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THE Lz-TRANSFORM METHOD FOR THE RELIABILITY AND FAULT TOLERANCE ASSESSMENT OF NORILSK-TYPE SHIP'S DIESEL-GEARED TRACTION DRIVES

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This paper focuses on a comparative analysis of the most important parameters of an icebreaker ship's sustainable operations: the operational availability, power performance and power performance deficiency of the multi-state Multi-Power Source Traction Drives of Norilsk-type Arctic icebreaker ships. These parameters have a significant impact on the correct choice of the propulsive system of icebreaking vessels. The parameters' evaluation was based on statistical operational data on Arctic icebreaker ships with diesel-geared traction drive. The *Lz*-transform approach was used to arrive at a solution of that problem. This approach drastically simplifies the solution compared with the straightforward Markov method.

Keywords: Multi-Power Source Traction Drive, icebreaker ship, multi-state systems reliability, *Lz*-transform method, availability, power performance, power performance deficiency

1. Introduction

Vehicle traction drives are safety-critical systems, which are subject to stringent requirements for safety, survivability and sustainability. Especially important is the implementation of these requirements for Arctic icebreaker ships. In this paper, an analysis of important parameters of an icebreaker ship's operational sustainability will be presented. The Multi-Power Source diesel-geared traction drive of Norilsk-type Arctic icebreaker ships will be analysed.

With the active decrease in the value of the ice cover of the Arctic Ocean and the planned year-round transportation of cargoes along the Northern Sea Route, it is planned to increase significantly the number of icebreaker ships for operation in the Arctic ice conditions. In this regard, the task of evaluating the compliance of the reliability characteristics of ice navigation ships with the operation conditions requirements becomes even more urgent.

Due to the nature of a propulsion system, a fault in a single unit has only a partial effect on the entire power performance. A partial failure of the multi-power source traction drive initially and automatically leads to a partial system failure (reduction of output nominal power), as well as multiple consecutive failures and ultimately to a total system failure. Thus, a ship's multi-power source traction drive can be regarded as a multi-state system (MSS) whose components as well as the whole system can be considered to have a finite number of states associated with various performance rates (Bolvashenkov and Herzog, 2016; Bolvashenkov *et al*. 2016; Frenkel *et al*. 2016, 2017). The system's performance rate (output nominal power) can be viewed as a discrete-state continuous-time stochastic process. Such models, even in simple settings, are quite complex because they may contain several hundred states. Therefore, not only the construction of such a model but also the solution of the associated system of differential equations via a straightforward Markov method is very complicated.

In recent years, a special technique known as *Lz*-transform has been proposed and investigated (Lisnianski *et al.*, 2010) for discrete-state continuous-time Markov processes. This approach is an extension of the universal generating function (UGF) technique proposed by Ushakov (1986) that has been extensively implemented for the analysis of the reliability of multi-state systems. *Lz*-transform has turned out to be a powerful and highly efficient tool for the availability analysis of MSSs needed for constant and variable demand (Jia *et al*., 2017; Yu *et al*., 2014). It should be noted here that the above technique has great applicability for numerous structure functions (Lisnianski *et al*., 2010; Natvig, 2011).

In this paper, the *Lz*-transform method is applied for the analysis of an MSS multi-power source traction drive that must function under various weather conditions: Its availability, power performance and power performance deficiency are investigated. We established that the implementation of the *Lz*-transform simplifies things considerably, as compared with the standard Markov model for the computation of a system's availability.

2. Brief description of the *Lz*-transform method

Let us consider here a multi-state system, consisting of n multi-state components. Any j-component can have k_j different states, corresponding to different performances g_{ji}, represented by the set $\mathbf{g}_j = \{g_{j1},...,g_{jk_j}\}$, $j = \{1,...,n\}$; $i = \{1,2,...,k_j\}$. The performance stochastic processes $G_j(t) \in \mathbf{g}_j$ and the system structure function $G(t) = f(G_1(t),...,G_n(t))$ that produces the stochastic process corresponding to the output performance of the entire MSS fully define the MSS model.

