Annex H

Report of Large Motor Reliability Survey of Industrial and Commercial Installations Parts I, II, and III

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***Abstract*—The Power Systems Reliability Subcommittee of the IEEE Industry Applications Society recently initiated a survey of the reliability of large motors in industrial and commercial installations in keeping with its commitment to support or update results of the survey published in 1973 and 1974. Moreover, the new survey has emphasized and expanded on one type of electrical equipment only. The previous survey results were heavily biased by one class of motors in the motor category and contained some results that appeared unreasonable and were considered questionable. The results of this new survey are presented here and intended to expand failure data to additional influencing categories and at the same time be oriented to the more common types in use today. A restriction to a lower limit in size also distinguishes the results to motors in relatively critical applications. A further explanation of the reasons for this survey and intended results is presented in a subcommittee report included for reference in the Appendix.**

INTRODUCTION

THE RESULTS of the 1982 survey on the reliability of motors in industrial and commercial installations are summarized in Tables I–XIX. The data obtained allowed the various categories to be shown here which provide failure data on a more expanded and detailed basis, for the most part, than was presented in the 1973/1974 survey results. Also comparisons are made with the previous survey where results are of similar format.

To focus on motors that are of a critical nature, where reliability is most important, this survey differs from the other in that only motors larger than 200 hp are considered. In addition, to present data on motors most commonly manufactured and used today and to avoid distorted failure data from old motors that are expected to have high failure rates, this survey has limited the age of motors to no more than 15 years.

A brief discussion is included for each table identifying significant points and results of the survey. The intent of this working group report is to present these results as updated experience in industry applications, and the drawing of definite conclusions is left to the reader.

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SURVEY RESPONSE

The cover letter and questionaire form used in the survey are included in the Appendix. The form is specifically oriented to motors greater than 200 hp in size and no older than 15 years. As in other surveys succeeding the 1973 overall survey, this form is simplified into two sections: total population data and failure data.

Although the response was inadequate to identify a substantial number of industry types, the number of companies and plants identified was encouraging and the overall response was considered a success. Total population is less in this survey than in the 1973 survey, but this was anticipated due to the restriction on age and size. However, the total number of plants in the new survey is greater which adds credibility to the data as being representative of industry applications. The following list summarizes the magnitude of the response:

number of plants	75
number of companies	33
number of motors	1141
total population (unit years)	5085.0
total failures	360.

Some respondents did not submit data for every category evidenced by the comment "not specified" in the tables. Where response was insufficient to identify the motor and/or period reported the response was not used. As in previous survey reports, this report maintains the standard for credibility of failure rates by identifying categories that contain an insufficient number of failures to be representative.

SURVEY RESULTS

Summary

Table I summarizes the results in types of motors and voltage classes in similar fashion to the previous survey summary table. The previous data have been rearranged for comparison and presented here as Table II. In the new survey there was not enough response to separate the petroleum industry and chemical industry or to separate out other industry types and still show meaningful results.

TABLE I
OVERALL SUMMARY—LARGE MOTORS

Number of Plants in Sample Size	Sample Size (Unit Yr)	Number of Failures Reported	Industry	Equipment Subclass	Failure Rate (Failures/ Unit Yr)	Average Hours Downtime/ Failure	Median Hours Downtime/ Failure
75	5085.0	360	all	all	0.0708	69.3	16.0
				induction			
33	1080.3	89	all	0–1000 V	0.0824	42.5	12.0
52	2844.4	203	all	1001–5000 V	0.0714	75.1	12.0
5	78.1	2*	all	5001–15 000 V	*	*	*
1	13.5	—	all	not specified	—	—	—
				synchronous			
19	459.3	35	all	1001–5000 V	0.0762	78.9	16.0
2	29.5	3*	all	5001–15 000 V	*	*	*
				wound rotor			
5	137.0	10	all	0–1000 V	0.0730	*	*
9	251.1	8	all	1001–5000 V	0.0319	*	*
2	39.0	4*	all	5001–15 000 V	*	*	*
				direct current			
5	122.7	6*	all	0–1000 V	*	*	*
1	30.0	—	—	1001–5000 V	—	—	—
				induction			
11	484.3	39	petrochemical	0–1000 V	0.0805	88.3	40.0
28	1349.0	108	petrochemical	1001–5000 V	0.0801	109.4	48.0
2	10.3	1*	petrochemical	5001–15 000 V	*	—	—
				synchronous			
7	73.0	8	petrochemical	1001–5000 V	0.1096	72	16.0
				wound rotor			
2	20.8	4*	petrochemical	0–1000 V	*	—	—
3	17.6	3*	petrochemical	1001–5000 V	*	—	—

* Small sample size.

TABLE II
1973 OVERALL SUMMARY—MOTORS

Number of Plants in Sample Size	Sample Size (Unit Yr)	Number of Failures Reported	Industry	Equipment Subclass	Failure Rate (Failures/ Unit Yr)	Average Hours Downtime/ Failure	Median Hours Downtime/ Failure
—	42 463	561	all	all	0.0132	111.6	—
				induction			
17	19 610	213	all	0–600 V	0.0109	114.0	18.3
17	4229	171	all	601–15 000 V	0.0404	76.0	91.5
				synchronous			
2	13 790	10	all	0–600 V	0.0007	35.3	35.3
11	4276	136	all	601–15 000	0.0318	175.0	153.0
6	558	31	all	direct current	0.0556	37.5	16.2
				induction			
9	16 105	196	petrochemical	0–600 V	0.0122	123.4	—
10	3834	156	petrochemical	601–15 000 V	0.0407	74.3	—
				synchronous			
1	13 750	10	petrochemical	0–600 V	0.0007	35.3	35.3
6	4027	130	petrochemical	601–15 000 V	0.0323	175.8	—

Response was adequate in this survey to show an intermediate voltage class (1001–5000 V) not shown in the previous survey. Induction motors in the first two voltage classes show failures rates very nearly the same, with the lower voltage class slightly higher. Both are substantially higher than the earlier results (Table II).

The response for synchronous motors was dominated by the 1001–5000-V class, and again the new survey shows a failure rate twice that of the higher voltage rated synchronous motors in Table II. The new results show failure rates for synchronous and induction motors approximately equal for the same voltage class. The "petrochemical" industry shows a slightly higher failure rate for synchronous motors than for all industries.

The new survey obtained data on wound rotor induction motors with results showing a failure rate only slightly less than induction motors of the same lower voltage class. The next higher voltage class has a failure rate less than half that of synchronous and induction motors.

Although the sample size for dc motors was considered inadequate, this failure rate was the only one showing some consistency with the previous survey. The previous survey did not show a voltage class for dc motors.

Overall, the median hours downtime per failure was reported as less in the new survey than in the 1973 survey. Again the downtime reported was biased with unusually high periods and the average value for each class is consistently higher than the median value. The overall average and median downtime values calculated for all categories in this table include the downtime data omitted in the specific categories with "small sample size." Also, downtime for two failures was exceptionally and unusually high and therefore omitted from the results. One was reported as 960 h for an induction motor in the 0–1000-V class and replaced with a spare to restore service. The other was reported as 6570 h for an induction motor in the 1001–5000-V class and repaired during normal working hours.

Horsepower

Table III is presented to show a relationship of failure rate with size. The response gives a good comparison between the first two size categories with the failure rates calculating very nearly the same and also approximating those in Table I showing voltage classes. The third size category (5001–10 000 hp) shows a relatively high failure rate but calculated with a small population in sample size.

Speed

Failure rate is generally considered affected by speed, but Table IV shows somewhat unexpected results. The highest speed range, essentially 3600 r/min was included in this survey because of the increasing popularity in industry of two-pole motors. These results show the highest speed motors as most reliable and the lowest speed as least reliable.

Enclosure Type

This population type was added to expand on any notable effects on failure rate. Table V shows that open motors experienced the highest failure rate among those with substantial sample size. Depending on the application this result might have been expected except the table below on causes does not support this result in the obvious causes of moisture and aggressive chemicals. It is suspected that more supporting data may be hidden in the relatively high response to causes reported as "other."

TABLE III
HORSEPOWER VERSUS FAILURE RATE

	201-500 hp	501-5000 hp	5001-10 000 hp	> 10 000 hp	Not Specified
Sample size (unit-yr)	3185.6	1822.5	46.1	17.2	13.5
Number of failures	217	133	10	—	—
Failure rate (failures/unit-yr)	0.0681	0.0730	0.2169	—	—

TABLE IV
SPEED VERSUS FAILURE RATE

	0–720 r/min	721–1800 r/min	1801–3600 r/min	Not Specified
Sample size (unit yr)	657.1	3219.8	1194.6	13.5
Number of failures	66	232	62	—
Failure rate (failures/unit yr)	0.1004	0.0721	0.0519	—

Environment

In Table VI the survey results show failure rate as affected by indoor and outdoor applications. It was expected that outdoor motors would show a higher failure rate than indoor motors, but the opposite was true. This follows from Table V which shows open type enclosures with the highest failure rate. One might conclude that when all environmentally related causes are combined as one, they support the results of Tables V and VI.

Duty Application

This population type breaks out continuous and intermittent application in Table VII. The total sample size was heavily dominated by continuous duty use with this category showing the highest failure rate at about twice that of intermittent duty. Some motors were reported as intermittent in a backup or standby role and operated only a small fraction of the period reported which may account partly for the large difference in failure rates.

Service Factor

Reliability versus service factor (SF) is an important consideration for those who must apply motors at varying load conditions that sometime exceed the normal nameplate rating of the motors. Table VIII shows a higher failure for 1.15-SF

TABLE V
ENCLOSURE TYPE VERSUS FAILURE RATE

	Open	Weather Protected	Totally Enclosed (TEFC, E.P., D.I.P)	Totally Enclosed (Open Pipe Vent)	Totally Enclosed (Water-Air)	Totally Enclosed (Air-Air)	Not Specified
Sample size (unit yr)	2597.6	569.5	1339.9	40.7	119.5	332.5	85.2
Number of failures	224	25	78	6*	6*	20	1*
Failure rate (failures/unit yr)	0.0862	0.0439	0.0582	*	*	0.0602	*

*Small sample size.

TABLE VI
ENVIRONMENT VERSUS FAILURE RATE

	Indoor	Outdoor	Not Specified
Sample size (unit yr)	3359.9	1663.8	61.3
Number of failures	263	97	—
Failure rate (failures/unit yr)	0.0783	0.0583	—

TABLE VII
DUTY APPLICATION VERSUS FAILURE RATE

	Continuous	Intermittent	Not Specified
Sample size (unit yr)	4412.2	659.3	13.5
Number of failures	334	26	—
Failure rate (failures/unit yr)	0.0757	0.0394	—

TABLE VIII
SERVICE FACTOR VERSUS FAILURE RATE

	1.0SF	1.15SF	>1.15SF	Not Specified
Sample size (unit yr)	2557.9	2314.9	102.3	109.9
Number of failures	158	187	4*	11
Failure rate (failures/unit yr)	0.0618	0.0808	0.0391	0.1001

*Small sample size.

motors than for 1.0-SF motors. Under causes, overheating was reported as a significant failure initiator which raises the suspicion that exceeding temperature rises might be an application problem. These results do not show the effect of full service factor operation on field equipment of synchronous and dc motors or on secondary equipment of wound rotor motors. However, slip rings and brushes were not reported as obvious major problem areas as shown in Table XI.

