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Measurement and analysis of vibrations of electric motors on board container ships

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Abstract. The purpose of this paper is to measure and analysis the vibrations of electric motors on board container ships, in order to reduce the maintenance costs and implicitly in making the optimal decisions. In general, the faults that underlie electric motors are primarily due to mechanical and electrical efforts. Mechanical stresses occur as a result the overloads and rapid load variations. On the other hand, the overcurrents and overvoltages are usually in the close accordance with the power supplies. In this regard the mechanical faults cannot be analyzed by changing the parameters like voltage, current, power, frequency but in practice we can do analysis by used the high-performance testers with intelligent software for measuring the motor vibrations. The MarVib DC650 tester was used in this paper for analysis and measurement the vibrations of electric motors.

1. Introduction

In practice for a detailed analysis of vibrations, there are three common measurements that characterize their periodic motion namely:

- displacement
- velocity
- acceleration

These three measurements are related to each other by mathematical formulations. For example, the periodic motion may be represented by a unit vector rotating at ω radians per second. A radian per second equals 21t times revolutions per second.

In this case, amplitude represented by x is:

$$x(t) = \sin \omega t \tag{1}$$

and the velocity, v, represents the rate of change of amplitude x or analytically:

$$v(t) = \frac{dx}{dt} = \omega \cdot \cos \omega t \tag{2}$$

and the acceleration, a, represents the rate of change of the velocity v, or analytically:

$$a(t) = \frac{dv}{dt} = \frac{d^2 v}{dt^2} = -\omega^2 \cdot \cos \omega t \tag{3}$$

In case of plotting the values from x, v and a, on a time scale the velocity leads the displacement by π/2 rad and the acceleration leads the displacement by π rad.

Velocity represents the most useful measurement of the electric motor vibration severity [1].

2. MarVib DC650 Vibration Measurement and Analysis Tester

The MarVib DC650 tester (figure 1) is a high-performance device for measuring the vibrations of electrical machines approved on board ships [5].

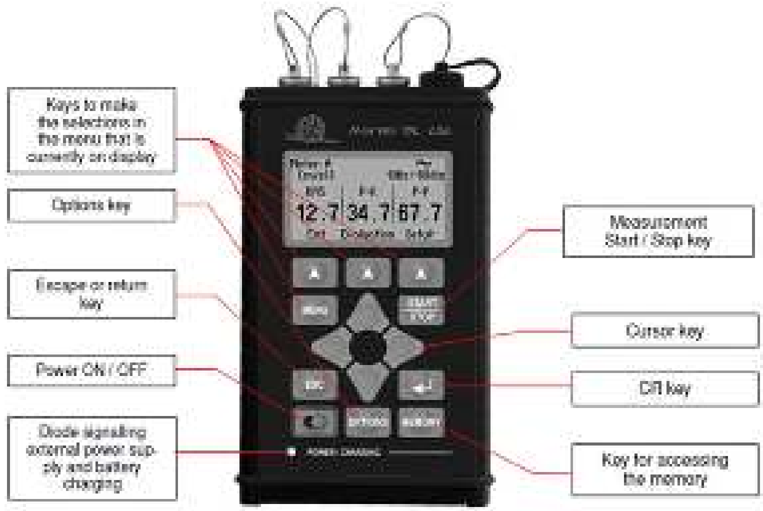


Figure 1. Frontal view of MarVib DC650 tester

Figure 2 shows how to connect the sensors to the vibration's tester. The corresponding connectors and plugs are PUSH-PULL type, each protected, meaning it is impossible to insert a plug into a connector that does not fit. Descriptions of connectors is printed on back panel as it is shown on the figure 2.

