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 USA. In some cases, cash incentives are being offered towards 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 (ASDs) for induction motors. 30 out of 40 users, primarily from the Petro-Chemical industry in the USA and Canada, participated in completing a detailed questionnaire and reported on 66 medium voltage drives ranging from 800 - 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.

Introduction

ASDs have provided the industries significant advantages in improved process control, higher efficiencies and energy savings. The reliability of ASDs have improved significantly in the last decade due to improvements in switching devices, cooling system, harmonic mitigation, design of converters/inverters and control systems. ASD technology has matured and the cost of adopting it have become more economical as is evident by the increased number of drives put in 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 are in general associated with critical process areas of the plant, and any shutdown of the system could result in major process upset and loss of production. The concerns about reliability of ASDs in such critical applications might have provided impediments to wider application of these ASDs. 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 leading to a better dialogue between the users, manufacturers and utilities, and to alleviate users' main concerns. The survey data was compiled in March 1995, and though mostly from the Petro-Chemical industry it could be applied equally to other types of industries.

Study Objectives

The study was designed to investigate the technical issues related to the performance of medium-voltage ASDs 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:

(1) Survey/Review the application of medium - voltage drives for AC induction motors with special emphasis on Petro - Chemical 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 ASDs 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 record and any other concerns. This would help the utilities to address the needs and concerns of their customers who are using or considering employing ASDs.

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Methodology

For the purpose of this project, medium voltage drives were characterized to be those rated 700HP and up operating at 2300V and above. Since these high-power drives are designed for and used in customized applications, co-operation was sought from manufacturers and vendors in preparing the lists of users. The study focused specially on ASDs for induction motors used mainly in Petro - Chemical industries. Load Commutated Inverter (LCI) used with the synchronous motors was outside the scope of this project. The study covered both the manufacturers and users of the drives.

Separate questionnaires were designed for manufacturers and the users. Extensive consultations with both of these 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 were identified from the list with more than one hundred drives used in their systems. Emphasis was placed on those users in Petro - Chemical industry to meet the objectives of the study. The response from users was overwhelming with 75% participating in the study.

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 ASDs and the other set to the manufacturers of ASDs.

1. 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 comprised of twenty 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, and is grouped under several sections.

A. 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

***B.** ASD Detail*

- Drive data: type, rating, voltage, years in service, cooling
- Redundancy
- Provision of UPS
- Drive sizing and application
- By-pass mode for direct on-line starting
- Failures while in service
- Average time between failures
- Average downtime for repair
- Average cost of repair

C. *Mechanical Driven Equipment*

- Type of driven load
- Load duty cycle
- Type of service
- Mechanical problems due to ASD

D. Isolation Transformer

- Transformer data
- Two or three windings
- Failures, if any

E. Line Harmonic Filter

- Application
- Compliance with guidelines

F. ASD Selection and Application

- Selection and feasibility study
- Environmental control
- Space limitations
- Support from the manufacturer
- Start-up time
- Diagnostic system
- Efficiency specification
- Selection criteria

- Payback period for the installation
- Torsional analysis
- Harmonic study & mitigation
- Effects of power line disturbances
- Need for power factor correction capacitors
- Noise levels
- Success of the installations

2 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 and a summary of areas covered are as followed:

A. Adjustable Speed Drive System Information:

- Name plate information, Approximate number of ASDs marketed by the company in USA & Canada
- Approximate list price in $/HP
- Need for isolation transformer
- Approximate values of efficiencies and power-factors at different loads
- Average number of drives for induction motors sold per year
- Standards for medium voltage drives
- Estimated noise levels

B. 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

C. 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)

D. 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 5 years.

"Users' Experiences" - Survey Responses And Analysis

Most of the participants (67%) were from the Petro-Chemical industry and the remaining 33% distributed amongst 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.

1. 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 are shown in **Table I**.

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

- 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 RPM operation, 11.9% at 1800 RPM, 4.8% at 1200, 4.8% at 900 RPM, 2.4% at 6000 RPM and 1.2 % at 10000 RPM. The highest speed motor was rated 10000 RPM at 8000 HP.
- Majority of the motors (61%) with ASDs were required to operate in speed ranges of 50 - 105%, 23% at 40-110%, 8% at 70-100% and 8% at 20-100%.
- Majority of the motors particularly for retrofit applications were 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 input isolation transformer.
- Of the 33 new motors reported, 20 motors (60.6%) underwent heat-run tests when connected to ASD, and all reported that test results met the specifications.
- 73.8% of motors were located in Class I, Div 2 area followed by 16.7% in non-hazardous and 9.5% in Class I, Div 1 areas. Almost all the new or retrofit motors were equipped with RTDs for thermal protection of stator windings and bearings.
- Majority of the motors in service had not experienced failures or problems attributed to the use of ASD. However, a few reported that the motors experienced vibration and overheating problems.