TABLE IX
AVERAGE NUMBER OF STARTS/DAY VERSUS FAILURE RATE

	<1	1-10	11-30	>30	Not Specified
Sample size (unit yr)	3654.8	1274.5	104.9	37.3	13.5
Number of failures	257	97	2*	4*	—
Failure rate (failure/unit yr)	0.0703	0.0761	0.0191	0.1072	—

*Small sample size.

TABLE X
POWER SUPPLY GROUNDING TYPE VERSUS FAILURE RATE

	Solid Ground	Impedence Ground	Ungrounded	Not Specified
Sample size (unit yr)	2287.7	1873.9	909.9	13.5
Number of failures	127	150	83	—
Failure rate (failures/unit yr)	0.0555	0.0800	0.0912	—

Average Number of Starts per Day

This population type was expected to provide data to show the effects of increasing severity in duty cycle, as related to starting, on failure rate. Surprisingly, the results (Table IX) show only a slight difference in failure rate between the first two categories. The response was disappointing in the last two categories, and no obvious trend in evident.

Power Supply Grounding Type

Much has been written about the effects of how the power supply system neutral is handled on reliability of electrical equipment and especially on motors. Table X shows results that support many generalizations and expected consequences of grounding types. The least failure rate is with solidly grounded power supplies, and the highest is with ungrounded power supplies. Commonly expected causes of failures in ungrounded systems include transient overvoltage and abnormal voltage levels, but the table on causes did not support this.

TABLE XI
FAILED COMPONENT

Failed Component*	Number of Failures: Induction Motors	Synchronous Motors	Wound Rotor Motors	DC Motors	Total All Types
Bearing	152	2	10	2	166
Windings	75	16	6	—	97
Rotor	8	1	4	—	13
Shaft or CPLG	19	—	—	—	19
Brushes or slip ring	—	6	8	2	16
External device	10	7	1	—	18
Not specified	40	9	—	2	51

* Some respondents reported more than one failed component per motor failure.

However, insulation breakdown and deterioration from age might be interpreted as being affected by ungrounded systems.

Failed Component

Table XI shows which components failed most often for the four types of motors surveyed. Similar to the previous survey, bearings and windings were the predominate trouble areas. However, in this survey bearings by far led all other individual components in failures. In the previous survey windings failed most often. A significant number of failures occurred where the failed component was not specified in this survey.

Time Failure Discovered

The data in Table XII give an indication of when users discover most failures. Two-thirds of the failures were discovered during normal operation, and almost one third were discovered during testing or maintenance. Many feel that under a good maintenance program, most failures are discovered or prevented during testing or maintenance. Table XIV shows that about one-third of the total population reported excellent maintenance. The previous survey showed the same trend in when failures were discovered. The causes table lists major types that support the result of most failures being discovered during normal operation.

Causes of Failures

These results, shown in Table XIII are very close to those of the 1973 survey with some minor differences. The three most common failure initiators are mechanical breakage, overheating, and insulation breakdown. These causes, combined, are supportive of the previous survey results.

The major contributing cause reported is normal deterioration from age, as was also a major contributer in the other survey. Unlike the previous survey, high vibration and poor lubrication were also reported as significant causes which reinforce the problem areas of mechanical breakage and consequently bearing failures. Both surveys reported defective components and inadequate maintenance as major underlying causes.

Considering the combined contributing causes related to environmental conditions such as high ambient temperature, abnormal moisture, aggressive chemicals, and poor ventilation, the failure rates of open and indoor motors shown in

TABLE XII
TIME FAILURE DISCOVERED

	Number of Failures	Percent of Total
During normal operation	240	66.7
During routine maintenance or testing	101	28
Other	13	3.6
Not specified	6	1.7

TABLE XIII
CAUSES OF FAILURES

	Number of Failures	Percent
Failure Initiator		
1) Transient overvoltage	5	1.5
2) Overheating	45	13.2
3) Other insulation breakdown	42	12.3
4) Mechanical breakage	113	33.1
5) Electrical fault or malfunction	26	7.6
6) Stalled motor	3	0.9
7) Other	107	31.4
Failure Contributor		
1) Persistent overloading	14	4.2
2) High ambient temperature	10	3.0
3) Abnormal moisture	19	5.8
4) Abnormal voltage	5	1.5
5) Abnormal frequency	2	0.6
6) High vibration	51	15.5
7) Agressive chemicals	14	4.2
8) Poor lubrication	50	15.2
9) Poor ventilation or cooling	13	3.9
10) Normal deterioration from age	87	26.4
11) Other	65	19.7
Failure Underlying Cause		
1) Defective component	62	20.1
2) Poor installation/testing	40	12.9
3) Inadequate maintenance	66	21.4
4) Improper operation	11	3.6
5) Improper handling/shipping	2	0.6
6) Inadequate physical protection	19	6.1
7) Inadequate electrical protection	18	5.8
8) Personnel error	21	6.8
9) Outside agency other than personnel	12	3.9
10) Motor-driven equipment mismatch	15	4.9
11) Other	43	13.9

TABLE XIV
MAINTENANCE VERSUS FAILURE RATE

Maintenance Quality and Cycle	Sample Size (Unit Yr)	Number of Failures	Failure Rate (Failures/Unit Yr)	Median Hours Downtime/Failure	Average Hours Downtime/Failure
Excellent					
< 12 mo	834.0	93	0.1115	8	53.6
12–24 mo	660.1	24	0.0364	24	40
> 24 mo	285.5	9	0.0315	36	48
All	1779.6	126	0.0708	16	50.9
Fair[a]					
< 12 mo	1776.8	155	0.0872	16	37.7
12–24 mo	967.7	39	0.0403	54	166.3
> 24 mo	167.0	12	0.0719	165	264.4
Not Specified	4.0	1*	*	*	*
All	2915.5	207	0.0710	16	87.3
Poor[b]					
< 12 mo	37.1	3*	*	*	*
12–24 mo	195.4	15	0.0563	96	83.6
> 24 mo	6.0	1*	*	*	*
All	238.5	19	0.0797	72	70.7
None	123.3	7*	*	*	*
Not specified	28.0	1*	*	*	*

*Small sample size.
[a] 960 h downtime for one failure omitted.
[b] 6570 h downtime for one failure omitted.

Tables V and VI may not be abnormal. Additionally, this survey shows improper application as a significant problem area when the combined effects of poor installation/testing, physical and electrical protection, personnel error, and equipment mismatch are considered.

Maintenance Versus Failure Rate

Table XIV shows the results of failure rate compared to maintenance quality and maintenance cycle as reported in this survey. The previous survey results did not report maintenance cycle versus failure rate. However, Table XV has arranged available data to show quality versus failure rate. One notable difference can be seen in the maintenance cycle response in each quality category. The previous survey showed a trend in more frequent maintenance associated with higher quality. In the new survey response was greatest in the most frequent maintenance cycle in both the excellent and fair quality categories. So an obvious trend is not evident.

In both surveys, the largest response was to fair maintenance. However, the new survey had much more response to poor maintenance. Both had about the same division in response between fair and excellence qualities.

The most surprising result in the new data is the failure rate under reported excellent maintenance. Excellent maintenance with the most frequent cycle had the highest failure rate. Overall, in each quality category there is very little difference in failure rate.

The downtime listed in Table XIV does show an expected trend between the categories. The data suggest that the higher the quality and more frequent the cycle, the less severe the failure.

Description of Maintenance

Response was adequate to present a description of the methods of maintenance reported under the categories of quality and cycle. In Table XVI data are listed as percentages of the number of types of motor population reported (e.g., one plant reported six different types of motors with maintenance data listed for each type; these were counted as six population types for the purposes of this table). The differences and similarities between the various categories are quite obvious. The most commonly used method of maintenance under excellent and fair is "clean."

TABLE XV
1973 MAINTENANCE QUALITY VERSUS FAILURE RATE

Maintenance Quality and Cycle	Sample Size (Unit Yr)	Number of Failures	Failure Rate (Failures/Unit Yr)
Excellent			
< 12 mo	14 650		
12–24 mo	1372		
> 24 mo	1259		
All	17 281	77	0.0045
Fair			
< 12 mo	121		
12–24 mo	21 930		
> 24 mo	2958		
All	25 009	439	0.0175
Poor			
< 12 mo	—		
12–24 mo	—		
> 24 mo	74		
All	74	2*	0.0270*

*Small sample size.

Failure Repair/Replace Urgency

Table XVII is intended to give some insight to the urgency reported for restoring motors to service and the resulting downtime of the failures. In these data the following two responses were considered unusual and exceptional and were omitted: downtime for one failure under "repair during normal working hours" was reported as 6570 h and downtime

TABLE XVI
DESCRIPTION OF MAINTENANCE REPORTED

Maintenance Description	Excellent < 12 mo	Excellent 12–24 mo	Excellent > 24 mo	Excellent All	Fair < 12 mo	Fair 12–24 mo	Fair > 24 mo	Fair All	Poor < 12 mo	Poor 12–24 mo	Poor > 24 mo	Poor All
	Percent of Population Types											
1) Visual	12.5	2.3	—	6.5	24.7	43.1	41.7	32.6	—	31.2	—	33.3
2) Meggar	39.6	47.7	25.0	40.7	53.5	50.8	33.3	51.1	—	12.5	—	23.8
3) Clean	43.7	56.8	25.0	46.3	91.1	38.5	83.3	71.4	—	37.5	—	33.3
4) Lub. and/or filters	33.3	36.4	37.5	35.2	64.4	52.3	16.7	56.8	—	62.5	—	52.4
5) Vibration check	20.8	2.3	—	10.2	29.7	—	16.7	18.0	—	—	—	—
6) Bearing check	18.7	34.1	43.7	28.7	1.0	16.9	41.7	9.5	—	6.2	—	4.8
7) Reinsulate	4.2	—	18.7	4.6	—	3.1	33.3	3.4	—	6.2	—	4.8
8) Ampere or temperature check	4.2	—	—	1.9	3.0	13.8	8.3	7.3	—	12.5	—	9.5
9) Air gap check	2.1	20.5	—	9.3	8.9	—	—	5.1	—	—	—	—
10) Alignment	4.2	15.9	—	8.3	—	—	—	—	—	—	—	—
11) Change or check brushes	6.2	4.5	—	4.6	8.9	1.5	8.3	6.2	—	—	—	—
12) Overhaul	—	—	—	—	—	—	8.3	—	—	—	—	—
13) Paint	—	—	—	—	5.9	—	33.3	5.6	—	—	—	—
14) Check cooling system	—	—	—	—	3.0	—	—	1.7	—	—	—	—
15) Not specified	22.9	22.7	37.5	25.0	—	3.1	—	1.1	—	—	—	4.8
Number of Population Types	48	44	16	108	101	65	12	178	4	16	1	21

TABLE XVII
REPAIR/REPLACE URGENCY VERSUS DOWNTIME

	Number of Failures	Average Hours Downtime/Failure	Median Hours Downtime/Failure
Normal working hours[a]	87	97.7	24.0
Round the clock	45	81.4	72.0
Replace with spare[b]	111	18.2	8.0
Low priority	4*	370.0*	400.0*
Not specified	6*	288.0*	240.0*
Total	251	69.3	16.0

*Small sample size.
[a] 6570 h for one failure omitted.
[b] 960 h for one failure omitted.