The construction of MSS model definitions can be divided into several steps. For each multi-state component, we will build a model of stochastic process. The Markov performance stochastic process for each component j can be represented by the expression $G_j(t) = \{\mathbf{g}_j, \mathbf{A}_j, \mathbf{p}_{j0}\}$, where $\mathbf{g}_j$ is the set of possible component states, as defined below, $\mathbf{A}_j = \left(a_{lm}^{(j)}(t)\right)$, $l,m = 1,...,k; j = 1,...n$ the transition intensities matrix and $\mathbf{p}_{j0} = \left[p_{10}^{(j)} = \Pr\{G_j(0) = g_{10}\},..., p_{k_j0}^{(j)} = \Pr\{G_j(0) = g_{k_j0}\}\right]$ the probable distribution of initial states.

For each component j, the system of Kolmogorov forward differential equations (Trivedi, 2002) can be written for determination of state probabilities: $p_{ji}(t) = \Pr\{G_j(t) = g_{ji}\}$, $i = 1,...k_j$, $j = 1,...,n$ under initial conditions $\mathbf{p}_{j0}$. The *Lz*-transform of a discrete-state continuous-time (DSCT) Markov process $G_j(t)$ for each component j can be written as follows:

$$L_Z\{G_j(t)\} = \sum_{i=1}^{k_j} p_{ji}(t) z^{g_{ji}} \ . \tag{1}$$

The next step, which we must carry out in order to find the *Lz*-transform of the MSS's entire output performance Markov Process $G(t)$ is to apply the Ushakov's Universal Generating Operator (Ushakov, 1986) to all individual *Lz*-transforms $L_Z\{G_j(t)\}$ over all time points $t \ge 0$:

$$L_Z\{G(t)\} = \Omega_f\{L_Z[G_1(t)],...,L_Z[G_n(t)]\} = \sum_{i=1}^{K} p_i(t) z^{g_i} \ . \tag{2}$$

The technique of Ushakov's operator application is well established for many different structure functions (Lisnianski *et al.*, 2010).

Using the resulting *Lz*-transform, MSS mean instantaneous availability for constant demand level w can be derived as the sum of all probabilities in *Lz*-transform for terms where g_i, the powers of z, are not less than demand level w:

$$A(t) = \sum_{g_i \ge w} p_i(t) \ . \tag{3}$$

An MSS's mean instantaneous performance may be calculated as the sum of all probabilities multiplied to performance in *Lz*-transform for terms where the powers of z are positive:

$$E(t) = \sum_{g_i > 0} p_i(t) g_i \ . \tag{4}$$

The instantaneous performance deficiency $D(t)$ at any time t for constant demand w can be calculated as follows:

$$D(t) = \sum_{i=1}^{K} p_i(t) \cdot \max(w - g_i, 0) \ . \tag{5}$$

3. A Multi-state models of Multi-Power Source Traction Drives

3.1. Description of system

We analyse a diesel-geared power drive, used in Norilsk-type Arctic cargo ships, which is based on a diesel-geared propulsion system. The structure of the ship's diesel-geared traction drive is shown in Figure 1. The system consists of two subsystems, each consisting of a medium-speed diesel engine, a fluid coupling and a clutch, a gearbox and a variable pitch propeller.

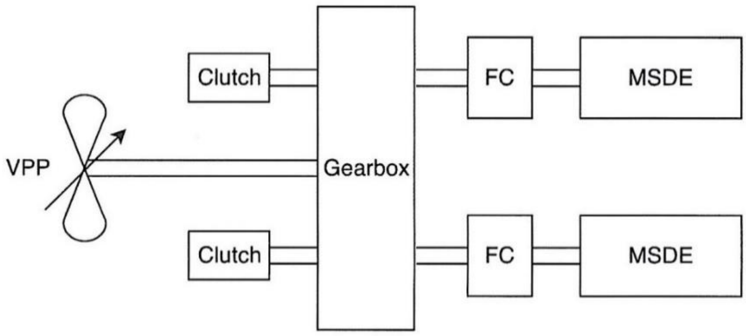

Figure 1. Structure of a Norilsk-type ship's diesel-geared traction drive

The power performance of the whole system is 15440 kW. Depending on ice conditions, the amount of cargo and other conditions of navigation, the ship's propulsion system operates with both subsystems or with only one of them. It realizes the required value of power performance and as a consequence attains the high survivability of the ship in the face of the possible occurrence of the critical failure of the power equipment.

