

Medium-Voltage Adjustable-Speed Drives—Users' and Manufacturers' Experiences

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Abstract—Energy management and efficient use of electricity are being promoted by most utilities in Canada and the U.S. In some cases, cash incentives are being offered toward conducting feasibility studies and project implementation when the energy paybacks are attractive. This paper presents the results of a comprehensive study completed in July 1995 for a large Canadian utility, covering users' and manufacturers' experiences with medium-voltage adjustable-speed drives (ASD's) for induction motors. Thirty out of forty users, primarily from the petrochemical industry in the U.S. and Canada, participated in completing a detailed questionnaire and reported on 66 medium-voltage drives ranging from 800 to 10 000 hp. Information was gathered on the performance and reliability of the total drive system, including the motor, drive, driven equipment, isolation transformer, line filters, and selection criteria. Also, four manufacturers of medium-voltage drives provided pertinent information on their ASD system, technology, features, customer requirements, and future trends. This paper presents the analysis of the data gathered from both the users and the manufacturers. Based on the study findings, suggestions and recommendations are made to ASD manufacturers, users, and utilities.

Index Terms—Adjustable-speed drives, medium voltage, users' and manufacturers' experiences.

I. INTRODUCTION

SIGNIFICANT advantages in improved process control, higher efficiencies, and energy savings have been provided to industry by adjustable-speed drives (ASD's). The reliability of ASD's has improved significantly in the last decade due to improvements in switching devices, cooling systems, harmonic mitigation, design of converters/inverters, and control systems. ASD technology has matured, and the cost of adopting it has become more economical, as is evident by the increased number of drives put into service over the last few years. In spite of these advancements in ASD technology and application, there is still some apprehension and concern expressed by some users to readily accept and implement this technology. The application of these high-power medium-voltage drives is, in general, associated with critical process areas of the plant, and any shutdown of the system could result in a major

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process upset and loss of production. The concerns about reliability in such critical applications might have provided impediments to wider application of these ASD's. It is felt that the best solution to overcome these concerns is to publicize the operating experiences of the users and manufacturers of medium-voltage drives.

This paper will hopefully provide the necessary information which will lead to a better dialogue between the users, manufacturers, and utilities and alleviate users' main concerns. The survey data was compiled in March 1995 and, although it is mostly from the petrochemical industry, it could be applied equally to other types of industries.

II. STUDY OBJECTIVES

The study was designed to investigate the technical issues related to the performance of medium-voltage ASD's, as well as the manufacturers' perspectives of the developments in the technology and the future of the industry. The primary objectives of the study were as follows:

- 1) survey/review the application of medium-voltage drives for ac induction motors, with special emphasis on the petrochemical industry;
- 2) review and present users' operating experiences and performances of the medium-voltage drives and provide the manufacturers and vendors of motors, pumps, fans, and ASD's with necessary information and feedback that will assist them to better address the users' concerns and needs;
- 3) review the manufacturers' experiences and summarize the data on the ASD technology;
- 4) provide the electric utilities with first-hand operating experiences and information on ASD reliability, performances, maintenance records, and any other concerns to help the utilities to address the needs and concerns of their customers who are using or considering employing ASD's.

III. METHODOLOGY

For the purpose of this paper, medium-voltage drives were characterized as those rated 700 hp and up, operating at 2300 V and above. Since these high-power drives are designed for and used in customized applications, cooperation was sought from manufacturers and vendors in preparing the lists of users. The study focused especially on ASD's for induction motors used mainly in petrochemical industries. Load-commutated inverters (LCI's) used with the synchronous

motors was outside the scope of this paper. The study covered both the manufacturers and users of the drives.

Separate questionnaires were designed for manufacturers and users. Extensive consultations with both parties led to the development of questionnaires that provided meaningful and detailed responses. In addition, plant visits and personal interviews were also conducted with selected users and manufacturers to ensure obtaining first-hand information on ASD technology and operating experiences.

Identification of users of medium-voltage drives was mainly done through the cooperation of manufacturers and vendors of the drives. A total of 40 users was identified from the list, with more than 100 drives used in their systems. Emphasis was placed on those users in the petrochemical industry, to meet the objectives of the study. The response from users was overwhelming, with 75% participating in the study.