TABLE XVIII
1973 REPAIR/REPLACE URGENCY VERSUS DOWNTIME

	Number of Failures	Average Hours Downtime/Failure
Normal working hours	323	136.0
Working round the clock	54	110.3
Replace with spare	94	21.0
Low priority	7*	*
Total	478	108.5

*Small sample size.

for one failure under "replace with spare" was reported as 960 h. Data from the previous survey were rearranged and presented here as Table XVIII. Unlike the previous survey, median hours downtime per failure is included in the new data to reflect the influence of numerous long downtime periods reported.

In the first two categories the new survey shows obvious shorter average downtime per failure than the older survey, but the category on replace-with-spare is very close. An obvious uncertainty in the new results is evident in the median value for round-the-clock urgency. The downtime is higher than for less urgent repair. This suggests the possibility of some data being reported erroneously. Another interesting result is that half of the failures were reported as "replaced with spare" in the new survey. Only about one fifth of those of the old survey were in this category. This might be expected since the new survey covered only larger more critical applications. The previous survey results presented no downtime data for the "low priority" category, and thus the total average in Table XVIII is calculated using only the data shown.

GENERAL DISCUSSION

It is the general consensus of the subcommittee sponsoring this activity that the new motor reliability data of this survey, contingent on reporting accuracy of the respondents, is more practical and useful for its intended purpose than the older survey data because of the restrictions on age and size. This survey also produced an attractive cross section of experience in the number of plants represented. One very obvious difference in the findings in this survey over the 1973 survey is the general trend of higher failure rates in the new data.

For obvious reasons, maintenance is expected to have a significant impact on failure rate and downtime. This paper, for the most part, presents results of responses to the population types as requested in the survey questionnaire.

TABLE XIX
90 PERCENT CONFIDENCE INTERVALS FOR FAILURE RATE

	Induction Motors	Synchronous Motors	Wound Rotor Motors	DC Motors	All
Lower limit	0.0659	0.0583	0.0350	0.0169	0.0644
Survey result	0.0732	0.0777	0.0515	0.0393	0.0708
Upper limit	0.0798	0.1026	0.0737	0.0699	0.0772
Percent deviation, L	10	25	32	57	9
Percent deviation, U	9	32	43	78	9

There are many possible combinations of categories, especially including those related to maintenance, that can be formulated from the responses. The questions and uncertainties stimulated by the results presented here warrant continued analysis and an additional report is planned to present this expanded analysis of the correlation between the various categorical results with particular emphasis on the effects of maintenance.

As an additional tool, Table XIX provides a measure of confidence in the use of the new data in this report. The table illustrates the statistical limits within which 90 percent of the failures could be expected to occur. The confidence limits are based on curves assuming a homogeneous population since it would be impractical to search out every variable affecting confidence levels and determine curves for each one.

APPENDIX

REASONS FOR CONDUCTING A NEW RELIABILITY SURVEY ON MOTORS

By: Power Systems Reliability Subcommittee,
Industrial and Commercial Power Systems Committee,
IEEE Industry Applications Society
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The IEEE "Report on Reliability Survey of Industrial Plants, Part I: Reliability of Electrical Equipment" published in 1973 contained information on failure rates and downtime/failure for motors.

In their meeting on May 12, 1980, in Houston, TX, and in keeping with their commitment to update the previous survey, the Power Systems Reliability Subcommittee of the IEEE Industrial Power Systems Department is conducting a new survey on the reliability of motors.

Overall the main purpose of this reliability survey is to identify failure data and the effects of preventive maintenance on important classes, types, and applications of motors, thus providing the designer and planner the valuable basic information needed to install a reliable and economic system.

The data in the previous reliability survey show that for motors rated 0–600 V the failure rate for induction motors is 15 times higher than synchronous motors. Since induction motors are normally considered more reliable than synchronous motors, it is presumed that the survey data were inadequate to cover enough applications to bring this out.

The data in the previous reliability survey shows that for induction motors 0–600 V (this category represents over 50 percent of the total motor population), the failure rate is 0.0109 (one unit failure per 92 unit years). This failure rate appears to be unreasonably low when compared with other equipment categories (i.e., motor starters = one failure per 72 unit years, steam turbine driven generators one failure per 32 unit years, transformers one failure per 244 unit years). Failure rate of this overall class of motors is obviously valuable information to users and manufacturers. This new survey will support or update this failure rate.

Motor designs, shop fabrication facilities, and manufacturing procedures for NEMA frame ac motors (ratings 1–200 hp) are significantly different from those for motors rated over 200 hp. In the previous motor reliability survey, the failure data for motors of all horsepower ratings were lumped together. The new motor reliability survey will collect failure data only on ac motors rated above 200 hp. Usually, motors rated above 200 hp are driving critical equipment. The reliability of these large motors is of prime importance to the industrial system design engineer. Recent user experience with reliability of the current generation of large ac motor designs (over 200 hp) indicates a trend toward a higher number of failures per unit time.

The previous survey data show that the industry average time to repair ac low-voltage motors (0–600 V) is 114 h compared to 76 h for medium-voltage ac motors (601–15 000 V). This information should be updated with a larger sample size of medium voltage motors.

The increased emphasis on minimizing capital investment in industrial facilities has resulted in a significant increase in the use of two-pole ac induction motors. Because of these relatively high speeds (3600 r/min), reliability of these two-pole motors is expected to be lower than the lower speed ac motors (four and six poles). The previous reliability study did not differentiate between 3600 r/min two-pole motors and the slower speed motors. The new motor reliability survey will collect separate reliability data on two-pole motors. Relative reliability data on two-pole motors and those with four or more poles will be useful to the industrial design engineer in evaluating the equipment cost savings inherent in two-pole (3600 r/min) operating speeds for motor and associated driven equipment.

The database for the previous reliability study (both unit years and number of units) represents something in the order of only a few hundredths of a percent of the total motor population.

The mailing list for the new survey will be expanded and edited to obtain failure data on a larger percentage of the total motor population.

COMPANY NAME AND PLANT: ____________________

INDUSTRY TYPE: ____________________

PERIOD REPORTED - FROM: MONTH ________ YEAR ________

TO: MONTH ________ YEAR ________

LOCATION: ____________________

CONTAMINATION LEVEL AND TYPE: ____________________

Fig. 1. Reliability survey for electric motors larger than 200 hp.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
	Identification Number	Total Number of Motors	Type	Horsepower	Voltage	Speed	Enclosure Type	Environment	Duty Application	Service Factor	Average Number of Starts/Day	Grounding Type (Power Supply)	Maintenance Cycle	Maintenance Quality	Brief Description of Maintenance
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															

Fig. 2. Total population data.

COVER LETTER

Pat O'Donnell
El Paso Natural Gas Company
P.O. Box 1492
El Paso, TX 79978
(915) 541-2080

Dear Sir,

RE: Motor Reliability Survey for Motors Larger than 200 hp

The Reliability Subcommittee of the Industrial Power Systems Department requests your cooperation in a survey to determine the reliability of electric motors in industrial installations. As with previous surveys you may have seen, this survey is a followup to the general reliability survey of plant equipment in 1971 and is intended to provide more meaningful data on motors. Attached for your information is a report by the subcommittee on reasons for the survey.

The results of this survey will be published in an IEEE paper for value to system planners and designers in reliability evaluation of alternatives. Of course, individual responses will be held in strict confidence and only summaries published.

Survey Instructions

The survey form is reasonably self-explanatory, but a sample filled-out form is included for your guidance and some brief instructions follow. We emphasize that all requested data are important, but where some of these data are unknown, simply provide the known data and leave the other spaces blank. We also encourage any explanatory comments as you feel appropriate. If additional data sheets are needed, please duplicate those provided. *This survey is restricted to motors greater than 200 hp and no older than 15 years.*

General Data [Fig. 1]:

1) It is vitally important that the period reported be given.

2) Plant contamination level and type should be your best estimate.

Total Population Data [Fig. 2]:

1) Using the "total population" data block, give requested data for all motors greater than 200 hp and 15 years old or less, in service during the period reported *whether or not failures have occurred.* (Note: When the period reported exceeds the age of a motor, use separate data sheets for the new motors.)

2) Use the categories attached to the data block to describe the data.

3) When one data sheet is insufficient to list the total population of motors, use consecutive identification numbers in the first column of the data sheets (e.g., 1, 2, 3, etc., for first sheet; 11, 12, 13, etc., for the second sheet, and so on).

Failure Data [Fig. 3]:

1) List each motor failure event separately using the attached categories to describe the failure.

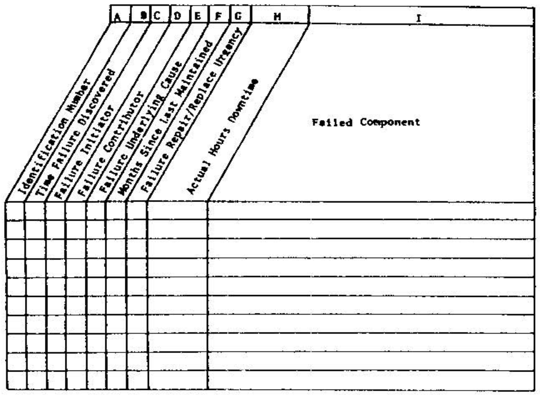

Fig. 3. Failure data.

2) Identify each failure with the corresponding identification number in the "total population" data.

3) Under column I describe the component on the motor that failed.

Our schedule dictates that responses be received no later than April 15, 1982. Your participation in this project will be greatly appreciated.

Sincerely,

Pat O'Donnell
Chairman, Motor Reliability Survey Working Group

REFERENCES

[1] IEEE Committee Report, "Report on reliability survey of industrial plants," *IEEE Trans. Ind. Appl.*, Mar./Apr., July/Aug., and Sept./Oct. 1974.

[2] *IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems*, IEEE Standard 493, pts. I, III, IV, and VI.

Discussion

P. F. Albrecht (General Electric Company, Schenectady, NY), **E. L. Owen** (General Electric Company, Schenectady, NY), and **D. K. Sharma** (Electric Power Research Institute, Palo Alto, CA): This Working Group Report provides interesting and timely information which adds to a growing body of information about the reliability of electric motor drives. This information should be useful to owners, operators, and designers of motor equipments in their efforts to obtain improved motor reliability. The discussers welcome this additional information and support the objectives of the Working Group. We are hopeful that information of this type will become increasingly available as we feel it will assist all those involved in motor applications in obtaining increased reliability.