Each subsystem consists of a medium-speed diesel engine, a fluid coupling and a clutch. The power performance of each subsystem is 7720 kW. The connected subsystems in parallel support the nominal performance required for the functioning of the whole system.

The gearbox and variable pitch propeller have nominal performance.

The variable pitch propeller (VPP) is designed to limit the changes of the MSDE load, which depends significantly on the operating conditions. This limitation of the changes of the MSDE load is performed through changes in the pitch of the screw. The nominal power of the variable pitch propeller is the same as the nominal power of the whole system and totals 15440 kW.

The Reliability Block Diagram of a Norilsk-type ship's diesel-geared traction drive is presented in Figure 2.

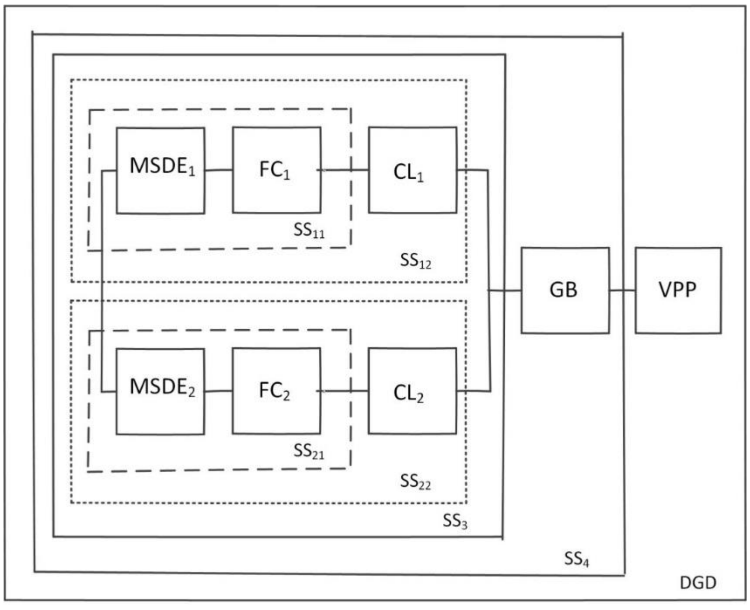

Figure 2. The Reliability Block Diagram of a Norilsk-type ship's diesel-geared traction drive

The possible structure of an Arctic ship's propulsion system is determined by the operating conditions of the Arctic ship and by ice and temperature conditions.

The typical operational modes of Arctic cargo ships are as follows:

- Navigation with an ice-breaker in heavy ice and navigation without an icebreaker in solid ice uses 75% of the generated power.
- Navigation in open water, depending on required velocity, uses 50% of the generated power.

3.2. Description of the system's elements

The system's elements have two states (fully working and fully failed). According to *Lz*-transform method, described in the Section 2, in order to calculate the probabilities for each state, we built a state space diagram (Figure 3) and the following system of differential equations (Trivedi, 2002):

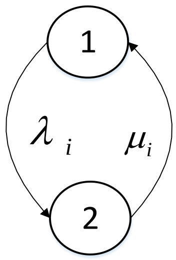

Figure 3. State space diagram

$$\begin{cases} \dfrac{dp_{i1}(t)}{dt} = -\lambda_i p_{i1}(t) + \mu_i p_{i2}(t), \\ \dfrac{dp_{i2}(t)}{dt} = \lambda_i p_{i1}(t) - \mu_i p_{i2}(t). \end{cases} \quad (6)$$

i = MSDE$_1$, MSDE$_2$, FC$_1$, FC$_2$, CL$_1$, CL$_2$, GB, VPP

Initial conditions are: $p_{i1}(0)=1;\ p_{i2}(0)=0.$

We used MATLAB® for the numerical solution of these systems of differential equations to obtain probabilities $p_{i1}(t), p_{i2}(t)$, (i= MSDE$_1$, MSDE$_2$, FC$_1$, FC$_2$, CL$_1$, CL$_2$, GB, VPP).