IV. SURVEY QUESTIONNAIRES

The quality of the information acquired from a survey is limited by the questions asked in the survey and its clarity. The questionnaires were designed with the objectives of being simple and user friendly, addressing the key technical issues and concerns of respective groups, and acquisition of quality information. Two sets of questionnaires were developed; one set was sent to the users of ASD's and the other was sent to the manufacturers of ASD's.

A. Users' Questionnaire

The survey questionnaire for users consisted of two main parts. Part I consisted of 59 questions and requested specific information for each ASD application. This part was divided into five sections that covered motor, drive, mechanical driven equipment, isolation transformer, line harmonic filter, ASD selection, and application. Part II was comprised of 20 questions and asked more general questions to obtain the company's overall experiences with all medium-voltage induction motor drives in service.

The following is a summary of the questionnaire, grouped under several sections.

1) Motor:

- name plate details;
- operating speed range;
- new or retrofit;
- modifications, if any, for retrofit;
- need for extra insulation in new motors;
- heat-run test;
- location of motor;
- thermal protection;
- capability of starting on line;
- mechanical resonance;
- failures/problems while in service;
- mean time between failures;
- average downtime for repair;
- average cost of repair.

2) ASD detail:

- drive data—type, rating, voltage, years in service, cooling;

- redundancy;
- provision of UPS;
- drive sizing and application;
- bypass mode for direct on-line starting;
- failures while in service;
- average time between failures;
- average downtime for repair;
- average cost of repair.

3) Mechanical driven equipment:

- type of driven load;
- load duty cycle;
- type of service;
- mechanical problems due to ASD.

4) Isolation transformer:

- transformer data;
- two, three, or multiple windings;
- failures, if any.

5) Line harmonic filter:

- application;
- compliance with guidelines.

6) ASD selection and application:

- selection and feasibility study;
- environmental control;
- space limitations;
- support from the manufacturer;
- startup time;
- diagnostic system;
- efficiency specification;
- selection criteria;
- payback period for the installation;
- torsional analysis;
- harmonic study and mitigation;
- effects of power line disturbances;
- need for power factor correction capacitors;
- noise levels;
- success of the installations.

B. Manufacturers' Questionnaire

The questionnaire was designed to gather information concerning the ASD product and customers' requirements. This questionnaire consisted of four separate sections addressing specific types of information. A summary of areas covered are as follows.

1) Adjustable-speed drive system information:

- name plate information, approximate number of ASD's marketed by the company in U.S. and Canada;
- approximate list price in dollars per horsepower;
- need for isolation transformer;
- approximate values of efficiencies and power factors at different speed/load;
- average number of drives for induction motors sold per year;
- standards for medium-voltage drives;
- estimated noise levels.

2) Technology information:

- type of inverter;

- type of switching devices used for both the rectifier and inverter;
- built-in redundancy;
- recommendation of 12-pulse inverter and converter;
- alarms for failure of switching devices;
- cooling method;
- heat generated by drive;
- total harmonic distortion (THD) levels.

3) Protection features:

- isolation of low-voltage compartment;
- reliability information;
- failures attributed to common-mode voltages;
- most common failures in the field;
- estimated motor temperature rise;
- torsional analysis;
- provision of uninterruptible power supply (UPS).

4) General information:

- typical information requirements needed before quoting;
- space requirements;
- warranty requirements;
- maintenance contract;
- ISO 9000 requirements;
- availability of spare parts;
- training;
- retrofit applications;
- trends in technological improvements;
- trends in costs over the next five years.

V. "USERS' EXPERIENCES"—SURVEY RESPONSES AND ANALYSIS

Most of the participants (67%) were from the petrochemical industry, and the remaining 33% distributed among cement, pulp and paper, utilities, municipality, and manufacturing industries.

The data gathered was reviewed and analyzed using the frequency tabulation method. The method involves sorting and counting responses to each question in the questionnaire, and the reporting of this number is compared to the total responses as a percent. Considerable observations and conclusions can be derived from the data. The following is a summary of responses, findings, and some general observations.