Surveys have been conducted by other groups seeking similar data for their industries. Under the sponsorship of the Electric Power Research Institute (EPRI), Palo Alto, CA, General Electric conducted an Industry Assessment Study (IAS) to evaluate the present reliability of powerhouse motors and to identify design and operational characteristics which, through advanced development, offer the potential of increased motor reliability [3]. Further work is presently underway to add data received after the closing date originally scheduled for the EPRI study. Analysis based on this additional data will be published at a later date.

We have compared the scope and results of this survey, as presented by the Working Group, with the results reported for the EPRI survey. Although the motor populations in the two studies are from different industries, we find many aspects of this Working Group Report which corroborates the findings of the EPRI study. The survey response achieved in the two studies are compared in Table XX.

In the EPRI study, it was found that failures subsequent to the first failure had a much different distribution than time to first failure. Therefore, the primary analysis was conducted in terms of time to first failure. Thus the failure rate from the EPRI study is not directly comparable with the Working Group results.

An important result of the EPRI study was to identify those motor components which are most subject to failure. This information was considered in setting priorities for development work to improve motor reliability. The type of motor involved in the EPRI survey was largely the squirrel-cage induction motor (approximately 97 percent of the "known" types were reported as cage induction motors), and the information about failure by component is most representative of this motor type. There are differences in the categories of

TABLE XX
SCOPE OF RELIABILITY STUDIES

Parameter Working Group — Nomenclature — (EPRI)		Working Group	EPRI Phase I
Number of companies	(Utilities)	33	56
Number of plants	(Units)	75	132
Number of motors	(Motors)	1141	4797
Total population (unit-years)	(Motor-years)	5085	24914*
Total failures		360	872
Failure rate (all motors)		0.0708	0.035*

*Based on first failure only.

failed component as reported in the two studies, which makes a direct comparison of results very difficult.

However, both studies found that for squirrel-cage induction motors, bearing and stator winding related failures accounted for approximately three-fourths of all failures, while roto: related failures accounted for only ten percent of the failure.. These results seem to corroborate each other and gives us greater confidence in our conclusions as to where emphasis should be placed. Fig. 4 and Table XXI show the percentage failure by component as reported by the EPRI study.

As a part of the EPRI study, additional analysis was performed to understand reliability issues better. We found that the most significant variable affecting motor failure rate was the plant (unit) where the motor was installed. For example, in the EPRI study a 90 percent confidence interval for failure rate of each of the 132 units was calculated. If all units had the same underlying failure rate, about 13 units would have a 90 percent confidence interval which does not include the failure rate for the entire population. However, in the EPRI study, 40 units had a 90-percent interval entirely below the population average, and 22 units were entirely above the population average.

We felt it was important to consider this unit variation when investigating other factors such as application or size effects. Was any such effect between respondents investigated in the Working Group survey? In particular, could the effect of horsepower noted in Table III of your report be *partly* due to the different companies represented in various size ranges.

Table III of the Working Group report suggests a tendency for the motor failure rate to increase with motor size. Booz, *et al.* also made an analysis based on motor size [4]. However, it was felt that horsepower per pole, rather than horsepower, better represented exposure to such failure mechanisms as

- fatigue resulting from differential expansion,
- high stress during operation,
- susceptibility to lateral vibration.

Would it be possible to analyze the Working Group data on the basis of horsepower per pole, similar to the EPRI analysis?

As a final comment, the detail of analysis must be commensurate with the size of the database. With the large database in the EPRI Phase II study, we hope to be able to investigate such factors as the effect of first failure on subsequent failure rate. We again compliment the Working Group on a good survey and hope to see more of the same.

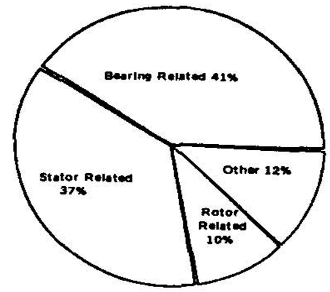

Fig. 4. Percentage failure by component.

TABLE XXI
PERCENTAGE FAILURE BY COMPONENT

Bearing related	
Sleeve bearings	16
Antifriction bearings	8
Seals	6
Thrust bearing	5
Oil leakage	3
Other	3
Total	41
Stator related	
Ground insulation	23
Turn insulation	4
Bracing	3
Wedges	1
Frame	1
Core	1
Other	4
Total	37
Rotor related	
Cage	5
Shaft	2
Core	1
Other	2
Total	10

REFERENCES

[3] "Improved motors for utility applications," EPRI EL-2678, vol. 1, 1763-1, final rep., Oct. 1982.

[4] "Improved motors for utility applications, industry assessment study," EPRI EL-2678, vol. 2, 1763-1, final rep., Oct. 1982.

Pat O'Donnell (Coordinating Author): First, to address specific questions of the Discussion, we find the result of variation of reliability of motors in three different categories of units or groups very interesting and useful. However, the IEEE survey data do not lend themselves to this specific analysis. Our immediate response to this result is concern over the obvious cause or reason for this grouping to emerge. The IEEE data results attempted to classify industry types, which may follow a similar purpose, but the results related to maintenance more specifically categorize users in the IEEE report. We believe the IEEE and EPRI surveys are distinctly different in this respect but, as such, are complementary.

The IEEE survey collected data on a range of horsepower sizes and a range of speed ratings. We are not able to identify a fine resolution of horsepower per pole ratios but only general ranges. A quick analysis of our data for induction motors only allows the result shown in Table XXII.

The IEEE survey emphasized motor size and speed range separately with the intent of comparing these categories mutually and with others. Again, these results seem to be an excellent complement to the EPRI results, which diminish the significance of motor size in horsepower and speed as separate considerations. That is, a small high-speed motor might have the same horsepower/pole ratio as a large slow-speed motor.

We also are enthused about the added confidence in our data showing similarities in failed component trends. Bearing and winding failure trends were very similar in the two survey results. The IEEE survey did not collect detailed data to break down failed components into more subcategories of types, but data were collected on causes which helped determine *why* bearing and winding failures occurred. We are very interested in whether or not the difference in reliability between the "high" and "low" groups in the EPRI results supports the causes found in our survey results.

Finally, there is a significant difference in the basis of the two surveys that add, possibly, to some of the differences in results. The IEEE survey acquired data only on motors larger than 200 hp. The EPRI survey included sizes down to and including 100 hp. This surely accounts for some of the difference in total populations, but additionally, the IEEE data exclude standard NEMA frame size motors. It would be of interest to compare our results with EPRI results excluding motors 200 hp and smaller. This working group is enthused about the EPRI results, and we look forward to seeing further analysis of the data.

TABLE XXII
HORSEPOWER VERSUS SPEED
(INDUCTION MOTORS)

	Number of Failures	Unit Years	Failure Rate
0–720 r/min			
201–500 hp	7	137.92	0.0508
501–5000 hp	12	175.16	0.0685
5001–10 000 hp	—	—	—
> 10 000 hp	—	—	—
721–1800 r/min			
201–500 hp	148	1922.43	0.0770
501–5000 hp	66	740.1	0.0892
5001–10 000 hp	1	2.83	0.3534
> 10 000 hp	—	7.5	—
3600 r/min			
201–500 hp	42	655.75	0.0640
501–5000 hp	16	358.66	0.0446
5001–10 000 hp	—	—	—
> 10 000 hp	—	—	—

Pat O'Donnell (S'64–M'68–SM'80) was born in El Paso, TX, in 1942. He received the B.S.E.E. degree from Texas Western College (now University of Texas at El Paso) in 1965.

After brief employment with Schlumberger Well Surveying Corporation, he joined El Paso Natural Gas Company in 1966 and is presently Principal Electrical Engineer in the main office Engineering Department in El Paso.

Mr. O'Donnell is currently active in the Industrial and Commercial Power Systems Department of the IEEE Industry Applications Society and currently serves as Secretary of the department. He is a member of and past Chairman of the Power System Technologies Committee and current Chairman of the Emergency and Standby Power Systems Subcommittee. He is also a member of the Power Systems Reliability Subcommittee, serving as Chairman of the Motor Reliability Working Group, and the Power Systems Analysis Subcommittee. Outside of IEEE, he is a member of the ASME Standards Committee on Ignition Systems for Industrial Engines. He is a Registered Professional Engineer in the States of Texas and New Mexico.

Report of Large Motor Reliability Survey of Industrial and Commercial Installations, Part II

MOTOR RELIABILITY WORKING GROUP
POWER SYSTEMS RELIABILITY SUBCOMMITTEE
POWER SYSTEMS ENGINEERING COMMITTEE
INDUSTRIAL AND COMMERCIAL POWER SYSTEMS DEPARTMENT
IEEE INDUSTRY APPLICATIONS SOCIETY

***Abstract*—In 1983 the initial results of an IEEE survey on large motors was published and presented at the 1983 I&CPS Conference. This was the first presentation of the results of a survey completed in 1982 of motors larger than 200 hp and no older than 15 years. The results presented here of the 1982 survey are to investigate the data further to address questions generated by the results of the earlier paper, to find additional correlations of the reliability criteria of some of the more interesting categories, and to bring out more results and categories available from the survey data. For information on the overall survey response and the general results of the surveyed categories, refer to the previous paper.**

INTRODUCTION

THE SECOND set of results of the 1982 survey of the reliability of large motors in industrial and commercial installations is summarized in Tables I–XIII. Reference is occasionally made to the results presented in 1983 which will hereafter be called Part 1 [1].

In addition to new comparisons of categories to reveal more detailed analysis of the results of Part 1, these new results focus more on the effects of maintenance and especially more on the effects of causes. Of particular interest are the comparisons of reliability data for induction and synchronous motors, further analysis of service factor and speed, further analysis of bearing and winding failures, a closer look at the effect of inadequate maintenance on reliability, additional comparisons of indoor and outdoor applications, and additional grounding type comparisons.

Some comments about the data in the tables are in order to clarify some questions that may arise. Where no data are given, there was either no response or the number of failures (FLR's) and population were insufficient for meaningful results. A footnote marks insufficient response where failures were reported, but the total was less than eight. This is in keeping with the standard of credibility previously established by the Power Systems Reliability Subcommittee. In preparation of this paper, a careful, closer look was taken and some of the minor errors in counting were corrected. Thus the total count in some areas will differ slightly from those of Part 1. However, the corrections are minor and no trends are affected. Also, as in the Part 1 results, downtime (DT) for two failures was omitted. One was 960 h for an induction motor, 0–1000 V and replaced-with-spare. The other was 6570 h for an induction motor, 1001–5000 V.

As with other survey results by this subcommittee, a brief discussion is included for each table emphasizing significant results, but there is no intent to draw definite conclusions. The tables are presented representing results from the data reported in the survey.

Paper IPSD 84-36, approved by the Power Systems Technologies Committee of the IEEE Industry Applications Society for presentation at the 1984 Industrial and Commercial Power Systems Conference, Atlanta, GA, May 7-10, 1984. Manuscript released for publication November 5, 1984.