Therefore, for the elements of such systems, the output performance stochastic processes can be obtained in the following manner:

For i= MSDE$_1$, MSDE$_2$, FC$_1$, FC$_2$, CL$_1$, CL$_2$

$$\begin{cases} \mathbf{g}_i = \{g_{i1}, g_{i1}\} = \{7720, 0\} \\ \mathbf{p}_i(t) = \{p_{i1}(t), p_{i1}(t)\}. \end{cases}$$

For i= GB, VPP

$$\begin{cases} \mathbf{g}_i = \{g_{i1}, g_{i1}\} = \{15540, 0\} \\ \mathbf{p}_i(t) = \{p_{i1}(t), p_{i1}(t)\}. \end{cases}$$

Sets $\mathbf{g}_i, \mathbf{p}_i(t)$ define *Lz*-transforms for each element in a Norilsk-type ship as follows:

Medium Speed Diesel Engine:

$$L_z\left\{G^{MSDE_i}(t)\right\} = p_1^{MSDE_i}(t) z^{g_1^{MSDE_i}} + p_2^{MSDE_i}(t) z^{g_2^{MSDE_i}} = p_1^{MSDE_i}(t) z^{7720} + p_2^{MSDE_i}(t) z^0,\ i=1,2\,. \quad (7)$$

Fluid coupling:

$$L_z\left\{G^{FC_i}(t)\right\} = p_1^{FC_i}(t) z^{g_1^{FC_i}} + p_2^{FC_i}(t) z^{g_2^{FC_i}} = p_1^{FC_i}(t) z^{7720} + p_2^{FC_i}(t) z^0,\ i=1,2\,. \quad (8)$$

Clutch:

$$L_z\left\{G^{CL_i}(t)\right\} = p_1^{CL_i}(t) z^{g_1^{CL_i}} + p_2^{CL_i}(t) z^{g_2^{CL_i}} = p_1^{CL_i}(t) z^{7720} + p_2^{CL_i}(t) z^0,\ i=1,2\,. \quad (9)$$

Gearbox:

$$L_z\left\{G^{GB}(t)\right\} = p_1^{GB}(t) z^{g_1^{GB}} + p_2^{GB}(t) z^{g_2^{GB}} = p_1^{GB}(t) z^{15440} + p_2^{GB}(t) z^0. \quad (10)$$

Variable pitch propeller:

$$L_z\left\{G^{VPP}(t)\right\} = p_1^{VPP}(t) z^{g_1^{VPP}} + p_2^{VPP}(t) z^{g_2^{VPP}} = p_1^{VPP}(t) z^{15440} + p_2^{VPP}(t) z^0. \quad (11)$$

3.3. Multi-state model for Multi-Power Source Traction Drive in Norilsk-type ships

As one can see in Figure 2, the multi-state model for Multi-Power Source Traction Drive in Norilsk-type ships may be presented as connected in series sub-system SS_3 with a gearbox and a variable pitch propeller. Sub-system SS_3 consists of connected in parallel two sub-systems. Each sub-system consists of connected in series a Medium-Speed Diesel Engine, a fluid coupling and a clutch. Using the recursive derivation approach (Lisnianski *et al*., 2010), we will present the whole system using the *Lz*-transform as follows:

$$\begin{aligned}
&L_z\left\{G^{SS_{11}}(t)\right\}=\Omega_{f_{ser}}\left(L_z\left\{G^{MSDE_1}(t)\right\},L_z\left\{G^{FC_1}(t)\right\}\right),\\
&L_z\left\{G^{SS_{12}}(t)\right\}=\Omega_{f_{ser}}\left(L_z\left\{G^{SS_{11}}(t)\right\},L_z\left\{G^{CL_1}(t)\right\}\right)\\
&L_z\left\{G^{SS_{21}}(t)\right\}=\Omega_{f_{ser}}\left(L_z\left\{G^{MSDE_2}(t)\right\},L_z\left\{G^{FC_2}(t)\right\}\right),\\
&L_z\left\{G^{SS_{22}}(t)\right\}=\Omega_{f_{ser}}\left(L_z\left\{G^{SS_{21}}(t)\right\},L_z\left\{G^{CL_2}(t)\right\}\right)\\
&L_z\left\{G^{SS_3}(t)\right\}=\Omega_{f_{par}}\left(L_z\left\{G^{SS_{11}}(t)\right\},L_z\left\{G^{SS_{22}}(t)\right\}\right)\\
&L_z\left\{G^{SS_4}(t)\right\}=\Omega_{f_{ser}}\left(L_z\left\{G^{SS_3}(t)\right\},L_z\left\{G^{GB}(t)\right\}\right)\\
&L_z\left\{G^{DGPS}(t)\right\}=\Omega_{f_{ser}}\left(L_z\left\{G^{SS_4}(t)\right\},L_z\left\{G^{VPP}(t)\right\}\right)
\end{aligned} \tag{12}$$