A. Motor Details

- The number of induction motors operated by 66 drives was 84.
- 64% of the motors reported were between 1000–3000 hp, the largest being 10 000 hp and the smallest 800 hp. The distribution of motor sizes is shown in Table I.
- 4160 V was the most common motor voltage rating (76%), followed by 2300 V (20%), and other voltages of 4530 V and 6000 V accounting for 4%.
- 75% of the motors were rated for 3600–3960 r/min operation, 11.9% at 1800 r/min, 4.8% at 1200 r/min, 4.8% at 900 r/min, 2.4% at 6000 r/min, and 1.2 % at 10 000 r/min. The highest speed motor was rated 10 000 r/min at 8000 hp.

TABLE I
MOTOR SIZE

Motor Size – HP	Number Of Motors
800 – 1000	7
1001 – 2000	18
2001 – 3000	35
3001 – 5000	15
5001 – 7000	7
7001 – 10000	2

- The majority of the motors (61%) with ASD's was required to operate in speed ranges of 50%–105%, with 23% at 40%–110%, 8% at 70%–100%, and 8% at 20%–100%.
- The majority of the motors, particularly for retrofit applications, was required to run at a maximum frequency slightly above 60 Hz. 19% of the motors operated at 60 Hz, 45.2% at 63 Hz, 29.8% at 66 Hz, 2.4% at 72Hz, 2.4% at 100 Hz, and 1.2% at 167 Hz.
- 60.7% of the motors used were retrofit, and 39.3% were new motors. No user reported any derating for retrofit applications. In retrofit applications, the motors reported on have been in service for an average of 20 years.
- No user indicated that extra insulation was specified for new motors to handle common-mode voltage. This was addressed by use of an input isolation transformer.
- Of the 33 new motors reported, 20 motors (60.6%) underwent heat-run tests when connected to the ASD, and all reported that test results met the specifications.
- 73.8% of motors were located in Class I, Div 2 areas, followed by 16.7% in nonhazardous and 9.5% in Class I, Div 1 areas. Almost all the new or retrofit motors were equipped with RTD's for thermal protection of stator windings and bearings.
- The majority of the motors in service had not experienced failures or problems attributed to the use of the ASD. However, a few reported that the motors experienced vibration and overheating problems.

B. Drive Details

- The horsepower ratings of the drives varied from 800 to 10 000 hp. The distribution of the sizes is as shown in Table II.
- 83% of the drives reported on were liquid cooled and the remainder were air cooled. Drives rated 2000 hp and above were, in general, of liquid-cooled design. Redundant pumps are standard features for liquid-cooled systems.
- Almost all drives had voltage ratings of either 2300 or 4160 V. 71% of the drives were rated 4160 V, with the remainder at 2300 V.
- The earliest reported application of a medium-voltage drive for induction motors is about ten years old. Almost 50% of the drives have been installed in the last three to four years. The average number of years of service of the other 50% is about six.
- The typical range of guaranteed values of drive efficiency (drive + filter) at rated load and 60 Hz is 96%–98%.

TABLE II
DRIVE RATING

HP	Number Of Drives
800 – 1000	5
1001 – 2000	15
2001 – 3000	26
3001 – 5000	7
5001 – 7000	11
7001 – 10000	2

TABLE III
TYPE OF DRIVE FAILURE

Type Of Failure	Number Of Drives
Blown Fuse	18
Incorrect Protective Settings	26
Accel/Decel Problems	28
Control Power Supply	33
Logic Board Failure	44
Under & Over Voltage Trip	48
Component Failure	55

TABLE IV
MEAN TIME BETWEEN FAILURES

Average Interval Between the Failures	Approximate % of the Users
1 - 6 months	30 %
7 - 12 months	33 %
13 - 24 months	20 %
> 24 months	16 %