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INDUCTION AND SYNCHRONOUS MOTORS

The results in Part 1 of the survey showed induction and synchronous motors with nearly equal failure rates. Some believe that synchronous motors, because of their complexity, should fail more than induction motors. Table I compares these types to various categories to identify any notable differences.

Two categories showed some deviation from the general results of Part 1. Where response was adequate in the first two classes, starts per day clearly affected synchronous motors more than induction motors. The induction motor failure rate changed very little, but the synchronous motor failure rate increased with an increase in starts per day. In the speed category it was the induction motors that showed some deviation from the trend of Part 1. One observation is the increase in failure rate with speed for the first two classes of speed. A second observation is the high failure rate for synchronous motors in the slowest speed class. So the two types of motors had opposite trends in failure rate with speed. The influence of synchronous motors on the slowest speed class is clearly evident where this class showed the highest failure rate in Part 1. For induction motors, the lowest failure rate was again in the highest speed class. The effects of speed are also evaluated in comparisons to horsepower, causes, and failed component.

TABLE I

	Starts/Day 1	1–10	11–30	>30	Duty Application Contin-uous	Inter-mittent	Environment Indoor	Outdoor	Speed (r/min) 0–720	721–1800	3600	Grounding Type Solid	Imped-ance	Un-grounded
INDUCTION MOTORS														
Number of FLR's	234	58	—	—	274	20	203	91	19	216	59	101	123	70
Sample size (unit yr)	3215.8	756.0	88.4*	8.0*	3480.3	587.8	2485.9	1582.3	313.1	2817.9	1037.2	1909.6	1492.0	666.6
FLR rate (FLR's/unit yr)	0.0728	0.0767	—	—	0.0787	0.0340	0.0817	0.0575	0.0607	0.0766	0.0569	0.0529	0.0824	0.1050
Average hours DT/FLR	61.1	83.8	—	—	57.9	194.0	51.1	96.8	191.2	54.5	48.1	69.2	58.0	71.5
Median hours DT/FLR	12.0	18.0	—	—	12.0	54.0	8.0	48.0	72.0	8.0	36.0	36.0	10.0	8.0
Number of FLR's with no DT given	84	13	—	—	90	7	72	48	0	86	11	37	58	2
SYNCHRONOUS MOTORS														
Number of failures	13	23	2*	—	36	2*	38	—	27	10	1*	12	24	2*
Sample size (unit yr)	194.5	266.1	8.0	—	426.6	42.0	451.2	17.4*	254.9	200.9	12.7	251.7	200.3	16.5
FLR rate (FLR's/unit yr)	0.0668	0.0864	—	—	0.0844	—	0.0842	—	0.1059	0.0498	—	0.0477	0.1198	—
Average hours DT/FLR	97.5	68.4	—	—	58.4	—	74.2	—	33.1	139.1	—	166.0	39.8	—
Median hours DT/FLR	24.0	16.0	—	—	16.0	—	16.0	—	16.0	96.0	—	60.0	16.0	—
Number of FLR's with no DT given	2	1	—	—	16	—	3	—	0	3	—	2	1	—

*Small sample size.

TABLE II
MOTOR TYPE VERSUS SERVICE FACTOR

	Induction 1.0	1.15	>1.15	Synchronous 1.0	1.15	>1.15	Wound Rotor 1.0	1.15	>1.15	Direct Current 1.0	1.15	>1.15
Number of FLR's	127	165	2*	25	10	3*	10	12	—	6*	—	—
Sample size (unit yr)	2062.7	1943.0	62.5	274.2	152.8	41.5	160.7	246.4	—	94.2	30.0*	7.3*
FLR rate (FLR's/unit yr)	0.0616	0.0849	—	0.0912	0.0654	—	0.0622	0.0487	—	—	—	—
Average hours DT/FLR	54.4	75.0	—	81.2	63.4	—	52.3	192.2	—	—	—	—
Median hours DT/FLR	8.0	24.0	—	16.0	20.0	—	24.0	162.0	—	—	—	—
Number of FLR's with no DT given	28	71	—	0	3	—	3	6	—	—	—	—

*Small sample size.

SERVICE FACTOR

Another interesting result of this survey in Part 1 was that 1.15 service factor (SF) motors had a higher failure rate than 1.0-SF motors. Tables II–IV take a closer look at this category by comparison to other categories.

Table II compares service factor to the various types of motors surveyed. The results show that 1.15-SF induction motors failed more than 1.0-SF induction motors, but the opposite was true with synchronous and wound rotor induction motors. The lowest failure rate of all was in 1.15-SF wound rotor induction motors.

In Table III the service factor is evaluated in horsepower classes. Only the first two size classes had adequate response. As in the results of Part 1 failure rate increased with increase in service factor in the smallest size class. However, in the next larger size class the failure rate was approximately the same for 1.0 and 1.15 SF.

The next category broken out with service factor is voltage, shown in Table IV. The same trend evident in Part 1 is again evident here. The failure rate increased with increase in service factor for each voltage class where response was adequate. The service factor is evaluated further in Table VIII with comparisons to failed component and causes.

SPEED

Part 1 of the survey results showed a decrease in failure rate with increase in speed rating for all categories. Most expect that failure rate with speed is most affected by motor size. Table V is presented to show these categories from this survey. The results show the same trend as Part 1 except for a slight deviation in the smallest motor class. The 721–1800

TABLE III
HORSEPOWER VERSUS SERVICE FACTOR

	201–500 hp			501–5000 hp			5001–10 000 hp			10 000 hp		
	1.0	1.15	>1.15	1.0	1.15	>1.15	1.0	1.15	>1.15	1.0	1.15	>1.15
Number of failures	105	114	—	56	71	5*	7*	2*	—	—	—	—
Sample size (unit yr)	1758.0	1405.9	34.1*	777.4	961.4	77.2	39.2	4.8	—	17.2*	—	—
FLR rate (FLR's/unit yr)	0.0597	0.0811	—	0.0720	0.0739	—	—	—	—	—	—	—
Average hours DT/FLR	47.7	'48.6	—	86.8	126.5	—	—	—	—	—	—	—
Median hours DT/FLR	8.0	12.0	—	16.0	50.0	—	—	—	—	—	—	—
Number of FLR's with no DT given	21	50	—	11	29	—	—	—	—	—	—	—

*Small sample size.

TABLE IV
VOLTAGE VERSUS SERVICE FACTOR

	0–1000 V			1001–5000 V			5001–15 000		
	1.0	1.15	>1.15	1.0	1.15	>1.15	1.0	1.15	>1.15
Number of FLR's	54	46	—	107	139	5*	8	1*	—
Sample size (unit yr)	745.5	509.0	7.3*	1725.4	1837.5	104.0	121	25.6	—
FLR rate (FLR's/unit yr)	0.0724	0.0904	—	0.0620	0.0756	—	0.0661	—	—
Average hours DT/FLR	38.8	88.3	—	75.3	75.9	—	22.7	—	—
Median hours DT/FLR	8.0	36.0	—	16.0	16.0	—	24.0	—	—
Number of FLR's with no DT given	6	18	—	24	61	—	2	—	—

*Small sample size.

TABLE V
HORSEPOWER VERSUS SPEED (r/min)

	201–500 hp			501–5000 hp			5001–10 000 hp			>10 000 hp		
	0–720	721–1800	8600	0–720	721–1800	3600	0–720	721–1800	3600	0–720	721–1800	3600
Number of FLR's	19	157	43	38	75	19	7*	2*	—	—	—	—
Sample size (unit yr)	277.3	2209.8	711.0	400.1	940.0	475.8	39.2	4.8	—	9.7*	7.5*	—
FLR rate (FLR's/unit yr)	0.0685	0.0710	0.0605	0.0950	0.0798	0.0399	—	—	—	—	—	—
Average Hours DT/FLR	156.2	35.7	39.9	99.4	109.2	116.1	—	—	—	—	—	—
Median Hours DT/FLR	70.0	8.0	36.0	16.0	24.0	52.0	—	—	—	—	—	—
Number of FLR's with no DT given	5	58	8	0	36	4	—	—	—	—	—	—

*Small sample size.

TABLE VI
ENCLOSURES—OUTDOOR

	Open	Weather Protected	Totally Enclosed (TEFC, E.P., D.I.P.)	Totally Enclosed (Open Pipe Vent)	Totally Enclosed (Water–Air)	Totally Enclosed (Air–Air)
Number of FLR's	18	17	49	2[a]	—	11
Sample size (unit yr)	111.1	379.0	1014.7	16.0	—	131.7
FLR rate (FLR's/unit yr)	0.1620	0.0449	0.0483	—	—	0.0835
Average hours DT/FLR	119.1	179.6	69.4	—	—	23.9
Median hours DT/FLR	48.0	80.0	48.0	—	—	12.0
Number of FLR's with no DT given	9	2	14	—	—	4
Failed component[b]						
Bearing	11	6	28	1	—	4
Winding	5	3	16	—	—	7
Rotor	1	1	2	—	—	—
Shaft or coupling	—	2	4	—	—	—
Brushes or slip rings	—	—	—	1	—	—
External dev.	—	3	—	—	—	—
Not specified	1	2	—	—	—	—

[a] Small sample size.
[b] Some respondents reported more than one failed component per failure.

TABLE VII
ENCLOSURES—INDOOR

	Open	Weather Protected	Totally Enclosed (TEFC, E.P., D.I.P.)	Totally Enclosed (Open Pipe Vent)	Totally Enclosed (Water–Air)	Totally Enclosed (Air–Air)
Number of FLR's	206	8	29	4[a]	6[a]	9
Sample size (unit yr)	2480.8	170.6	312.5	24.7	119.5	229.5
FLR rate (FLR's/unit yr)	0.0830	0.0469	0.0928	—	—	0.0392
Average hours DT/FLR	58.8	48.0	28.9	—	—	106.7
Median hours DT/FLR	16.0	16.0	10.0	—	—	8.0
Number of FLR's with no DT given	62	1	14	—	—	2
Failed component[b]						
Bearing	96	1	14	2	—	5
Winding	47	—	5	—	—	3
Rotor	3	—	2	—	—	—
Shaft or coupling	11	2	—	1	—	—
Brushes or slip rings	12	—	—	1	1	—
External dev.	6	4	—	—	4	—
Not specified	32	1	8	—	1	1

[a] Small sample size.
[b] Some respondents reported more than one failed component per failure.

r/min motors show a slightly higher failure rate than the 0–720 r/min motors. An interesting result is that the highest speed larger motors failed only approximately one-half the rate of the slowest speed smaller motors.

ENCLOSURES VERSUS ENVIRONMENT

Unexpected results of Part 1 were the relative failure rates of open and enclosed motors and the relative failure rates of indoor and outdoor motors. To evaluate these results further, the categories are combined in Tables VI and VII with failed components also included.

Table VI shows the highest failure rate with open type motors as would be expected since the environment is outdoor. In Table VII it was the second class of enclosed motors, which includes TEFC, explosion-proof (E.P.), and dust ignition proof (D.I.P.), with the highest failure rate. Combining all enclosed classes in each table shows very little difference in failure rate between indoor enclosed motors and outdoor enclosed motors.

