Reliability assessment and system performance improvement of ORV *Sagar Nidhi* propulsion system

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Diesel-electric propulsion system offers many advantages to research ships, viz. economical, environment friendly, reliable, ease of operation and control, optimal manoeuvering and positioning, low vibration and noise levels. ORV *Sagar Nidhi* is equipped with diesel electric propulsion. The propulsion power is provided by azimuth thrusters which are driven by frequency controlled AC motors. The ship has dynamic positioning system for station keeping and better manoeuvering. During a scientific cruise, starboard azimuth thruster motor tripped due to zero resistance in winding, thereby reducing the propulsion power. Because there is no redundant motor available, vessel completed the voyage with single thruster. As a result of motor failure, propulsive power of the vessel was reduced drastically and the voyage plan had to be altered to match the ship schedule which resulted in skipping many sampling stations. In this article, the possible cause of thruster motor failure was analysed and remedial action was taken to rectify the same. This article also provides different solutions to improve the reliability of propulsion system and minimizing the downtime of vessel.

Keywords: Azimuth thruster, dynamic positioning, redundancy, reliability.

Introduction

ORV *Sagar Nidhi* is a highly sophisticated state of art ice class research vessel equipped with special equipments, viz. deep sea winch, specially designed cranes for launching and retrieval of remotely operable vehicle, deep-sea mining crawler, tsunami systems, manned/unmanned submersible and autonomous coring system and other facilities that support research in Indian, international and Antarctic waters. The ship has twin screw diesel-electric propulsion system along with dynamic positioning capability. ORV *Sagar Nidhi* (Figure 1) has successfully completed many international expeditions in the Indian Ocean. While en-route to Mauritius, the air circuit breaker (ACB) for starboard azimuth thruster tripped off due to low insulation fault, thereby reducing propulsive power of the vessel. The vessel operated on single thruster as there is no redundant motor in the system. Considering the safety of the vessel, the voyage plan was altered by skipping many sampling stations and the vessel reached Mauritius safely. The starboard side propulsion thruster consists of an induction motor controlled by variable frequency drive (VFD), which is fed from main switch board (MSB). Onboard vessel management team inspected the system. Further features of stator winding, insulation and stator winding failure mechanism were studied and considered during troubleshooting. The stator winding insulation system contains several different components and features which together ensure that electrical shorts do not occur. Heat losses, i.e. I^2R (I: current, R: resistance) are transmitted to a heat sink and conductors do not vibrate in spite of magnetic forces. The basic stator insulation system components are strand, turn and ground wall insulation. There are different types of failure mechanisms associated with stator windings and each of them is studied in detail to analyse the cause of stator failure. Some of failure mechanisms will only occur on form-wound stators and some only in random-wound

Figure 1. ORV *Sagar Nidhi.*

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stators. However, most of failure processes can occur in either type of stator. Thermal deterioration on form-wound stator is probably one of the most common reasons for stator windings failure. In form-wound stators, the reduced bonding strength between strands and ground insulation allows mica tape layers to start separating, resulting in delamination. Thermal cycling is most likely to occur in machines with long stator cores and in form-wound coils/bars in machines experiencing many rapid starts and stops or rapidly changing loads. Deterioration will be more rapid with faster load changes, longer stator cores, higher operating temperatures, and/or more frequent load changes. Figure 2 shows loose coils in slot which are normally associated with form-wound stators manufactured in a conventional way.

The failure of the motor is due to degradation of winding over nine years of continuous operation. Being a research vessel, *Sagar Nidhi* was kept in DP mode more frequently which resulted in sudden load change on motor. It was also observed that starboard thruster motor has more running hours compared to Port Azimuth motor. The root cause[1] and inference are mentioned below.

(a) The motor is powered by two converters with in-built power management system, which protects drive and motor from overload. As the rated current is under permissible set limits, based on calculated overload response time of VFD and its input protection fuse characteristics, it is found that motor fault current should have been instantaneous.
(b) Fuse is a secondary protection to the system after air circuit breaker (ACB), the same has not blown.
(c) ACB, VFD power management system, fuse characteristics and according to the present protection discrimination, the ACB has responded in instantaneous protection mode, prior to other two protections. Hence it is confirmed that fault in the motor must have been instantaneous in nature.