- The rectifier/inverter pulse design depended on the load and customers' requirements. 74.2% of the drives were of 12/6-pulse design, while 6/6-pulse design drives accounted for 22.7% and 12/12-pulse designs for 3.1%. The two drives with 12/12-pulse design were rated 8000 and 10000 hp and, in this case, an input transformer and an output transformer were used. This design was adopted to reduce harmonics at drive input and output and to match the motor rated voltage.
- 77.3% of the reported drives had (N-1) capabilities and 7.5% had (N-2) capabilities to provide built-in redundancy, while 15.2% of the drives did not opt for this feature. A drive having (N-1) redundancy implies that it will continue to safely operate with one switching device failed in any or all converter bridge legs. The failure is usually alarmed, but does not cause a trip. A repair can be made during a scheduled maintenance period.
- 95.5% of the drives had the provision of using UPS to control power circuits. The presence of UPS provides the drive with ride-through capabilities up to several seconds and also reduces susceptibility to line disturbances.
- Almost all drives (97%) were used for variable-torque applications and the balance for constant torque.
- 83.3% of the drives used were provided with the "bypass" mode to start the motor directly on-line at 60 Hz. Only 16.7% of the drives were not provided with the bypass. This feature is selected to run the motor directly on-line, while the drive is down for regular maintenance, and is also selected to start multiple motors on a single drive.
- The medium-voltage drive technology is continuously undergoing developments to improve product quality and performance and to better meet users' requirements. In spite of this, all users reported having ASD problems. The majority (70%) was attributed to component failures (e.g., SCR's, gate-turn-off switches (GTO's), filters, diodes, control modules, etc.). 50% of the users had experienced undervoltage and overvoltage trips, 43% of the users had their logic boards fail, and more than 40% had the fuses in the drive blow for one reason or the other. Nearly 30% of the users had problems with control power supply, 13.3% of the users had incurred problems with incorrect protective settings and acceleration/deceleration of the drives. Most users reported having more than one kind of problem with their drives (see Table III).

It is interesting to note that the above results replicate the findings of an earlier study conducted in 1992 [1] on users' experiences with drives rated 500 hp and above that utilized a 600-V inverter technology.

- 63% of users experienced drive failures during the first 12 months of the drive in operation (see Table IV).
- More than 75% of the failures/problems were repaired within a day, and about 20% took about one to four days. Only one incident reported required between five to ten days. One failure of a dc reactor required more than ten days.
- More than 75% of the responses indicated the financial cost of these repairs to be less than \$4999, and about 20% reported the cost to be between \$5000–\$9999. One failure that accounted for more than \$10000 was due to the dc reactor failure. About 15% of the responses suggested that the repairs were done under warranty.

C. Mechanical Driven Equipment

- Most drives (73%) were used in pump applications, followed by 15% for compressor load and 12% for fan/blower load.
- Load duty cycle of the driven equipment (over a period of 24 hours) was either continuously or slightly changing. 55% of the drives had slightly changing and 36% had continuously changing load duty cycle. Steady duty-cycle loads accounted for only 9%.
- More than 95% of the driven equipment was used for continuous service over the day, i.e., 24-h operation. Two loads were running under normal service of eight hours and the site was operated between 12–16 h.
- Almost all of the users reported having no mechanical problems with the driven equipment, which could be directly attributed to the use of the ASD. A few users reported experiencing torsional vibrations during commissioning. In one case, the motor/compressor shaft experienced excessive vibration at the twelfth harmonic and within the operating speed range.

D. Isolation Transformer

- All users reported that isolation transformers were used on

the input side of the drive. This should not be interpreted that an input transformer is always required. In some cases, particularly for small horsepower drives (≤ 1000 hp) with new motors, line reactors are being specified.

- 74% of the transformers installed were of oil type, with allowable temperature rise of 55 °C–65 °C. The remaining transformers were of dry type, with temperature rise of 80 °C–115 °C.
- Isolation transformers, except one, were installed outdoors. However, indoor transformers could also be used, as this, in general, depends on the drive size, location, and manufacturer preferred practices.
- Approximately 78% of the transformers were of three-winding type and the rest were of two-winding type.
- Almost all users reported having no isolating transformer failures. Two users, however, reported transformer overheating, and these had to be returned to the shop for modifications.

E. Line Harmonic Filter

- 60% of the users had used input line filters, while 40% did not see the need for any filters.
- Filters were mainly installed for harmonic reduction, but nearly 44% of these filters were also required for improving the power factor.