TABLE VIII
SPEED AND SERVICE FACTOR VERSUS FAILED COMPONENT AND CAUSES[a]

	Service Factor			Speed (r/min)		
	1.0	1.15	>1.15	0–720	721–1800	3600
Failed Component[b]						
Bearing	47.8	39.6	40	21.1	46.2	56.5
Winding	27.8	24.8	—	29.6	25.9	21.7
Rotor	2.8	5.0	—	8.5	2.0	5.8
Shaft or Coupling	6.7	6.4	—	5.6	6.9	5.8
Brushes or slip ring	7.2	1.5	—	15.5	2.0	—
External Device	0.6	6.4	60	8.5	2.8	5.8
Not Specified	7.2	16.3	—	11.3	14.2	4.3
Total FLR's	180	202	5	71	247	69
Failure initiator						
Transient Overvoltage	2.5	0.6	—	1.6	0.5	1.8
Overheating	15.2	11.2	20.0	8.1	13.5	17.9
Other Insulation Breakdown	12.7	12.8	—	12.9	14.4	5.4
Mechanical Breakage	36.7	30.2	20.0	16.1	36.0	41.1
Electrical Fault	10.1	3.9	60.0	12.9	6.8	5.4
Stalled Motor	1.3	0.6	—	3.2	—	1.8
Other	21.5	40.8	—	45.2	28.8	26.8
Total FLR's	158	179	5	62	222	56
Failure contributor						
Persistent Overloading	5.7	3.3	—	4.8	5.1	—
High-Ambient Temperature	5.7	1.1	—	1.6	3.3	3.8
Abnormal Moisture	7.1	4.9	—	4.8	6.5	3.8
Abnormal Voltage	2.1	1.1	—	1.6	0.9	3.8
Abnormal Frequency	—	1.1	—	—	4.7	1.9
High Vibration	14.2	16.8	—	14.5	14.9	18.9
Aggressive Chemicals	7.1	2.2	—	3.2	5.1	1.9
Poor Lubrication	19.9	10.9	40.0	9.7	14.4	24.5
Poor Ventilation or Cooling	2.1	4.9	—	8.1	2.8	1.9
Normal Deterioration/Age	17.0	33.2	60.0	25.8	28.8	18.9
Other	19.1	20.1	—	25.8	17.7	20.8
Total FLR's	141	184	5	62	215	53
Failure underlying cause						
Defective Component	12.9	25.6	60.0	19.4	19.6	23.1
Poor Installation/Testing	12.9	13.5	—	4.8	14.4	17.3
Inadequate Maintenance	22.4	20.5	20.0	16.1	25.8	11.5
Improper Operation	2.0	5.1	—	4.8	2.6	5.8
Improper Handling/Shipping	0.7	0.6	—	—	1.0	—
Inadequate Physical Protection	10.9	1.9	—	3.2	6.7	7.7
Inadequate Electrical Protection	9.5	3.2	—	4.8	6.7	5.8
Personnel Error	4.1	7.7	20.0	11.3	4.1	7.7
Outside Agency-Not Personnel	5.4	2.6	—	8.1	3.6	—
Motor-Driven Equipment Mismatch	4.1	5.8	—	8.1	4.6	1.9
Other	15.0	13.5	—	19.4	10.8	19.2
Total FLR's	147	156	5	62	194	52

[a] Number of failures in percent.
[b] Some respondents reported more than one failed component per failure.

The failed components followed the general overall trend with bearings and windings failing most, with bearings predominant. Only in the last enclosure class of outdoor motors was the trend between bearings and windings reversed.

FAILED COMPONENT AND CAUSES

Table VIII takes the speed analysis a step further by showing the failed components and causes of failure reported for the speed classes. With failed components distributed between the speed classes, the slowest speed motors show windings as the leading failed component and an increase in bearing failure percentages with increasing speed rating. Under causes an interesting result is the relative low percent blamed on inadequate maintenance for the highest speed rating. Also, deterioration from age was less for this class. This supports the low failure rate for high-speed motors.

Table VIII also breaks down service factor with failed component and causes. Bearings again led all components in failures with windings second. There seems to be no real outstanding difference in causes between 1.0 and 1.15 SF. However one difference that undoubtedly contributed to the failure rate of 1.15-SF motors is the contributing cause of

TABLE IX
CAUSES VERSUS VARIOUS CATEGORIES*

	Type		Grounding			Components	
	Induction	Synchronous	Solid	Impedence	Ungrounded	Bearings	Windings
Failure initiator							
Transient overvoltage	1.4	—	0.9	1.4	2.4	—	4.1
Overheating	14.7	—	14.0	11.7	14.5	12.4	21.4
Other insul. breakdown	11.9	21.1	16.7	11.0	9.6	1.9	36.7
Mechanical breakage	37.4	5.3	31.6	26.2	47.0	50.3	10.2
Electrical fault	5.8	23.7	8.8	4.8	10.8	3.7	11.2
Stalled motor	0.7	2.6	—	0.7	2.4	—	2.0
Other	28.1	47.4	28.1	44.1	13.3	31.7	14.3
Total FLR's	278	38	114	145	83	161	98
Failure contributor							
Persistent overload	4.9	2.7	4.5	4.4	3.7	1.4	6.5
High ambient temperature	3.4	—	3.6	0.7	6.1	.7	7.6
Abnormal moisture	6.7	2.7	8.0	4.4	4.9	2.7	18.5
Abnormal voltage	1.5	2.7	—	2.2	2.4	—	5.4
Abnormal frequency	0.7	—	0.9	0.7	—	—	1.1
High vibration	17.6	.5.4	16.1	13.2	18.3	21.8	8.7
Aggressive chemicals	4.5	2.7	1.8	4.4	7.3	5.4	6.5
Poor lubrication	16.9	8.1	5.4	16.2	26.8	31.3	5.4
Poor ventilation or cooling	2.2	2.7	8.0	—	3.7	—	7.6
Normal deterioration/age	24.0	51.4	33.9	30.9	9.8	20.4	18.5
Other	17.6	21.6	17.9	22.8	17.1	16.3	14.1
Total FLR's	267	37	112	136	82	147	92
Failure underlying cause							
Defective component	20.3	22.2	23.5	14.5	24.4	17.8	10.9
Poor install/testing	15.9	—	7.8	12.9	19.5	14.5	10.9
Inadequate maintenance	22.8	11.1	25.5	18.5	20.7	27.6	19.6
Improper operation	3.3	2.8	3.9	4.0	2.4	2.0	6.5
Improper handling/shipping	.8	—	1.0	0.8	—	0.7	—
Inadequate physical protection	6.5	2.8	2.9	7.3	8.5	7.9	7.6
Inadequate electrical protection	5.3	11.1	6.9	6.5	4.9	2.6	15.2
Personnel error	5.7	5.6	3.9	6.5	8.5	7.2	5.4
Outside agency-not personnel	2.8	13.9	3.9	4.8	2.4	2.0	3.3
Motor-driven equip. mismatch	4.9	—	5.9	6.5	1.2	5.9	4.3
Other	11.8	30.6	14.7	17.7	7.3	11.8	16.3
Total FLR's	246	36	102	124	82	152	92

* Number of failures in percent.

normal deterioration from age which is about twice that for 1.0-SF motors.

Table IX is somewhat of a mix of some of the interesting categories brought out in other tables with emphasis on causes. Comparing induction and synchronous motors is difficult here because of the overwhelming response of induction motors. However, some of the results of other categories are supported. For instance, continuous duty induction motors had a higher failure rate than intermittent duty induction motors. Aside from the obvious influence of mechanical breakage, overheating and insulation breakdown are supportive. The contributing cause of normal deterioration from age is also evident.

The table correlates bearing and winding failures with causes rather well. Additionally, underlying causes show that both defective component and inadequate maintenance were reported as major factors in bearing and winding failures with inadequate maintenance the most significant. Failure initiators and contributors follow a reasonably logical trend.

The trend in failure rates for the categories of grounding do not appear supportive in this table if voltage related causes are expected to be obvious. This category exemplifies others where causes do not correlate well. It seems that in these results bearing and winding failures (especially bearing failures) and their related causes obscure some of the other cause reasoning.

MAINTENANCE

Tables X–XII attempt to delve further into the effects of maintenance on failure data. Table X reveals when the failed components were discovered. It gives some correlation to the effect of maintenance since one would expect a significant number of failures to be discovered during maintenance or testing under a good maintenance program. One observation for these data is that 56 percent of the bearing failures were discovered during normal operation. This is supported reasonably well by Table IX which shows inadequate maintenance as significant. Except for brushes and slip rings, all failed components show an obvious greater percentage of discovery during normal operation.

Tables XI and XII are presented to take a closer look at the underlying cause, inadequate maintenance, and associated failure data blamed on this cause. Again bearings by far led all other components in failures. Approximately 25 percent of all

TABLE X
FAILED COMPONENT VERSUS TIME DISCOVERED[a]

Failed Component[b]	Time Discovered Normal Operation	Maintenance or Test	Other
Bearing	36.6	60.6	50.0
Winding	33.1	8.3	28.6
Rotor	5.1	1.8	—
Shaft or coupling	5.8	8.3	14.3
Brushes or slip rings	3.1	7.3	—
External device	5.1	3.7	—
Not specified	11.3	10.1	7.1
Total FLR's	257	109	14

[a] Number of failures in percent.
[b] Some respondents reported more than one failed component per failure.

TABLE XI
INADEQUATE MAINTENANCE
FAILED COMPONENTS AND CAUSES[a]

Failed component[b]	
Bearing	59.6
Winding	25.4
Rotor	1.4
Shaft or coupling	—
Brushes or slip ring	8.5
External device	1.4
Other	4.2
Total FLR's	71
Failure initiator	
Transient overvoltage	—
Overheating	4.2
Other insulation breakdown	14.1
Mechanical breakage	52.1
Electrical fault	2.8
Stalled motor	—
Other	26.8
Total FLR's	71
Failure contributor	
Persistent overloading	—
High ambient temperature	4.2
Abnormal moisture	7.0
Abnormal voltage	—
Abnormal frequency	—
High vibration	4.2
Aggressive chemicals	9.9
Poor lubrication	43.7
Poor ventilation/cooling	1.4
Normal deterioration/age	18.3
Other	11.3
Total FLR's	71

[a] Number of failures in percent.
[b] Some respondents reported more than one failed component per failure.

TABLE XII
INADEQUATE MAINTENANCE FAILURE DATA

Number of FLR's	66
Sample size (unit yr)	603.6
FLR rate (FLR's/unit yr)	0.1093
Average hours DT/FLR	80.8
Median hours DT/FLR	9.0
Number of FLR's with no DT given	13
Maintenance quality and cycle	Number of FLR's (percent)
Excellent	
< 12 mo	25.8
12–24 mo	—
> 24 mo	—
Fair	
< 12 mo	37.9
12–24 mo	7.6
> 24 mo	3.0
Poor	
< 12 mo	3.0
12–24 mo	12.1
> 24 mo	—
Total FLR's	66

bearing failures were reported due to inadequate maintenance. Close to 44 percent of the brush and ship ring failures were reported due to this cause which does not follow well from Table X. The single largest contributor with this underlying cause is poor lubrication.