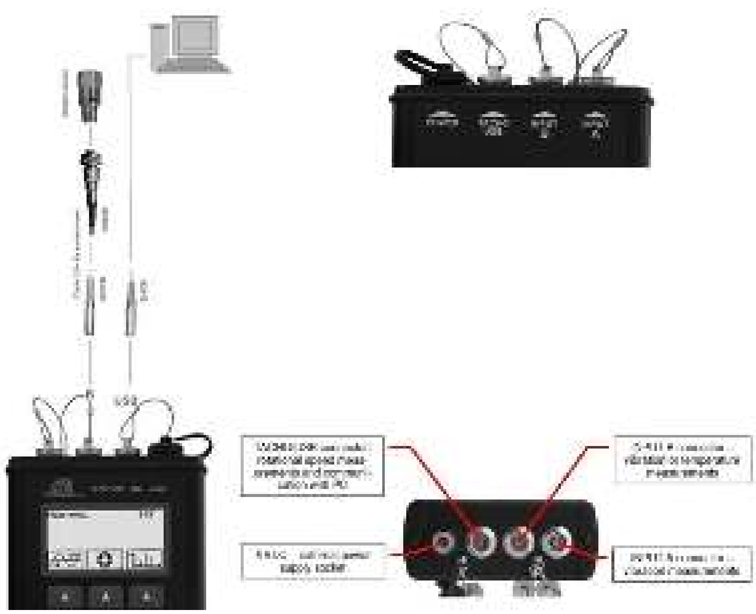
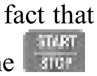


Figure 2. Connect mode the sensors to the tester

The tester route memory has a three type structure:

- the first level is reserved for electrical machines
- the second level is reserved for the measurement points on respective electrical machines
- and the third level refers to the measurements corresponding to these points in order to perform them

The list of points for which the measurements are performed is displayed in the memory menu and if an arbitrary point is read then by pressing the  key the automatic measurement at this point will be executed.

„Automatic measurement" refers to the fact that all consecutive measurements at that point will be performed without having to hold down the  key. If all the measurements corresponding to the points for a given branch have been completed on the display next to the name of the respective electric car, the sign appears (√). In this case, the next electric motor will be selected following the same steps. So once all the set of measurements of the respective route are completed the sign (√) will be displayed on the first line, next to the word Route.

In order to transfer the measurement data to the computer, respectively the communication of the tester with the computer, the following steps are followed:

1. Connect the MarVib to the USB port in PC.
2. On the tester press the button and then press the button  under the communication with PC option. After connecting on the display appears the message Ready. During data transfer to the computer, the Transmission message appears on the tester screen
3. Next, the VMComm PC program is launched, and the route we want to download to the computer must be selected by clicking the Read measurements option. Select the location of the file and name it (for example Engine_Room_date).

The route should appear in "Location in routes database", see the figure 3:

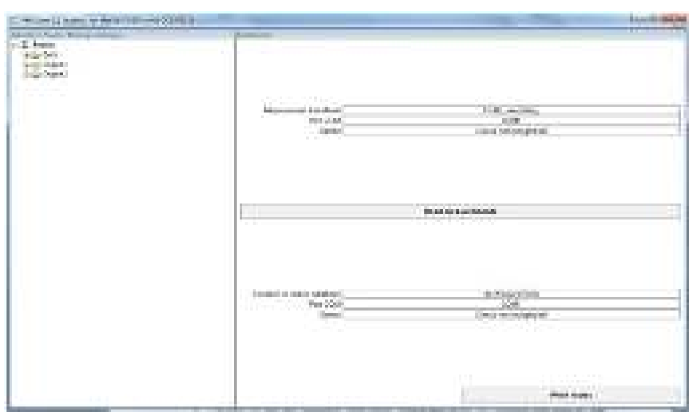


Figure 3. Route location to download in computer folder

3. Ways of measuring the vibrations of electric motors

Vibration diagnosis is based on the measuring trend. The next measurement should be conducted in the same places and in the similar operating conditions. Mark with the waterproof marker the place of measurement with the description of measurement. In case of measured devices with tactile skewer drill the place of measurement slightly, what prevent the sensor from slipping. At the same time RPM should be measured using attached Optical Tachometer ST723. It should also be written down in the measuring card. A few rules, which should be taken into account to obtain the right result with the correct description of the places of measure on the device.

There are three measuring points on the ship: H – horizontal, V – vertical and A – axial.

In the case of horizontal electrical machines, start the measurement from the free end of the device. In most cases the devices which drives the machine is engine, but there are few exceptions like power generators, when the device is driven by mechanical engine. Measurement is obtained from bearing node, always from right to left, looking from the free end [2]. Measuring points are on the horizontal level (H) and vertical level (V) and they are 90° away from each other. Figure 4 shows how to measure vibrations in the case of an electric motor (horizontal positioning).