F. Users' Experience with ASD Selection and Application

- 76.7% of the users reported that the ASD selection/design was done by in-house personnel. 16.7% of the users had a consultant to select/design the ASD system. 6.6% of the users had the manufacturers assist them in the design/selection of the drive.
- The amount of indoor heat generated by a drive depends on the method of cooling, maximum ambient temperature, and size. Air-cooled drives produce 1.5%–2% KW loss of drive horsepower rating. For liquid-cooled drives, 60%–80% of heat loss generated is rejected outdoors. Drives, in general, require a temperature-controlled environment, and this was normally achieved by installing an air-conditioning system.
- Typical dimensions of a medium-voltage drive range are (116–250 in) W \times (36–54 in) D \times (90–115 in) H, depending on ratings, option selected, and cooling. Dimensions given are for drives using an outdoor isolating transformer. The lower range is typical of drives rated 500–1500 hp, and the upper range is for drives above 5000 hp. Space requirements should be carefully evaluated during the conceptual design phase.
- All of the users reported that the information received from the manufacturers for the operation and maintenance of the ASD's was adequate.
- Only four out of 30 users had purchased the preventative maintenance contract for the ASD's.
- 62.1% of the ASD installations required three to seven days for startup and commissioning, 27.6% required eight days to one month, and 10.3% of the installations were commissioned in less than three days.

TABLE V
PAYBACK

Payback Period	% of Users
< 1.5 years	13.0 %
1.5 to 3.0 years	47.8 %
3.0 to 5.0 years	30.5 %
> 5.0 years	8.7 %

- 81.5% of the users were satisfied with the diagnostic system provided for the drives, while 18.5% asked for improvement.
- "Reliability" was quoted by 77% of users as the main reason for selecting the ASD, 7.5% stated "energy efficiency," and 6.7% mentioned "process efficiency." One user reported that "soft start" was the main reason for selecting the ASD.
- The approximate payback period for ASD installation is given in Table V.
- 25% of the respondents reported less than two years as the acceptable payback period by their company to consider ASD application, whereas 44% reported two to three years, and 31% quoted three to five years.
- 70% of the users had torsional analysis performed for the ASD installed. Of these, 62% of the cases analyzed were done by the ASD manufacturer, 9.5% by the driven equipment manufacturer, and 28.5% by the consultants.
- Of the 19 out of 30 users who responded to the question concerning whether special coupling requirements were recommended, 79% replied that there were no recommendations for either a special coupling or any limitation on the operating speed range. Only 21% said that special couplings were used to avoid torsional vibrations across the operating speed range.
- 82.1% of the users indicated that a harmonic study was conducted to identify harmonic resonance and to calculate current and voltage THD at point of common coupling (PCC). Users of medium-voltage drives in the Western Canadian Provinces of Alberta, Saskatchewan, and Manitoba indicated that the ASD installations had to meet both the voltage THD at PCC and IT product. (IT product represents harmonic interference with telephone lines when running in the proximity of power lines [2].) These IT product levels are more stringent than the values required by the IEEE [2]. The IT product recognizes the interference between harmonics generated by ASD's and the communication circuits in the proximity of power lines.
- 57% of the users did not report any tripping problems due to utility line disturbances, but 43% stated having problems. Most users did not convey line disturbance problems to their local utilities. Users reported that line disturbances were caused by thunderstorms, capacitor switching, and voltage dip when starting other loads.
- Only three of the 28 users reported that noise generated by ASD's was a problem, while the majority (89.3%) did not consider the noise an issue.

- Almost all the users reported that their ASD application was a success. The fact that the users were satisfied is a strong indication that the technology is viable and economical.
- There was a unanimous consensus by the users that they would consider purchasing an ASD again for a similar application. The interesting statistics were that 22 of 28 users reported that they would consider buying the equipment from the same manufacturer, whereas six users would follow the bid process.

VI. "MANUFACTURERS' EXPERIENCES"—SURVEY RESPONSES AND ANALYSIS

A total of four out of six manufacturers in North America of medium-voltage ASD's participated in fully completing the questionnaires. One manufacturer declined because, at present, it does not have the capability to produce medium-voltage drives. Considerable observations and conclusions can be drawn from the information gathered. The following is a summary of the responses, findings, and general observations.