Table XII shows a definite higher failure rate for inadequate maintenance related failures than the Part 1 failure rates for maintenance quality. In Part 1 the failure rate results for excellent to poor maintenance ranged from 0.0708 to 0.0797, respectively.

Data for when failures were discovered versus maintenance quality are presented in Table XIII. It was expected that the fair and excellent categories would be significantly different in when failures were discovered, but the results show very little difference. The same table also includes months since last maintenance versus maintenance quality. The failures seem to follow the same trend as scheduled cycle reported with most occurring less than 12 mo since maintenance. This table is presented in the same format as [2, table 70]. Those results showed an obvious difference between fair and excellent maintenance overall. The trend in failures was to a certain degree increasing directly with months since maintenance and indirectly with maintenance quality. The new survey results here show a very different trend with most failures occurring where last maintenance was less than 12 mo prior to the failure.

GENERAL DISCUSSION

The additional comparisons and analyses made in this paper have supported results of Part 1 in some cases and in other cases have revealed results that were obscured in the general categorical tables of Part 1. Not all questions are answered here, and there are certainly many more categories and comparisons that can be made with the data of this survey. As examples, bearing and winding failures compared to starts per

TABLE XIII
MAINTENANCE QUALITY VERSUS TIME FAILURES DISCOVERED AND MONTHS SINCE MAINTENANCE*

Maintenance Quality	Time Discovered Normal Operation	Maintenance or Test	Other	Months Since Maintenance < 12	12–24	> 24
Excellent	85	35	1	87	17	6
Fair	132	63	10	102	22	8
Poor	15	3	1	11	5	—
None	7	—	—	—	1	5
Total	239	101	12	200	45	19
Inadequate Maintenance Cause						
Excellent	5	12	—	17	—	—
Fair	22	8	2	16	1	1
Poor	8	1	1	4	1	—
None	7	—	—	—	1	5
Total	42	21	3	37	3	6

* Number of failures.

day and duty application could add meaning to the results. The Reliability Subcommittee is presently evaluating criteria that should be presented in a third set of results, Part 3. Interested readers should submit comments and suggestions on information they would like to see in Part 3. In the format presented in these results, bearing failures and their causes were very dominant and likely prevent other less significant correlations to be evident.

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Pat O'Donnell (S'64–M'68–SM'80), for a photograph and biography, please see page 864 of this issue.

Report of Large Motor Reliability Survey of Industrial and Commercial Installations: Part 3

MOTOR RELIABILITY WORKING GROUP
POWER SYSTEMS RELIABILITY SUBCOMMITTEE
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IEEE INDUSTRY APPLICATIONS SOCIETY

***Abstract*—Results of a survey conducted in 1982 of the reliability of large motors have been presented and published in two parts [1], [2]. These results have generated numerous questions and comments and, consequently, the need to further analyze the data of the survey was recognized. Part 1 presents general results based on categories of motor types and applications specifically requested in the survey questionnaire. Part 2 combines various categories and addresses some questions resulting from Part 1. Part 3 of the survey results is presented here to address new questions and comments and to add more specific analyses of areas not yet explored. These results, along with Parts 1 and 2, provide the complete complement of analysis to date.**

Introduction

THE THIRD part of the results of the 1982 survey of reliability of large motors is presented here and summarized in Tables I through VII. As with Part 2, these results focus on new comparisons of the data. The tables address some questions and comments received since presentation of Part 2 and provide additional analysis of causes. The order of the tables as presented is more or less random and there is no intent to portray a delibrate order.

As in Parts 1 and 2, where no data is given, there is insufficient response to the questionnaire. An asterisk represents failures reported but with insufficient number (less than eight) for credible results. Additionally it is again emphasized that the tables and corresponding discussions represent results of the survey and that there is no intent to draw definite conclusions. Finally, as in Parts 1 and 2, differences in total failures between the various categories of Part 3 reflect missing data from some survey responses.

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Enclosure—Indoor and Outdoor

Tables I and II are presented to take a closer look at the causes of failures reported for various enclosures in both indoor and outdoor environments. As was evident in the previously published results, most indoor applications were "open" motors and most outdoor applications were totally enclosed fan-cooled (TEFC), explosion-proof or dust ignition-proof motors.

For the outdoor motors with the above enclosures, Table I shows that the major failure initiators are well supported by the failure contributors. The main underlying causes point to defective components and inadequate maintenance. For indoor open motors in Table II, failure initiators and failure contributors again match, but inadequate maintenance was by far the single largest underlying cause.

Comparison of indoor and outdoor environments also reveals certain opposite trends relative to causes of all failures (Part 1, Table 13). For instance, the following causes show opposite trends between indoor and outdoor applications when their respective percentages of total are compared to the same for all applications of Part 1, Table 13: mechanical breakage, electrical fault or malfunction, abnormal moisture, poor lubrication, inadequate electrical protection, inadequate maintenance, and personnel error. An example will make this more clear. For outdoor motors, mechanical breakage is 26/90 or 28.9 percent of the total number of failures for "failure initiator," while for all applications 113/341 is 33.1 percent of the number of failures for "failure initiator." Indoor motors show 85/240, or 35.4 percent versus 33.1 percent.

High Vibration Cause

Tables III and IV present additional results to Parts 1 and 2 for failures blamed on vibration. Table III shows 48 failures blamed on vibration where data are also available on failure initiator and underlying cause. As would be expected, most failures were initiated by mechanical breakage. It is interesting that most underlying causes were reported as defective component and poor installation or testing. Only three failures list inadequate maintenance as a contributing cause. For

TABLE I
ENCLOSURES—OUTDOOR
(No. of Failures)

Causes	Open	Weather-protected	Totally Enclosed TEFC, Exp., D.I.	Totally Enclosed Open Pipe Vent	Totally Enclosed Water-Air	Totally Enclosed Air-Air	Total	All Applications (Part I)
Failure Initiator								
Transient overvoltage	1	—	1	—	—	—	2	5
Overheating	2	4	9	—	—	—	15	45
Other insulation breakdown	4	1	10	1	—	—	16	42
Mechanical breakage	6	7	11	1	—	1	26	113
Electrical fault/malfunction	1	—	4	—	—	4	9	26
Stalled motor	—	—	1	—	—	—	1	3
Other	4	6	5	—	—	6	21	107
Failure Contributor								
Persistent overload	—	2	—	—	—	—	2	14
High ambient temperature	—	1	1	—	—	—	2	10
Abnormal moisture	2	2	5	—	—	—	9	19
Abnormal voltage	2	—	—	—	—	—	2	5
Abnormal frequency	—	—	—	—	—	—	—	2
High vibration	1	3	6	—	—	1	11	51
Aggressive chemicals	1	—	1	1	—	3	6	14
Poor lubrication	—	2	3	—	—	1	6	50
Poor ventilation/cooling	—	—	—	—	—	4	4	13
Normal deterioration/age	2	2	7	1	—	2	14	87
Other	2	5	9	—	—	—	16	65
Failure Underlying Cause								
Defective component	3	4	9	—	—	2	18	62
Poor installation/testing	2	3	4	—	—	—	9	40
Inadequate maintenance	3	2	7	1	—	—	13	66
Improper operation	—	—	—	—	—	1	1	11
Improper handling	1	—	—	—	—	—	1	2
Inadequate physical protection	4	2	—	—	—	—	6	19
Inadequate electrical protection	2	2	3	1	—	—	8	18
Personnel error	—	—	1	—	—	1	2	21
Outside agency-not pers.	—	—	—	—	—	2	2	12
Motor–load mismatch	—	1	1	—	—	3	5	15
Other	—	3	9	—	—	2	14	43

convenience, the total of 51 failures blamed on high vibration (Part 1) is also shown.

Table IV compares vibration failure causes to size. Only two size ranges have sufficient response to allow meaningful results. The table shows that the percent of vibration failures to total failures increases slightly with size.

Starts/Day Versus Continuous Duty Application

The results in Table V attempt to further evaluate the effects of starting on failures. Only continuous duty applications are considered, to avoid confusion over trying to distinguish between various degrees of intermittent duty. The first two voltage classes of induction motors, in which most of the survey data were collected, are emphasized. Also, very little data were collected for the categories of more than ten starts per day.

As can be seen from the table, overall there is very little difference in failure rates between less-than-one and one-to-ten starts per day, and very little difference between the two voltage classes. There does, however, seem to be a trend in longer downtimes for the one-to-ten starts per day category, suggesting that failures were more severe.

Downtime Versus Repair Urgency and Time Discovered

Downtime is expected to be affected by the urgency with which repairs are made and also by when failures are discovered, which would seem to affect the severity of failures. Table VI compares downtime with these categories to get a different view than Parts 1 and 2 provide. Overall the trend in number of failures decreases as downtime increases. There are some obvious deviations from this trend at the range of 51–100 h downtime per failure. Also this trend is obscure under the repair urgency "round-the-clock." It is interesting that for this category there are practically as many failures in the higher downtime ranges as in the lower downtime ranges. Another somewhat unexpected result is that there is no obvious difference in the distribution of failures between the categories under the heading "time discovered." However, the results show that failures corrected by "replace with spare" are predominantly in the least downtime range, as would be expected.

Horsepower Versus Speed: Induction Motors

A recent motor reliability survey [3] sponsored by the Electric Power Research Institute (EPRI) and conducted by the

TABLE II
ENCLOSURES—INDOOR
(No. of Failures)

Causes	Open	Weather-protected	Totally Enclosed TEFC, Exp., D.I.	Totally Enclosed Open Pipe Vent.	Totally Enclosed Water-Air	Totally Enclosed Air-Air	Total
Failure Initiator							
Transient overvoltage	3	—	—	—	—	—	3
Overheating	25	—	3	—	1	1	30
Other insulation breakdown	22	—	3	—	1	1	27
Mechanical breakage	68	1	11	2	—	3	85
Electrical fault/malfunction	—	5	1	—	—	3	9
Stalled motor	—	—	—	—	—	—	—
Other	68	1	10	2	4	1	86
Failure Contributor							
Persistent overload	—	—	3	—	—	1	4
High ambient temperature	—	—	3	—	—	1	4
Abnormal moisture	10	—	—	—	—	—	10
Abnormal voltage	—	—	—	—	—	—	—
Abnormal frequency	—	—	—	—	—	—	—
High vibration	35	1	1	—	—	2	39
Aggressive chemicals	—	1	—	1	—	—	2
Poor lubrication	38	—	3	—	1	2	44
Poor ventilation/cooling	—	1	—	2	1	—	4
Normal deterioration/age	38	3	14	1	—	3	59
Other	38	1	5	—	4	—	48
Failure Underlying Cause							
Defective component	27	4	6	1	5	—	43
Poor installation/testing	28	—	1	—	—	1	30
Inadequate maintenance	41	1	8	1	—	2	53
Improper operation	—	—	1	—	—	1	2
Improper handling	—	—	—	—	—	—	—
Inadequate physical protection	10	—	1	1	—	1	13
Inadequate electrical protection	—	1	—	—	—	2	3
Personnel error	16	—	—	—	—	1	17
Outside agency—not pers.	7	—	1	1	1	—	10
Motor-load mismatch	9	—	1	—	—	—	10
Other	23	1	4	—	—	1	29

TABLE III
VIBRATION FAILURES
(No. of Failures)

Failure Initiator	Transient overvoltage	0
	Overheating	6
	Other insulation breakdown	2
	Mechanical breakage	23
	Electrical fault/malfunction	3
	Stalled motor	1
	Other	13
Failure Underlying Cause	Defective component	14
	Poor installation/test.	15
	Inadequate maintanance	3
	Improper operation	0
	Improper handling/shipping	1
	Inadequate physical protection	3
	Inadequate electrical protection	0
	Personnel error	4
	Outside agency—not pers.	0
	Motor-load mismatch	3
	Other	5
Total Vibration Failures (From Part 1)		51

TABLE IV
VIBRATION FAILURES VERSUS SIZE

Motor Size	No. of Vibration Failures	Total No. Of Failures—All Causes	Percent
201-500 hp	27	218	12.4
501-5000 hp	22	131	16.8
5001-10 000 hp	1	9	*
< 10 000 hp	—	—	—

* Small sample size.