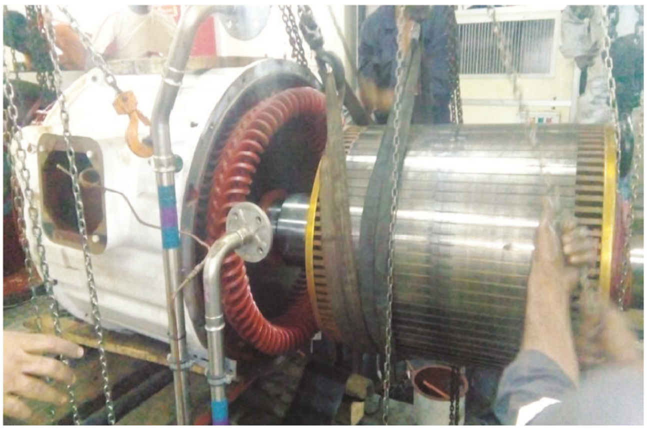

Figure 2. Loose coils in slot.

(d) Inference: The motor fault could have been incipient in nature initially which could have been matured into a multiple earth fault, during the time ACB tripped.

Systematic troubleshooting was carried out as mentioned below: (a) Checked insulation of power cables from MSB to VFD. (b) Checked VFD panel for any earth fault. (c) Checked insulation of power cables from VFD to motor. (d) Checked winding terminal of motor: It was found that, the induction motor was having earth fault. Megger test was carried between motor terminals and motor body showed zero insulation. (e) Measurement of degraded motor winding parameters with precision instruments. (f) Analysis of protection/trip settings in power conversion systems and switch-gears ahead of thruster motor for proper protection discrimination during fault conditions.

Cooler unit was dismantled and visual inspections were carried out. It was decided to dismantle the motor and accordingly rotor was removed for inspection. It was found that few wedges were missing in stator slot, which may have led to zero insulation in winding. It was inferred that the failure is due to degradation of winding[2]. It was found that the lead time for supply of new motor is around ten months and three months for carrying out rewinding of stator. Damaged winding were taken out from the slots and special insulation tape was wrapped on the winding. New wedges were fixed on the slots wherever necessary. Complete re-varnishing was done in order to improve insulation of the winding. Megger test in 1000 V (ref. 3) mode was carried out and it was found that the insulation has improved to 6 Giga ohms.

After completion of standard repair procedure, the motor was re-assembled and it was tested under no load condition with 400 to 500 revolutions per minute (RPM) prior sea trials. The speed of motor gradually increased up to 810 RPM (ref. 4) and it was observed that all parameters were normal. Upon completion of no load test, the motor was assembled to thruster unit. Sea trial was carried out for 6 h with different speeds initially and at full speed for one hour. The above repair work and sea trials were conducted under the supervision of surveyors from Indian Registry of Shipping (IRS) and Det Norske Veritas (DNV). Though the work was completed successfully, the reliability of propulsion system remained the same

Table 1. Propulsion system specifications

System component	Specifications
Power generation	4 × 1710 KVA
Power distribution	690 V MSB
Azimuth thruster motor	3 phase motor, 660 V, 1600 kW, 1816 A, insulation class F, PF 0.8 and speed 810 RPM

Table 2. Operation and mitigation measures using FMEA

Item	Potential failure mode	Potential cause(s)	Local effect of failure	Higher level effect system	Occurrence (O)	Detection (D)	Severity (S)	RPN	Remarks
Generator	Complete loss of function	Mechanical or electrical failure	None	None	3	Alarm system-1	Minor 2	6	Use redundant A/E
VFD component failure (capacitor bank, relay)	Loss of function	Electrical failure	Loss of propulsion	Loss of propulsion	3	Alarm 1	Major 5	15	Components can be bypassed to avoid loss of propulsion
VFD component failure (IGBT, cooler line)	Complete loss of propulsion	Electrical failure	Loss of propulsion	Loss of propulsion	5	Trouble-shoot based on alarm code 5	Major 9	225	Propulsion loss
Propulsion motor	Complete loss of function	Winding failure	Loss of propulsion	Loss of propulsion	2	Trouble-shoot based on alarm code 5	Major 9	90	Propulsion loss

and it is necessary to have redundant components in propulsion system to avoid loss of propulsive power during this kind of situation. Table 1 shows specification of propulsion system of ORV *Sagar Nidhi*.