A. ASD System Information

- Manufacturers varied in their capabilities to build medium-voltage ASD's; this ranged between 500–20 000 hp. The largest medium-voltage drive for induction motors built to date is 15 000 hp.
- The highest speed for which an ASD was designed is 11 000 r/min, and the corresponding horsepower is 3500 hp [3].
- All the manufacturers indicated that they produce 2300- and 4160-V drives. Drives with voltage ratings of 3300, 6900, and 7200 V were also quoted by some of the manufacturers.
- Range of drive frequency control varied from a few to 300 Hz.
- Two companies introduced the medium-voltage drives in the mid-1980's and the other two in 1990 and 1994.
- At the time of survey completion in April 1995, the total number of medium-voltage drives for induction motors installed in Canada was about 53, with the majority installed in Alberta, and more than 500 were installed in the U.S.
- The total number of medium-voltage drives sold in 1995 by all responding manufacturers was about 210, and this figure was doubled for 1996. It is anticipated that the overall number of ASD's sold/installed in 1997 will exceed 500.
- The approximate range of prices of ASD equipment, which covers line filters, isolating transformers, and drives (excluding motors) varied depending on the horsepower range and option selected; these are shown in Table VI in U.S. dollars.

As expected, the prices of ASD equipment decrease with the increase in horsepower ratings. These prices do not cover ASD installation costs, as this depends on equipment location, HVAC requirements, space availability, etc. The ASD prices listed here are for general information only, and these could

TABLE VI
APPROXIMATE PRICES OF ASD EQUIPMENT (U.S. DOLLARS)

HP Range	ASD Cost \$/HP
500 - 1000 HP	\$170-140
1001- 2000 HP	\$140-100
2001- 3000 HP	\$140-85
3001- 5000 HP	\$130-70
> 5000 HP	\$80-50

TABLE VII
DRIVE EFFICIENCY

Load	Range of Overall Efficiencies
100%	96% - 97%
75%	94% - 96.5%
50%	90% - 95.5%

TABLE VIII
DRIVE POWER FACTOR

Load	Input ASD Power Factor
100% load/speed	0.85 - 0.95
75% load/speed	0.67 - 0.95
50% load/speed	0.45 - 0.95

considerably vary depending on application and features selected. Drive manufacturers should always be consulted for pricing.

- For retrofit applications, all the manufacturers recommend the use of an isolation transformer between the power source and the ASD to overcome the "common-mode voltage." For new motor applications, isolation transformers or line reactors may be used, depending on the size of the motor and the users' requirements.
- The values of approximate/estimated efficiency of the system that includes drive, transformers, and filter, as quoted by the four manufacturers, are shown in Table VII.
- The approximate values of ASD input power factors (excluding any correction) are shown in Table VIII.

The power factor for drives that use SCR's in the rectifier circuit drops with speed reduction, whereas it remains almost unchanged when diodes are used.

- The estimated noise levels in decibels of an ASD at 1 m distance, as reported by the participating manufacturers, varied between 70–85 dB. The noise level depends on drive size, method of cooling, namely, air or liquid, and switching frequencies.

B. Technology Information

- Current-source inverters (CSI) were used by two manufacturers, while the CSI-pulsewidth modulation (PWM) type was adopted by the third, and the voltage-source (VSI)-PWM [4] concept was used by the fourth. The differences between drive topologies are discussed in [5]. With regard to switching devices used, three manufacturers use SCR's for the rectifier, while diodes were the choice of the fourth. For the inverters, GTO's were used

by two, SCR's were the choice of the third, and insulated gate bipolar transistors (IGBT's) were used by the fourth. The use of SCR's or IGBT's is mainly governed by drive horsepower rating and manufacturer preference.

