprised of a diode-based rectifier bridge to convert ac to constant-voltage dc power, dc-link power circuit, and an insulated-gate-bipolar-transistor (IGBT)-based multilevel PWM voltage-source inverter bridge to convert the dc power to a variable-voltage/variable-frequency output power. The key ASD components are as follows:

- load break incoming disconnect switch;
- indoor multiwinding input isolation transformer suitable for rectifier-type load and constant-torque application;
- rectifier bridge configured in 30-pulse arrangement and in conjunction with the multiwinding 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 ft away for precise speed control and fast closed-loop regulator response.

The medium-voltage ASD is rated at 300 A continuous output current and 450 A for 1 min. Torque output from the ASD is based on the 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 ASD system, at the 1-min overload rating of the converter, is deigned for 165% of motor rated torque.

The medium-voltage ASD was purchased with optional features, including cell bypass for rectifier and inverter bridges, input and output power quality meters, redundant cooling fans with automatic switchover 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 operating speed range. However, arrangements were made to carry out vibration measurements during ASD start up and commissioning.

V. ASD 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 ASDs for induction motors. All ASDs share the same power conversion principle by first converting ac power to dc and then converting it back to ac to achieve a constant volts/hertz relationship in order not to compromise induction motor performance. The rectifier and inverter bridge configurations and switching components vary depending on the manufacturer experience and preference.

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

The ASD manufacturers are continuously reviewing their manufacturing processes and topology to improve reliability, availability, and performance. A superior ASD topology and design is one that includes 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 ASD operating voltage is classified at 2300, 3300, 4160, 6000, or 6600 V. The North American market has historically constituted the leading users of medium-voltage induction motor drives with the majority designed at 4160 V. The first medium-voltage drive for an induction motor was intro-

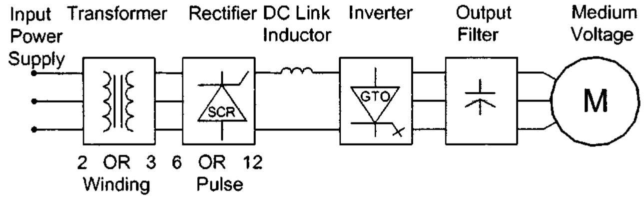

Fig. 2. Medium-voltage CSI with PWM and motor filter capacitors (CSI-PWM).

duced to the market in 1983 and, by end of 2000, it is believed that there will be more than 2000 medium-voltage ASDs in service in North America. The medium-voltage technology underwent 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 ASDs for induction motors can be grouped into three main categories. These are current-source inverter pulsewidth modulated (CSI-PWM) drives, three-level voltage-source inverter pulsewidth modulated drives (VSI-PWM), and multipulse VSI-PWM drives.

A. CSI-PWM Drives

This drive concept was introduced to the market in 1993 and, since then, there have been several hundreds of drives in service for pumps, fans, and compressor applications. Recently, this type of drive was used for a retrofit application for an extruder rated 2000 hp. The CSI-PWM drive (see Fig. 2) consists of a phase-controlled rectifier (similar to a dc drive) circuit utilizing SCRs to convert a 60-Hz input supply to a variable dc supply, a large reactor in the dc link, and a PWM inverter using gate-turn-off thyristors (GTOs). An output filter is utilized for high-order harmonic reduction. Based on the full PWM strategy in this case, the 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 fifth and seventh components. Very recently, this concept is being adapted to the line converter by having a PWM rectifier for harmonic reduction. The key features of CSI-PWM drives are the following:

- power rating up to 12 000 hp;
- suitable for variable-torque and constant-torque application;
- input isolating transformer required for retrofit applications and optional for new applications at smaller horsepower ratings;
- input converter (rectifier) can be configured in six pulse or 12 pulse for harmonic reduction; recently, 18 pulse is also available for greater harmonic cancellation (an 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;

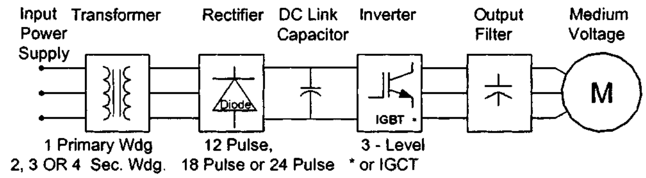

Fig. 3. Medium-voltage three-level voltage-source inverter (VSI-PWM) drive.