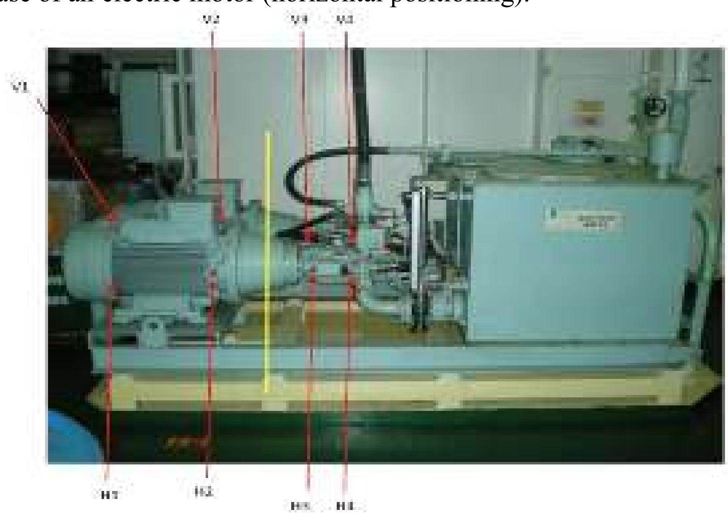


Figure 4. The vibrations measuring of the electric motor

There are H1 and V1 points, which are between the ribbing and close to the fan guard. They are measured with tactile sensor as a skewer. Skewer should be held perpendicularly to the motor surface, which it is adhered to by gently pressing. In this case, remember to hold the handle and not the sensor, while measuring with the tactile sensor (figure 5).

Wrong Correct

Figure 5. Sensor positioning mode

The other H2 and V2 measuring points on the motor are measured with magnetic sensor, which helps the measurement. In this situation the magnetic sensor has to adhere tightly to the round surfaces of electric motor. The measurement must be start in the horizontal device from the free end of the device, which drives the machine [3].

In the most case the devices, which drives the machine is engine, but there are few exceptions like hydraulic motor, when the device is driven by mechanical engine or prime mover).

In this case (figure 6) the sets of measurement are obtained from bearing node, always from the right to the left, and if you look from the free edge. Measuring points are on the horizontal level (H) first from right and horizontal level (HH) and they are 90° to the left side.

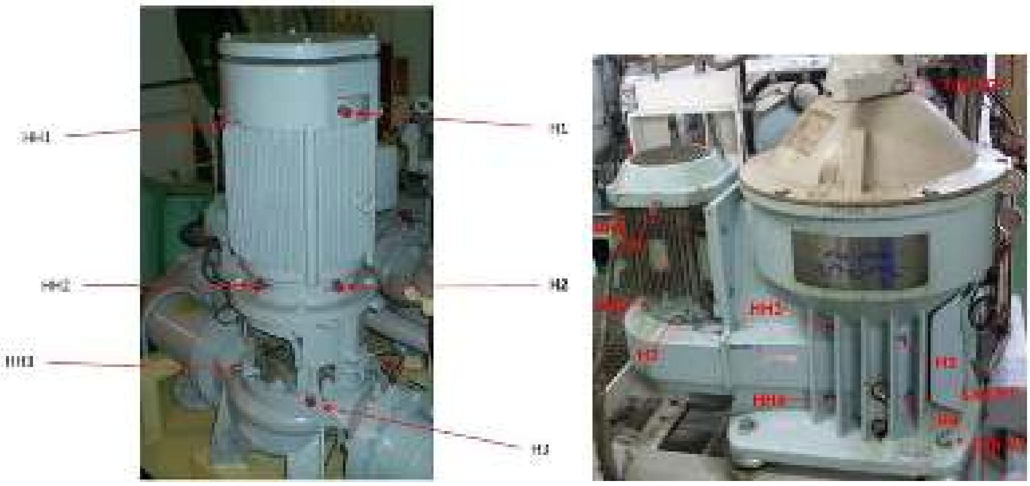


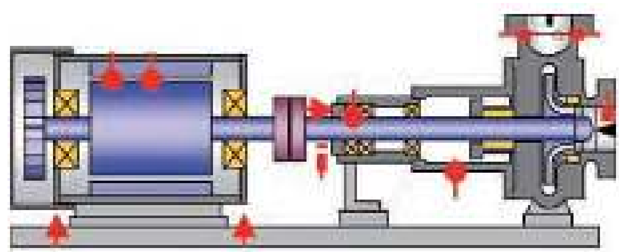
Figure 6. Vibration measurement points in the case of vertical devices and separator