Proposed solutions to improve redundancy

From the ship operator's point of view, redundancy is part of performance and it varies from 50% to 100% based on ship type. High availability requires higher redundancy level, i.e. more installed components, higher complexity and higher cost. Also, the failure rate would probably increase with more installed equipment. In this case, the following drive configuration is proposed to increase the redundancy of the system in case of propulsion motor failure which also results into fault tolerance and cost reductions.

(1) Drive train is extremely vulnerable in fault situations and provides high level of redundancy and fault tolerance, but the system cost is high.
(2) Propulsion motors can be directly connected to shafts or by using reduction gearbox.

Reliability analysis to identify the best configuration

A failure modes and effects analysis (FMEA) and reliability study is performed by considering components to improve reliability of propulsion system. Table 2 shows FMEA analysis of propulsion system of ORV *Sagar Nidhi*. Propulsion system is the heart of ship; its reliability directly determines the safe navigation and operating cost.

Reliability of system: $R(t) = e^{-\lambda(t)}$.

X: No. of failures, T: Total ship running hours, t: Time period, Failure rate: $\lambda = X/T$/hr

Components connected in series: $R_s = R_1 \times R_2 \times \ldots R_n$.

Components connected in parallel: $R_s = 1 - [(1 - R_1) \times (1 - R_2) \times \ldots \times (1 - R_n)]$.

Reliability of frequency drive: $R_{VFD}(4380) = e^{-\lambda \times t} = e^{-0.00024 \times 4380} = 0.343$ ($X = 5$, $T = 20500$ h, $t = 4380$ h).

Reliability of electric motor: $R_{EM}(4380) = e^{-\lambda \times t} = e^{-0.00009756 \times 4380} = 0.652$.

$R_{PROPULSION} = R_{VFD} \times R_{EM} = 0.343 \times 0.652 = 0.224$.

Redundant VFD: $R_{VFD} = 1 - [(1 - 0.343)(1 - 0.343)] = 0.568$.

Redundant motor $R_{EM} = 1 - [(1 - 0.652)(1 - 0.652)] = 0.878$.

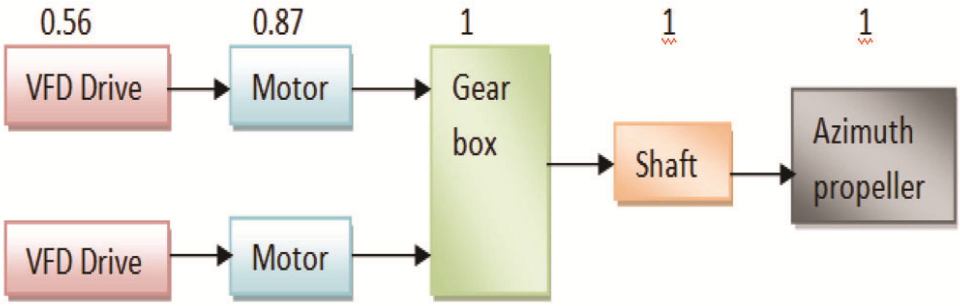

Figure 3. Proposed system reliability.

$$R_{\text{NEW SYSTEM}} = 1 - [(1 - 0.568) \times (1 - 0.878)] = 0.947.$$

The reliability of proposed propulsion system which is shown in Figure 3, has increased to 94.7% which is helpful for *Sagar Nidhi* to accomplish the critical scientific and technology demonstration operations.

Conclusions

This paper describes the procedure for analysing various possibilities of propulsion motor winding failure and for identifying the root cause. Further, the procedure followed to troubleshoot propulsion motor winding fault was presented in detail. The entire work was completed in two weeks wherein lead time for supply of new motor will take about 8–9 months. The repair work done in motor has helped the vessel to complete scheduled scientific cruises, thereby reducing the downtime of ship. A reliability study was conducted for different configurations of proposed propulsion to identify the best configurations. FMEA study and reliability assessment on propulsion system of *Sagar Nidhi* gave a prediction that single point failure impact the performance of propulsion and frequent failures reduce the reliability of system. By having a suitable redundant systems and following proper maintenance schedule, the frequency of failure can be minimized thereby increasing the reliability of propulsion system.

(a) Redundant motor and drive in parallel configurations resulted in increasing reliability to 94.7% from the current value of 22%.

(b) It is recommended to have a motor and drive in parallel configuration compared to series configuration and dual stator configurations which resulted in increase of reliability value.

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