- vector control for high-torque low-speed application (extruder).

B. Three-Level Neutral-Point-Clamped VSI-PWM Drives

This drive topology has been widely adopted by ASD manufacturers in Europe. In late 1997, an ASD 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 ASD design (see Fig. 3) include an isolating transformer with single primary winding and triple secondary windings, 18-pulse diode rectifier configuration, capacitor dc link, and three-level inverter utilizing IGBTs or insulated gate commutated thyristors (IGCTs) as switching devices. The key features of neutral-point-clamped VSI-PWM drives are the folowing:

- 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-, 18-, or 24-pulse configuration to meet IEEE 519-1992 harmonic guidelines without input filters;
- output converter (inverter) using neutral-point-clamped topology and IGBTs or IGCTs depending on the drive voltage ratings;
- input power factor is greater than 0.95 throughout the speed range;
- utilizes closed-loop cooling system (heat pipe technology);
- nonregenerative capability without modification.

C. Multilevel VSI-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 retrofit project for extruder application. The drive is characterized by the use of multiwinding indoor input isolating transformer, multipulse diode rectifier. and multipulse IGBTs PWM inverter (see Fig. 4). The drive converter consists of several series-connected cells (each rated 480 or 690 V) to produce the required motor voltage. Three 480-V cells in series (line to neutral) for 2300 V, four cells for 3300 V, and five cells for 4160 V. Similarly, five 690-V series-connected cells yields 6000-V output and six cells produce 7200 V. Each cell design is identical to a low-voltage 480-V PWM circuit except that the inverter includes only four IGBT switching devices that are connected in an H-bridge circuit. The main features of this drive are as follows:

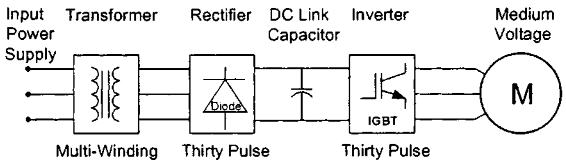

Fig. 4. Medium-voltage multilevel voltage-source inverter (VSI-PWM) drive.

- up to 10 000 hp rating built and capability up to 20 000 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, 24, 30, or 36 pulse for harmonic reduction;
- input power factor remains above 0.95 across operating speed range;
- meets 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 (example: extruder);
- nonregenerative capability.

VI. Factory Acceptance Testing

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

1) extended burn-in (12 h) 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.

Figs. 5–7 show a typical torque/speed response for a laboratory setup consisting of a 4160-V ASD 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. Fig. 5 shows ASD speed response with the motor running at 5 Hz and applying rated torque. Fig. 7 shows 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 very good speed regulation.

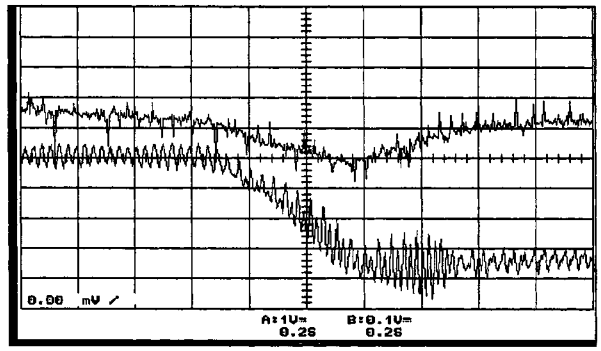

Fig. 5. ASD test at 5 Hz with 100% torque step load. Trace A = torque scaled 5 Vdc = 30 000 in/lb. Trace B = speed scaled 6 Vdc = 60 Hz. Trace A common at center. Trace B common at bottom.