The figure 6 shows the measuring points in the case of a vertical motors and separator. This tester is compatible with the ST723 optical tachometer for determining the rated speed of electric motors.

4. Results of vibration measurements

The vibration measurement conditions are:

- Vibration measurements were taken during normal operation of equipment.
- Measured points are split into source of power and executive elements [4].



1 2 Coupling 3 4

Figure 7. Typical machine arrangement with some measurement locations

Rotated equipment with RPM more than 120 when is apply ISO standard 10816-3. e.g., electrical machines below 300 kW on elastic foundation have the following limits:

Cl. A	0 – 2.3 mm/s	newly commissioned
Cl. B	2.3 – 4.5 mm/s	unrestricted
Cl. C	4.5 – 7.1 mm/s	restricted long-term operation
Cl. D	7.1 – above	high probability of damage

Limits of mechanical executive elements like pumps, engine pistons – allowed one group higher.

Cl. A newly commissioned
Cl. B unrestricted
Cl. C restricted long-term operation
Cl. D action required
Cl. D vibrations over the limits but actions are not required

In table 1 are presented only readings with max. RMS results for each electrical motor.

Table 1. Results of vibration measurements for electrical motors analyzed

Machine name	Velocity RMS (mm/s) Max 2020	ISO standard	Bearing Envelope (m/s^2) Max	Trend Velocity RMS (mm/s) Max	Remarks and suggestions
			BOW		
Bow thruster					
Bow thruster el. motor	7.709	Cl. B	20.258		Next measurement needs to be done up to one month
Hydraulic pump for BT electric motor	0.999	Cl. A	9.410		
Emergency fire pump					
EM fire pump electric motor	4.030	Cl. C	44.944		
			DECK		
Emergency Generator					
Emergency Alternator	5.674	V.1	73.689		
Windlass Mooring winch					
Windlass Mooring winch W1 el. motor	2.216	Cl. B	42.103		Next measurement needs to be done up to one month.
Windlass Mooring winch W2 el. motor	4.260	Cl. C	59.594		Next measurement needs to be done up to one month.
AFT Mooring winch					
Mooring winch M1 el. motor	3.781	Cl. C	12.841		
Mooring winch M2 el. motor	2.217	Cl. B	11.771		
Mooring winch M3 el. motor	4.375	Cl. C	12.989		
			ENGINE ROOM		
ME Aux blowers					
ME Aux blower no1 electric motor	1.250	Cl. A	6.937		
ME Aux blower no.2 electric motor	1.453	Cl. B	6.679		
Diesel Generators					
DG no.1 Alternator	6.195	V.1	-		
DG no.2 Alternator	6.992	V.1	-		
DG no.3 Alternator	7.276	V.1	-		
Air compressors					
Start Air compressor no1 el. motor	14.124	Cl. C	31.660		
Start Air compressor no2 el. motor	9.385	Cl. B	26.162		
SCW pumps					
SCW pump for harbour el. motor	2.921	Cl. C	7.934		
SCW pump no1 el. motor	4.570	**Cl. D**	38.413	↗ Last value 11.2019 **2.250**	Signal high only in one point. Trend needs to be controlled. Actions to be taken based on trend result.
SCW pump no2 el. motor	5.406	**Cl. D**	47.675	↗ Last value 11.2019 **4.586**	Signal high only in one point. Trend needs to be controlled. Actions to be taken based on trend result.