- (N-1) redundant capability in switching devices is considered a standard feature by two manufacturers, while the others offer it as an option.
- 12-pulse configuration is available from all drive manufacturers. 12-pulse input is used to reduce harmonics fed back to power systems, and 12-pulse output is used to reduce harmonics into the motor. There are no set rules of thumb as when to use a 12-pulse system, as this would depend on many factors, including size, THD limits, load/torque characteristics, and speed range. More recently, multipulse drives have been used to further control harmonics.
- All the manufacturers individually alarm the switching devices upon their failures.
- All manufacturers offer both liquid- and air-cooled drives. Liquid drives are normally offered for higher horsepower ratings, typically above 2500 hp.
- For air-cooled ASD's, three respondents provide redundant fans as an option, and two require power shutdown for the fan replacement, while shutdown is not needed for the third.
- For liquid-cooled ASD's, all respondents provide redundant pumps as a standard feature.
- The estimated amount of heat generated by the drive was quoted between 18.7–29.2 W/hp of drive rating.
- All manufacturers stated that the current THD level at drive output is less than 5% at rated load and speed, however, some drives exhibit higher harmonic distortions at lower operating speeds. It is prudent to request that the drive manufacturer provide current and voltage THD at minimum, maximum, and midpoint of the operating speed to properly account for harmonic effects on the motor.

C. Protection Features

- Drives are normally mounted in an indoor enclosure. For liquid-cooled systems, the dc-link and heat exchangers are typically outdoors. All manufacturers stated that their control terminal blocks are easily accessible for current waveform measurement.
- The mean time between failures (MTBF) reported by the manufacturers varied between 3.4–5.7 years. The mean time to repairs (MTTR) was reported to be one to four hours.
- All manufacturers reported no significant difference in temperature rise between motors when connected to a drive and operating at rated speed and load and when connected directly to a 60-Hz supply.
- Almost all manufacturers recommended performing torsional analysis for medium-voltage drive applications, particularly when the speed is greater than 1800 r/min and for high inertia loads.
- Two respondents indicated that UPS is normally provided as a standard feature to supply power for control circuits,

whereas the third offered it as an option, and the fourth did not suggest UPS.

D. General Information

- Typical manufacturer requirements from the users for quotation purposes include horsepower rating of motor and/or driven load, voltage of existing motor, source bus voltage, torsional system data, operating speed range, type of load, torque-versus-speed curve (operating), space availability for equipment, harmonic specification limits, and power factor specifications.
- All the respondents said that the standard warranty period offered to the customers was 12 months from startup, not to exceed 18 months from shipment.
- All the manufacturers offered a preventative maintenance contract to the users.
- Three manufacturers have their facility meet ISO 9000 level requirements, with two certified for ISO 9001, and the other for ISO 9002 certification.
- With regard to minimum duration of availability of spare parts, two responses were for six to ten years, and the other two said that the spares would be available for more than ten years.
- In-house and job-site training was available from all the manufacturers.
- Possible areas of improvement, as foreseen by ASD manufacturers, that could take place in the next three years are the following:
 - a) use of PWM rectifier instead of phase-shifting rectifier;
 - b) wider use of GTO and /or IGBT devices;
 - c) use of active filters as an integral part of rectifier/inverter circuits to further reduce the harmonics.
- With regard to forecasts on the costs of ASD's, the respondents predict that the cost in dollars per horsepower will reduce by 0%–5% annually over the next five years.

VII. CONCLUSIONS

The use of medium-voltage drives is increasing, judging by the number of new installations over the last three years. More manufacturers are entering the market to build medium-voltage drives, and this trend is expected to continue. Presently, there are at least six manufacturers of medium-voltage drives in North America. The users have accepted this technology and are employing it to control critical processes. There is good overall satisfaction among the users, and all would consider using an ASD again for future applications. The following are the main conclusions arising from the study.

- 1) The reliability and performance of medium-voltage drives have considerably improved since their inception some 12 years ago. Advancements made in logic boards, switching devices, diagnostic systems, and cooling, just to name a few, have all contributed to wider acceptance of this technology by users.
- 2) In 1995, manufacturers have collectively sold over 210 medium-voltage drives, and this is a clear indication

of the maturity of this business. In 1996, over 400 medium-voltage drives were sold and, for 1997, this figure is expected to exceed 500 drives.