TABLE V
STARTS PER DAY VERSUS CONTINUOUS DUTY

	No. of Starts Per Day	No. of Flrs	Total Population U-Yrs	Flr Rate	Avg. Hrs D.T./Flr	Med Hrs D.T./Flr
All Motors	< 1	241	3111.6	0.0775	48.7	12
	1-10	90	1178.1	0.0764	90.8	16
0-1000 V	All motors					
	< 1	71	854.5	0.0831	36.1	8
	1-10	22	244.5	0.0900	111.1	48
	Individual Motors					
	< 1	68	768.7	0.0885	37.2	8
	1-10	13	148.4	0.0876	50.7	36
1000-5000 V	All motors					
	< 1	163	2185.0	0.0746	55.7	12
	1-10	66	859.1	0.0768	83.6	16
	Individual Motors					
	< 10	152	1876.9	0.0810	54.7	12
	1-10	38	497.0	0.0765	102.6	16

TABLE VI
DOWNTIME VERSUS REPAIR URGENCY AND TIME DISCOVERED
(No. of Flrs)

	Repair Urgency				Time Discovered		
Downtime Per Flr. (Hours)	Normal Working Hours	Round the Clock	Replace with Spare	Low Priority	During Normal Operation	During Maintenance or Test	Other
1-12	14	2	89	—	66	35	4
13-24	32	13	9	—	35	20	—
25-50	10	6	2	—	12	6	—
51-100	13	11	2	—	20	6	—
101-150	6	6	—	—	12	—	—
151-200	4	4	1	1	5	4	2
201-350	3	3	1	3	7	3	—
< 350	5	—	1	2	8	1	—

TABLE VII
HORSEPOWER VERSUS SPEED
INDUCTION MOTORS

	No. of Failures	Unit Years	Failure Rate
0-720 r/min			
201-500 hp	7	137.92	0.0508
501-5 000 hp	12	175.16	0.0685
5001-10 000 hp	—	—	—
> 10 000 hp	—	—	—
721-1800 r/min			
201-500 hp	148	1922.43	0.0770
501-5000 hp	66	740.1	0.0892
5001-10 000 hp	1	2.83	
> 10 000 hp	—	7.5	—
3600 r/min			
201-500 hp	42	655.75	0.0640
501-5 000 hp	16	358.66	0.0446
5001-10 000 hp	—	—	—
> 10 000 hp	—	—	—

* Small sample size.

General Electric Company focused on electric utility powerhouse motors. Several interesting correlations between the EPRI survey and the IEEE survey emerged. In a Discussion [4] of Part 1 of the IEEE results by participants in the EPRI survey it was noted that hp per pole had been analyzed in past studies as affecting failure rate. The data in the IEEE survey did not allow this specific analysis. Table VII, presented here, is a more general representation of this subject, showing ranges of speed and of size. Induction motors are the most common type in use and consequently most survey data were collected for this type. Table VII has been limited to induction motors. It should be noted that this table was also published in the Closure to the Discussion referenced in the aforementioned. Similar results were published in Part 2, Table 5, but included all types of motors surveyed.

The highest failure rate appears in the middle speed range and at 501-5000 hp. One might observe that within the first two speed ranges, as hp per pole increases (assuming that, specifically, 720 r/min and 1800 R/min are predominant in these speed ranges) so also does failure rate. However, the highest speed range reverses this trend. Aside from this observation there is not a significant difference in failure rates between the different horsepower ranges within the first two speed ranges. Table 5 of Part 2, which included all motor types surveyed, showed similar trends.

General Discussion

The results of Part 3 have presented several new aspects of the data. Most are a result of questions and comments received concerning Parts 1 and 2, but in some cases the data did not allow exact analysis. In some cases trends are evident and in some cases they are not. Some of the results expected or at least anticipated, for example, were that most failures occurred with lower downtime per failure, high vibration resulted in mechanical breakage, and longer downtime per failure occurred with induction motors starting more than once per day. Some of the interesting results were the opposite trends in causes of failures between indoor and outdoor applications and vibration causes being blamed mostly on defective component and poor installation or testing.

Overall, Part 3 has added credibility to some previously published results and has reinforced some areas of causes that are otherwise normally speculated.

References

[1] Pat O'Donnell, Coordinating Author, "Report of large motor reliability survey of industrial and commercial installations—Part 1," IEEE Committee Report, in IEEE Trans. Ind. Appl., vol. IA-21, no. 4, pp. 853-864, July/Aug. 1985.

[2] Pat O'Donnell, Coordinating Author, "Report of large motor reliability survey of industrial and commercial installations—Part 2," IEEE Committee Report, in IEEE Trans. Ind. Appl., vol. IA-21, no. 4, pp. 865-872, July/Aug. 1985.

[3] P. F. Albrecht, J. C. Appiarius, R. M. McCoy, E. L. Owen, and D. K. Sharma, "Assessment of the reliability of motors in utility applications—Updated," IEEE Trans. Energy Conversion, vol. EC-1, no. 1, pp. 39-46, March 1986.

[4] E. L. Owen, Discussion of "Report of large motor reliability survey of industrial and commercial installations—Part 1," IEEE Trans. Ind. Appl., vol. IA-21, no. 4, pp. 863-864, July/Aug. 1985.

Discussion

Richard Bloss *(Independent Consultant, #5462 Banbury Drive, Cleveland, OH 44139, formerly with Booz, Allen & Hamilton):* I applaud the IEEE Motor Reliability Working Group for their efforts to build a better understanding of the factors that influence large motor reliability. I would like to add that my remarks here are my own and not those of the Electric Power Research Institute, the General Electric Company, the prime contractor for the EPRI study, or of Booz, Allen & Hamilton, the subcontractor for the survey phase.

There are certain differences in the focus of the two studies that are important to understand. The EPRI study was looking at power generation plant applications. The IEEE was looking at a much broader commercial and industrial application base. To capitalize on the commonality of applications, the EPRI study focused on possible effects of applications as well as basic motor failure modes. The EPRI study permits conclusions to be drawn across similar applications.

The General Electric Company representatives may have already drawn what may be the most significant conclusion to the EPRI study in earlier remarks they made relating to the first part of the IEEE study. That conclusion is that the most significant variable in motor reliability in the EPRI study was "who was the owner." My personal analysis of the findings leads me to draw the conclusion that those utilities which had developed their own motor specifications over and beyond the industry standards had the best reliability history.

As a result of the larger sample in the EPRI study and the greater focus on a limited range of applications, more conclusions can be drawn relating to applications. As an example, in the EPRI study a problem was identified relating to the failure of Weatherproof II enclosures to protect motors in outdoor installations in coastal regions affected by severe weather. In another case, a pattern of motor misapplication in purchased subsystems was identified. Data from a number of owners of a particular subsystem served to pinpoint the use of motors designed for horizontal use, with adequate axial thrust capacity, in vertical applications. The subsystem supplier had failed to understand the problem of lubrication of the bearings. Owners who had researched the problem of bearing failure were installing their own redesigned lube system while others who were unaware of the root cause were continuing to repair the same bearing failure over and over.

It does appear from the EPRI study that customer-generated specifications can impart a favorable impact on motor reliability. The IEEE may want to pursue, in conjunction with the EPRI and others, a further study of what specific factors in customer-generated motor specifications have this positive effect on motor reliability.

The payoff is clear. In the EPRI study the average cost per year of motor failures was identified as $300 000 per power generating unit. The "best" owners had much lower motor failure costs, approaching *zero* cost. The average unit had just 40 motors. The average cost per motor per year for failures was about $7500, *plus* the cost to repair the motor!

I feel the IEEE Working Group must enlist the help of major customers of large motors to develop improved specifications that will reduce motor failures.

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C. R. Heising and Pat O'Donnell: The Discussion by Mr. Bloss presents some additional views and comparisons of the EPRI and IEEE surveys of the reliability of large motors.

A notable difference in the published results from the IEEE survey is the omission of conclusions except for some obvious conclusions from the data. This omission is deliberate and may possibly lead to a false impression that the IEEE results are not conducive to definite conclusions. We believe the results present facts as accurate as can possibly be obtained in a survey conducted by mail. The IEEE survey was successful in obtaining data covering causes of failures, and in some cases this was related to pertinent design factors.

A major difference in the surveys by the EPRI and the IEEE is the population base of each. The EPRI results, based on a large population base, appear to be more complete and contain more detail in some specific areas such as the failed part and the application of the motor. The IEEE survey results are based upon a lesser population, but are more complete on the causes of the failures and the effect of maintenance. The cause data included failure initiating cause, failure contributing cause, and failure responsibility.

Mr. Bloss's comments about the effect that customer-generated specifications can have on improving the reliability of motors are very pertinent. He suggests that the IEEE may want to pursue this subject further and identify some of the most pertinent factors that could be specified in order to improve the reliability of motors. The IEEE-IAS Power Systems Reliability Subcommittee will consider this matter further.

Accurate and well-engineered specifications are certainly found desirable by most users and manufacturers. The inability to provide such specifications may often be caused by insufficient experience and expertise, and this may lead to poor reliability. The IEEE survey results are intended to aid this cause by revealing what is actually happening in the industry, thus allowing improved standards and specifications. These results reveal existing reliability with existing specifications. Mr. Bloss reports from his experience on the EPRI study that good specifications can coincide with good reliability.

The data from the IEEE motor reliability survey will be included in the next revision to IEEE Standard No. 493 (Gold Book), "Recommended Practice for Design of Reliable Industrial and Commercial Power Systems." This recommended practice standard and its future revisions contain much of the data collected in the IEEE equipment reliability surveys of industrial and commercial installations.

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