FW cooling pumps					
HT FCW pump no1 el. motor	19.423	Cl. D	5.129	↗ Last value 11.2019 **5.088**	Coupling needs to be checked/repaired. Next measurement needs to be done up two weeks.
HT FCW pump no2 el. motor	28.802	Cl. D	15.092	↗ Last value 11.2019 **21.520**	Coupling needs to be checked/repaired. Next measurement needs to be done up to two weeks.
Circ pump HT cooling water preheater el. motor	3.349	Cl. C	14.133		
LT FCW pump for harbour el. motor	1.992	Cl. B	22.103		
LT FCW pump no1 el. motor	1.672	Cl. B	34.059		
LT FCW pump no2 el. motor	1.418	Cl. B	18.266		
LO pumps					
Lub oil pump ME no1 el. motor	10.240	Cl. D	3.985	↗ Last value 11.2019 2.775	Check tightening of the foundation bolts.
Lub oil pump ME no2 el. motor	1.384	Cl. A	15.683		
DG1 Pre lub oil pump el. motor	2.637	Cl. B	28.265		
DG2 Pre lub oil pump el. motor	3.592	Cl. C	35.756		Next measurement needs to be done up to one month
DG3 Pre lub oil pump el. motor	10.041	**Cl. D**	66.236	↗ Last value 11.2019 **2.154**	High signal generated by pump. Trend needs to be controlled. Actions to be taken based on trend result. Next measurement needs to be done up to one month
Ballast pumps					
Ballast pump no1 el. motor	3.383	Cl. C	38.265		
Ballast pump no2 el. motor	3.359	Cl. C	27.786		
Transfer pumps					
HFO transfer pump no1 el. motor	17.170	Cl. D	62.066	↗ Last value 11.2019 **3.469**	
HFO transfer pump no2 el. motor	4.043	Cl. C	4.962		
MGO transfer pump el. motor	5.633	**Cl. D**	11.880	-	Trend needs to be controlled. Actions to be taken based on trend result.
AE LO transfer pump el. motor	2.638	Cl. B	28.376		
Cylinder oil transfer pump1 el. motor	2.114	Cl. B	16.236		

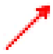
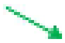
Cylinder oil transfer pump2 el. motor	1.863	Cl. B	16.900		
FWC transfer pump el. motor	3.836	Cl. C	16.302		
HPS units					
HPS unit no1 el. motor	2.457	Cl. B	33.800		
HPS unit no2 el. motor	6.824	**Cl. D**	39.704	-	Signal high only in one point. Trend needs to be controlled. Actions to be taken based on trend result.
Fire and Bilge pumps					
Bilge/Fire pump el. motor	3.849	Cl. C	37.823		
Bilge pump el. motor	2.407	Cl. B	7.638		
Fuel pumps					
MGO supply pump el. motor	2.136	Cl. B	13.505		
Boiler HFO feed pump1 el. motor	1.330	Cl. A	12.362		
Boiler HFO feed pump2 el. motor	2.033	Cl. B	14.908		
Boiler MDO feed pump1 el. motor	6.866	**Cl. D**	10.775		
Boiler MDO feed pump2 el. motor	5.856	**Cl. D**	9.594		
Booster pump for ME no1 el. motor	1.114	Cl. A	3.838		
Booster pump for ME no2 el. motor	1.187	Cl. A	6.105		
Feeder pump for ME no1 el. motor	5.545	**Cl. D**	25.830	↗ Last value 11.2019 **1.444**	Trend needs to be controlled. Actions to be taken based on trend result.
Feeder pump for ME no2 el. motor	1.519	Cl. B	13.210		
Aux booster pump no1 el. motor	1.149	Cl. B	11.255		
Aux booster pump no2 el. motor	2.007	Cl. B	4.354		
Aux feeder pump no1 el. motor	0.851	Cl. A	7.565		
Aux feeder pump no2 el. motor	3.697	Cl. C	34,206		
Separators					
HFO 1 separator el. motor	8.517	**Cl. D**	4.280	↗ Last value 11.2019 **1.570**	Trend needs to be controlled. Actions to be taken based on trend result. Next measurement needs to be done up to one month.
HFO 2 separator el. motor	2.615	Cl. B	21.144		
HFO 3 separator el. motor	16.034	**Cl. D**	4.613	↗ Last value 11.2019	High signal generated by purifier. Trend needs to be controlled. Actions to be taken based on trend result.