- 3) ASD's were successfully implemented in many retrofit applications without resulting in motor derating or serious vibration problems on the driven equipment.
- 4) Input harmonic control is normally accomplished by using a three-winding or multiwinding isolation transformer and/or filter.
- 5) Medium-voltage drives that utilize a phase control rectifier suffer from a poor input power factor, particularly at reduced speed. Power factor correction, if required, is normally achieved by adding a filter.
- 6) The drives' electronic components and switching devices are very sensitive to line disturbances and high temperatures. Input voltage deviation below 85% of rated voltage for more than one cycle could result in tripping the drive. The UPS is utilized to alleviate these nuisance trips.
- 7) Drives rated 2500 hp and above are generally built liquid cooled, and drives below 2500 hp are built air cooled, although overlap sometimes does exist. Installing these drives in an existing building may cause a considerable burden on the air-handling system, and careful reevaluation is necessary to avoid premature failures of the components.
- 8) A medium-voltage drive system requires far more space than the conventional on-line starter, and this could present a problem, particularly in retrofit applications.
- 9) The majority of the users listed "reliability" as the main reason for selecting medium-voltage drives, followed by energy efficiency and process control. In spite of this, almost all users reported experiencing drive tripping problems. They also indicated that the many advantages offered by the ASD system far outweigh the occasional trips.
- 10) CSI or CSI-PWM or VSI-PWM (multilevel) is the inverter technology used by the manufacturers. For the CSI type, a drive output capacitor is used to control harmonics to the motor to less than 5% THD.
- 11) Medium-voltage drives were originally introduced to the market to meet the requirements of motors rated 1500 hp and above. Due to the recent advancements in medium-voltage drive technology, drive ratings as low as 400 hp are being offered and, in some cases, are considered more economical when compared to the conventional low-voltage drives.

VIII. SUGGESTIONS AND RECOMMENDATIONS

A. Suggestions and Recommendations for ASD Users

- 1) Participate fully in the commissioning and startup of the ASD.
- 2) Record and analyze the complete performance data during commissioning.

- 3) Complete and thorough testing of the entire drive system is essential to ensure trouble-free operation. All design feature options selected and protective settings should be tested.
- 4) Proper understanding of the application and load-torque characteristics across the operating speed range is critical for successful drive implementation.
- 5) Provide training to operating and maintenance personnel.
- 6) Monitor the total drive system performance to establish the total benefits of improved process efficiencies, energy savings, and drive reliability.
- 7) Medium-voltage ASD technology is continuously changing. Better and more efficient electronics components and sophisticated microprocessor-based controls are being introduced to the market. Be knowledgeable of the limitations and benefits of these new technologies.

B. Recommendations for ASD Manufacturers

- 1) Follow the three I's of communication: instigate, increase, and improve the communication between the motor manufacturers, ASD manufacturers, driven equipment manufacturer, and the present and prospective users of the medium-voltage drives.
- 2) In marketing ASD's, the energy savings and payback, as much as it is important and critical, should not be the key feature. Many of the users, especially the operating personnel, do not seem to understand all the benefits of ASD's in the operation of the plant or process. The manufacturers should, in collaboration with the utilities, organizations such as the CEA and EPRI [6], and association of utilities provide the necessary forum and leadership to convince the present and potential customers of the many benefits of ASD's.
- 3) Develop economic models to quantify some of the other benefits of ASD operation.
- 4) Improve longevity and reliability of components and logic boards by continuously reviewing quality control procedures.
- 5) Coordinate with the motor manufacturer/vendor about the effects of the ASD on the motor performance, and establish guidelines for new and retrofit applications.
- 6) Redundancy, or lack of it, in switching devices should be discussed with the user in relation to the operation and reliability of the ASD.
- 7) Proper documentation of economic benefits and performance features of ASD's will create an increasing market for larger drives.
- 8) Provide the leadership, lend the expertise to setup a team, and develop industry-wide standards for medium-voltage drives.
- 9) Continue to develop techniques to control harmonics.
- 10) Enhance the reliability of the ASD by making it less sensitive to line transients and disturbances.

C. Suggestions and Recommendations for Utilities

- 1) Continue to promote the use of medium-voltage ASD's as a major segment of their energy management program.

- 2) Continue to sponsor symposiums and workshops to increase awareness of medium-voltage drives. These symposiums should not only expound the short-term benefits, but also the long-term benefits of these drives.
- 3) Provide a forum to encourage an effective communication between the manufacturers of ASD's, motors, driven equipment, and the primary users to develop standards applicable to the industry.

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