2. Drive Details

- HP rating of the drives varied from 800 HP to 10000 HP. The distribution of the sizes are as shown in **Table II:**

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

- 83% of the drives reported on were of liquid cool and the remaining were of air cooled. Drives rated 2000HP and above were in general of liquid cool design. Redundant pumps are standard features for liquid-cooled system
- Almost all drives had voltage ratings of either 2300 V or 4160 V. 71% of the drives were rated 4160 V, and the remainder at 2300 V.
- The earliest reported application of medium voltage drive for induction motors is about 10 years old. Almost 50% of the drives have been installed in the last 3 to 4 years. The average years of service of the other 50% is about 6 years.
- Typical range of guaranteed values of drive efficiency (drive + filter) at rated load and 60 Hz is 96-98%.
- 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 HP 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 reduce 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 'by-pass' mode to start the motor directly on-line at 60 Hz. Only 16.7% of the drives were not provided with the by-pass. 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, performance and better meeting users' requirements. In spite of this, all users reported having drive problems. The majority (70%) were attributed to components failures (ex: SCRs, GTOs, filters, diodes, control module etc.). 50% of the users had experienced under and over-voltage 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.**

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

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 drive in operation, see **Table IV**.

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 %

- More than 75% of the failures / problems were repaired within a day and about 20% took about 1-4 days. Only one incident reported required between 5-10 days. One failure of a DC reactor required more than 10 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 $5,000 - $9,999. One failure that accounted for more than $10,000 was due to the DC reactor failure. About 15% of the responses suggested that the repairs were done under warranty.

3. 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) were 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 were used for continuous service over the day i.e. 24 hours operation. Two loads were running under normal service of 8 hours and the site was operated between 12 to 16 hours.
- Almost all of the users reported having no mechanical problems with the driven equipment which could be directly attributed to the use of ASD. A few users reported experiencing torsional vibrations during commissioning. In one case the motor/compressor shaft experienced excessive vibration at the 12th harmonic and within the operating speed range.

4. 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 HP 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 55-65 °C. The remaining transformers were of dry type with temperature rise of 80-115 ° C.
- All the isolation transformers except one were installed outdoor. 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 3-winding type and the rest 2-winding type.
- Almost all users reported having no isolating transformer failures. Two users however reported transformer overheating and had to be returned to the shop for modifications.

5. 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.

6. 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 method of cooling, maximum ambient temperature and size. Air-cooled drives produce 1.5-2% KW loss of drive HP rating. For liquid-cooled, 60-80% of heat loss generated is rejected outdoor. Drives in general require a temperature control environment, and this was achieved either by users installing an air conditioning system, or by the manufacturer when the drive was assembled in a skid type building.
- Typical dimensions of a medium voltage drive line range from (116"-250") W x (36"-54") D x (90"-115") H, depending on ratings, option selected and cooling. The lower range is typical of drives rated 500-1500HP, and upper range is for drives above 5000HP. Space requirements should be carefully evaluated during conceptual design phase.
- All of the users reported that the information received from the manufacturers for the operation and maintenance of ASDs was adequate.
- Only four out of thirty users had purchased the preventative maintenance contract for the ASDs.
- 62.1% of the ASD installations required 3 to 7 days for start-up and commissioning, 27.6% required 8 days to 1 month and 10.3% of the installations were commissioned in less than 3 days.

- 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 ASD, 7.5% stated "energy efficiency" and 6.7% mentioned "process efficiency". One user reported that "soft-start" was the main reason for selecting ASD.
- The approximate payback period for ASD installation is given in **Table V.**

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 %

- 25% of the respondents reported less than 2 years as the acceptable payback period by their company to consider ASD application, whereas 44% reported 2-3 years and 31% quoted 3-5 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 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 Total Harmonic Distortion (THDs) at point of common coupling (PCC). Users of medium voltage drives in 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. These IT product levels are more stringent than the values required by IEEE [2]. The IT product recognizes the interference between harmonics generated by ASDs 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 3 of the 28 users reported that noise generated by ASDs was a problem while majority (89.3%) did not consider the noise a problem.
- 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 an 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 6 users would follow the bid process.

"Manufacturers' Experiences" : Survey Responses And Analysis

A total of 4 out of 6 manufacturers in North America of medium voltage ASDs participated in fully completing the questionnaires. One manufacturer declined because at present do 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.

1. ASD System Information

- Manufacturers varied in their capabilities to build medium voltage ASDs and this ranged between 500 HP and up to 20000 HP. The largest medium voltage drive for induction motors built to date is 15000 HP.
- The highest speed for which an ASD was designed is 11500 RPM and the corresponding HP is 3500 HP [3].
- All the manufacturers indicated that they produce 2300 V and 4160 V drives. Drives with voltage ratings of 3300 V, 6900 V and 7200 V were also quoted by some of the manufacturers.
- Range of drive frequency control varied from a few Hertz to 300 Hz.
- Two companies introduced the medium voltage drives in mid-eighties and the other two in 1990 and in 1994.
- At the time of survey completion in April 1995, the total number of medium voltage drives for induction motors installed in Canada were about 53 with majority installed in Alberta, and more than 500 in the USA.
- The total number of medium voltage drives sold in 1995 by all responding manufacturers is about 210, and this figure is expected to increase for 1996. It is anticipated that the overall number of the drives sold/installed will approach 1000 by the end of 1996.
- Approximate range of prices of ASDs equipment that covers line filters, isolating transformers and drives (excluding motors) varied depending on the HP range and option selected and these are shown in **Table VI** in US dollars:

TABLE VI
Approximate Prices of ASD Equipment

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

As expected the prices of ASD equipment decrease with the increase in HP ratings. These prices do not cover ASD installation costs as this depend on equipment location, HVAC requirements, space availability etc. The ASD prices listed here are for general information only, and these could 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 isolation transformer between the power source and the ASD to overcome the "common mode voltage". For new motor applications isolation transformer 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 as shown in **Table VII:**

TABLE VII
Drive Efficiency

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

- The approximate values of ASD input power factors (excluding any correction) are as shown in **Table VIII**:

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

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

2. Technology Information

- CSI inverters were used by two manufacturers while CSI-PWM type was adopted by the third and PWM type was used by the fourth. With regards to switching devices used, three manufacturers use SCRs for the rectifier while Diodes were the choice of the fourth. For the inverters, GTOs were used by two, SCR was the choice of the third and IGBT is used by the fourth.
- (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 12 pulse system as this would depend on many factors including size, THD limits, load/torque characteristics and speed range.
- The switching devices are individually alarmed upon their failures by all the manufacturers.
- Three manufacturers offer both liquid and air cooled drives while the fourth offers only liquid cooled.
- For air-cooled ASDs, three respondents provide redundant fans as an option and two require power shut-down for the fan replacement while shutdown is not needed for the third.
- For liquid-cooled ASDs, 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 Watts/HP of drive rating.
- All manufacturers stated that the current THD levels at drive output is less than 5% at rated load and speed, however some drives exhibit higher harmonic distortions at lower operating speed. It is prudent to request the drive manufacturer to provide current and voltage THD at minimum, maximum and midpoint of the operating speed to properly account for harmonic effects on the motor.

3. Protection Features

- Drives are normally mounted in an indoor enclosure. For liquid cooled systems, the DC link and heat exchanges are outdoor. All manufacturers stated that their 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 1-4 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 60 Hz supply.
- Almost all manufacturers recommended performing torsional analysis for medium voltage drive

applications particularly when speed is greater than 1800 RPM 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 require UPS.

4. General Information

- Typical manufacturer's requirements from the users for quotation purposes include HP rating of motor and/or driven load, voltage of existing motor, source bus voltage and torsional system data, operating speed range, type of load, torque vs 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 start-up not to exceed 18 months from shipment.
- All the manufacturers offered the 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 regards to minimum duration of availability of spare parts, two responses were for 6 to 10 years and the other two said that the spares will be available for more than 10 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:
  (1) Use of PWM rectifier instead of phase-shifting rectifier.
  (2) Wider use of GTO and /or IGBT devices.
  (3) Use of active filters as an integral part of rectifier/ inverter circuits to further reduce the harmonics.
- With regards to forecasts on costs of ASDs, the respondents predict that the cost in $/HP will reduce by 0 - 5 % annually over the next 5 years.

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 five 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 by the users and all would consider using 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 inceptions some 10 years ago. Advancements made in logic boards, switching devices, diagnostic system and cooling, just to name a few, have all contributed to wider acceptance of this technology by users.
2. In 1995, the manufacturers have collectively sold over 210 medium voltage drives and is a clear indication of the maturity of this business.
3. ASDs 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 isolation transformer and/or filter.
5. Medium voltage drives that utilize 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. 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 1 cycle could result in tripping the drive. The UPS is utilized to alleviate these nuisance trippings.
7. Drives rated 2500 HP and above are generally built liquid-cooled, and drives below 2500 HP are built with air-cooled although overlap sometimes do exist. Installing these drives in an existing building may cause considerable burden on the air handling system and careful re-evaluation is necessary to avoid premature failures of the components.
8. 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. 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 ASD system far outweigh the occasional trippings.
10. CSI or PWM or the combination of both is the inverter technology used by the manufacturers. In most cases output drive filter is used to control harmonic limits to less than 5% THD.
11. Medium voltage drives were orginally introduced to the market to meet the requirements of motors rated 1500HP and above. Due to the recent advancements of medium voltage drive technology, drive rating as low as 400HP are being offered, and in some cases are considered more economical when compared to the conventional low voltage drives.

Suggestions And Recommendations

A. *Suggestions And Recommendations For ASD Users*

1. Participate fully in the commissioning and start-up 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 features, options selected and protective settings should be tested.

4. Proper understanding of the application and load torque characteristics across 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 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 ASDs, 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 ASDs in the operation of the plant or process. The manufacturers should, in collaboration with the utilities, organizations such as CEA, EPRI, and association of utilities provide the necessary forum and leadership to convince the present and potential customers of the many benefits of ASDs.
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 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 ASDs will create an increasing market for larger drives.
8. Provide the leadership, lend the expertise to set-up a team and develop industry wide standards for medium voltage drives.
9. Develop techniques to reduce harmonics injected back into the power system.
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 ASDs 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 long-term benefits of these drives.
3. Provide a forum to encourage an effective communication between the manufacturers of ASDs , motors, driven equipment and the primary users to develop standards applicable to the industry.

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