				4.933	Next measurement needs to be done up to two weeks.
LO AE separator el. motor	4.473	Cl. C	13.579		
LO ME separator el. motor	5.150	**Cl. D**	26.531	↗ Last value 11.2019 **4.637**	Signal high only in one point. Trend needs to be controlled. Actions to be taken based on trend result. Next measurement needs to be done up to one month.
Separators feed pumps					
HFO separator feed pump no1 el. motor	2.681	Cl. B	21.919		
HFO separator feed pump no2 el. motor	1.197	Cl. A	13.136		
MDO separator feed pump el. motor	2.936	Cl. C	7.159		
Aux LO separator feed pump el. motor	1.816	Cl. B	6.753		
ME LO separator feed pump el. motor	1.955	Cl. A	11.402		
FW pumps					
FW Hydrofore pump no1 el. motor	2.276	Cl. B	14.391		
FW Hydrofore pump no2 el. motor	4.378	Cl. C	29.151		
FWG distillation pump el. motor	1.466	Cl. B	2.546		
FW ejector pump el. motor	8.594	**Cl. D**	16.605	-	Signal high only in one point. Trend needs to be controlled. Actions to be taken based on trend result. Next measurement needs to be done up to one month.
Boiler feed water pump1 el. motor	1.188	Cl. A	9.889		
Boiler feed water pump2 el. motor	1.338	Cl. A	11.328		
Technical water hydrofore pump el. motor	2.961	Cl. C	47.048		Next measurement needs to be done up to one month.
Hot water preheater pump el. motor	11.965	Cl. D	35.756	→ Last value 11.2019 **12.147**	Check shaft sleeve bolts tightening.
Hot water circ pump sanitary system el. motor	6.410	**Cl. D**	5.941	↗ Last value 11.2019 **3.975**	Trend needs to be controlled. Actions to be taken based on trend result.
Condensate filling up pump el. motor	4.200	Cl. C	26.199		
Incinerator					

Incinerator air blower el. motor	4,546	**Cl. D**	10.738		Signal high only in one point. Trend needs to be controlled. Actions to be taken based on trend result.
Sewage unit					
Sewage vacuum pump1 el. motor	12.490	**Cl. D**	44.354	-	Trend needs to be controlled. Actions to be taken based on trend result. Next measurement needs to be done up to one month with ME stopped.
Sewage vacuum pump2 el. motor	12.633	**Cl. D**	51.549	-	Trend needs to be controlled. Actions to be taken based on trend result. Next measurement needs to be done up to one month with ME stopped.
Sewage blower el. motor	4.719	**Cl. D**	56.051	-	Signal high only in one point. Trend needs to be controlled. Actions to be taken based on trend result.
Sewage discharge pump el. motor	4.204	Cl. C	24.575		
Steering gear pumps					
Steering gear no1 el. motor	0.837	Cl. A	11.476		
Steering gear no2 el. motor	0,730	Cl. A	3.985		
Power pack for lifeboat					
Power pack for lifeboat el. motor	5.644	**Cl. D**	18.192	-	Signal high only in one point. Trend needs to be controlled. Actions to be taken based on trend result.
AC unit					
AC fan el. motor	7.837	**Cl. D**	9.114	↗ Last value 11.2019 **1.844**	Signal high only in one point. Trend needs to be controlled. Actions to be taken based on trend result. Next measurement needs to be done up to one month.
Boiler burner fan					
Boiler burner fan el. motor	4.303	Cl. C	6.494		
OW Separator					
Oily water separator el. motor	8.744	**Cl. D**	9.889		Trend needs to be controlled. Actions to be taken based on trend result Next measurement needs to be done up to one month.
Dirty oil pump el. motor	5.898	**Cl. D**	14.539		Trend needs to be controlled. Actions to be taken based on trend result Next measurement needs to be done up to one month with ME stopped.
ME air cleaning chemical pump					

ME air cleaning chemical pump el. motor	5.052	**Cl. D**	82.472		Signal high only in one point. Trend needs to be controlled. Actions to be taken based on trend result Next measurement needs to be done up to one month.