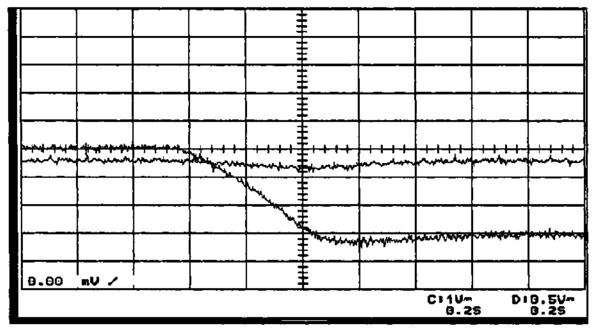

Fig. 6. ASD test at 18 Hz with 100% torque step load. Trace C = torque scaled 5 Vdc = 30 000 in/lb. Trace D = speed scaled 6 Vdc = 60 Hz. Trace C common at center. Trace D common at bottom.

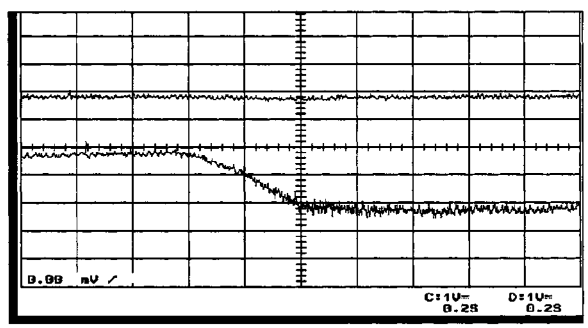

Fig. 7. ASD test at 60 Hz with 100% torque step load. Trace C = torque scaled 5 Vdc = 30 000 in/lb. Trace D = speed scaled 6 Vdc = 60 Hz. Trace C common at center. Trace D common at bottom.

VII. Startup and Field Results

In spite of the comprehensive testing that was conducted at the factory, the ASD startup was not as smooth as was anticipated. Some of these problems were due to component failure and others due to miscommunication. This ASD requires three-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 575 V. It was decided to proceed with startup by applying 4160 V to the transformer primary. A power cell experienced a failure and had to be replaced. The ASD 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 ft and the encoder supplier was contacted to expedite an encoder that is suitable for 300 ft and complies 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 startup in November 1996 for the entire train of ASD, 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.

VIII. Conclusions

Recent advancements in ASD technology and flux vector control have made it practical, technically and economically, to replace an ECC with a more efficient and reliable medium-voltage ASD for an extruder application. This was demonstrated by the successful operating experience of a #3 RA extruder with a medium-voltage ASD since November 1996. Based on the success of the initial installation, the second ECC, designated #2 RA and rated 2000 hp, was replaced in 1999 with the same type of ASD used for the #3 RA. In addition, a 7000-hp medium-voltage ASD, liquid cooled, was ordered and delivered in 1999 for another NOVA plant as part of a major capital project. This is an entirely new installation that consists of a 7000-hp ASD, 4160-V induction motor, gearbox, and an extruder. The ASD technology is identical to that used for the #3 RA and #2 RA applications. There are presently several vendors that are capable of providing medium-voltage ASDs to meet an extruder load requirement of high starting torque at a very low speed (0.5–5.0 Hz).

References

[1] R. A. Hanna and S. Prabhu, “Medium-voltage adjustable-speed drives-users’ and manufacturers’ experiences,” *IEEE Trans. Ind. Applicat.*, vol. 33, pp. 1407–1415, Nov./Dec. 1997.

[2] *IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems*, IEEE Standard 519-1992.

[3] B. Wu, S. Dewan, and G. Slemon, “PWM-CSI inverter for induction motor drives,” *IEEE Trans. Ind. Applicat.*, vol. 28, pp. 64–71, Jan./Feb. 1992.

[4] F. A. DeWinter and B. Wu, “Medium voltage motor harmonic heating, torques and voltage stress when applied on ASD’s,” in *Proc. IEEE PCIC*, 1996, pp. 131–139.

[5] P. W. Hammond, “A new approach to enhance power quality for medium voltage drives,” *IEEE Trans. Ind. Applicat.*, vol. 33, pp. 202–208, Jan./Feb. 1997.

[6] R. H. Osman, “A survey of design issues and performance characteristics of popular medium-voltage induction motor drives,” in *Proc. 2nd Int. Power Electronic and Motion Control Conf.*, vol. II, Hangchou, China, 1997, pp. 859–866.

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