The trend results of vibration analysis are:

-  Whenever new results are increased more than 5% of previous measurements
- Whenever new results are in range ±5% of previous measurements
-  Whenever new results are reduced more than 5% of previous measurements

5. Conclusions

In this paper the conditions in which the vibration measurements were performed, respectively the characteristics of the ship and the atmospheric conditions are:

- Ship type - container ship
- Main dimension
  - Length (b.p) - 169.94 m
  - Breadth (B) - 28 m
- Sea depth - Least two times greater than vessel draught
- Weather condition - Sea state: 2, sunny weather
- Measurement method: - According to standard ISO 10816: - procedure No.2 Measurement report

In technique, the term diagnosis intervenes with its usual acceptance, designating the action of identifying the conditions that generate the observed effects.

The diagnosis is based on the analysis of the technological parameters, obtained following the measurements performed with devices from the standard equipment on board the ships or through the one mounted especially for certain measurements and the statistical processing of the results.

The computer-assisted technical diagnosis signals the existence of the premises for the development of some phenomena that affect the safety of the electrical equipment operation.

The diagnosis can be of online type if the calculation programs process in real time the instantaneous values of the taken parameters, or of offline type if these values are stored so that they can be entered later as input data in the related diagnostic software.

The advantages of this tester and the applications for which it was intended are:

- inspection of electric machines in order to carry out preventive and scheduled maintenance
- necessary measures to be taken to avoid unforeseen failures
- measures to reduce maintenance costs and minimize the production losses
- maintenance and quality control

In this sense, the essential condition for the technical diagnosis of electric motors is vibration monitoring. Mainly the vibration analysis pursues two main objectives, namely:

- keeping the dynamic forces as low as possible, which has the effect of increasing the lifespan of electric motors on board ships
- early detection of failure trends, in order to optimize maintenance actions.

In practice, the dynamic forces cannot be measured directly and for this purpose it is necessary to follow some main parameters that characterize the vibrations:

- amplitude - indicates the severity of the problem
- frequency - allows to establish the source (place of defect)
- phase - identifies the direction of vibration
- shape - shows how the rotor moves (orbit)

In the analysis of vibrations, the possibility of losing important vibrational components should not be neglected, due to the weak response of the system at a given frequency. In practice, the amplitude and frequency parameters are followed in particular. The actual values of these quantities will finally be compared with the nominal values.

The algorithm regarding the stages of diagnosis based on vibrations mainly involves:

- transforming mechanical vibration into an electrical signal
- decomposition of the signal into its frequency components
- establishing the correlation between mechanical processes and frequency values
- appreciation of vibrations based on voltage values and limit values
- saving and interpreting the results of the analysis

The maintenance practiced on the basis of the diagnosis can be characterized as “predictive and to the object”, in the sense that it is “fixed as moments as an element within the diagnosed system.

The implementation of the technical diagnosis system with reference to the electric motors on board the container type ships, implies the following effects:

- increase in investment expenditures, on the whole
- reducing failure intervals and minimizing corrective maintenance times during the analysis period
- suppression of the scheduled preventive maintenance works and application of the predictive maintenance policy to the object
- favors the increase of the life of the electric motor
- increases the degree of automation and computerization of the system
- the operational reliability indicators of the electric motor are improving

Obviously, the effects of applying the technical diagnosis system also have contradictory components. Consequently, the decision on its adoption for a given system (in this case the electric motors on board ships) will be preceded by the application of an optimization criterion (minimum costs, maximum availability, etc.)

Most of the installations on board the ships are operated by means of electric motors so that their share is relatively high.

And in the case of electric motors, the contingency term can be used, which defines the state of the motor as a system where, owing to failures, one or more components are not available.

Each contingency is characterized by a certain probability and frequency of occurrence.

In the case of electric motors, the faults are divided into:

- mechanical faults
- electrical faults

Electrical faults are always a consequence of mechanical defects.

The main cause of mechanical defects during the operation of electric motors is the rotor.

The next set of measurements must be performed within a period of one month to obtain the trend value for each electric motor analyzed, after which the measurements can be performed at three-month intervals or whenever necessary earlier.

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