Using the composition operators Ω_{fser} and Ω_{fpar} for sub-systems and elements, we obtain the following *Lz*-transforms:

- L_Z-transforms for SS_{i1} subsystem i=1,2

$$\begin{aligned}
L_z\left\{G^{SS_{i1}}(t)\right\}&=\Omega_{f_{ser}}\left(L_z\left\{G^{MSDE_i}(t)\right\},L_z\left\{G^{FC_i}(t)\right\}\right)=\\
&=\Omega_{f_{ser}}\left(p_1^{MSDE_i}(t)z^{7720}+p_2^{MSDE_i}(t)z^0,\,p_1^{MSb}(t)z^{7720}+p_2^{MS}(t)z^0\right).\\
&=P_1^{SS_{i1}}(t)z^{7720}+P_2^{SS_{i1}}(t)z^0
\end{aligned} \tag{13}$$

where

$$P_1^{SS_{i1}}(t)=p_1^{MSDE_i}(t)\,p_1^{FC_i}(t),$$
$$P_2^{SS_1}(t)=p_2^{MSDE_i}(t)\,p_1^{FC_i}(t)+p_2^{FC_i}(t).$$

- L_Z-transforms for SS_{i2} subsystem, i=1,2

$$\begin{aligned}
L_z\left\{G^{SS_{i2}}(t)\right\}&=\Omega_{f_{ser}}\left(L_z\left\{G^{SS_{i1}}(t)\right\},L_z\left\{G^{CL_i}(t)\right\}\right)=\\
&=\Omega_{f_{ser}}\left(p_1^{SS_{i1}}(t)z^{7720}+p_2^{SS_{i1}}(t)z^0,\,p_1^{CL_i}(t)z^{7720}+p_2^{CL_i}(t)z^0\right).\\
&=P_1^{SS_{i2}}(t)z^{7720}+P_2^{SS_{i2}}(t)z^0
\end{aligned} \tag{14}$$

where

$$P_1^{SS_{i2}}(t)=P_1^{SS_{i1}}(t)\,p_1^{CL_i}(t),$$
$$P_5^{SS_2}(t)=P_2^{SS_{i1}}(t)\,p_1^{CL_i}(t)+p_2^{CL_i}(t).$$

- L_Z-transforms for the SS_3 subsystem

$$\begin{aligned} L_z\left\{G^{SS_3}(t)\right\} &= \Omega_{f_{par}}\left(L_z\left\{G^{SS_{12}}(t)\right\}, L_z\left\{G^{SS_{22}}(t)\right\}\right) \\ &= \Omega_{f_{par}}\left(P_1^{SS_{12}}(t)z^{7720} + P_2^{SS_{12}}(t)z^0, P_1^{SS_{22}}(t)z^{7720} + P_2^{SS_{22}}(t)z^0\right). \end{aligned} \quad (15)$$

Using simple algebraic calculations of the powers of z as the sum of the values of the powers of corresponding terms, the whole system's L_Z-transform expression is as follows:

$$L_z\left\{G^{SS_3}(t)\right\} = P_1^{SS_3}(t)z^{15440} + P_2^{SS_3}(t)z^{7720} + P_3^{SS_3}(t)z^0 \quad (16)$$

where

$$P_1^{SS_3}(t) = P_1^{SS_{12}}(t)P_1^{SS_{22}}(t),$$
$$P_2^{SS_3}(t) = P_1^{SS_{12}}(t)P_2^{SS_{22}}(t) + P_2^{SS_{12}}(t)P_1^{SS_{22}}(t),$$
$$P_3^{SS_3}(t) = P_2^{SS_{12}}(t)P_2^{SS_{22}}(t)$$

- L_Z-transforms for the SS_4 subsystem

$$\begin{aligned} L_z\left\{G^{SS_4}(t)\right\} &= \Omega_{f_{ser}}\left(L_z\left\{G^{SS_3}(t)\right\}, L_z\left\{G^{GB}(t)\right\}\right) \\ &= \Omega_{f_{ser}}\left(P_1^{SS_3}(t)z^{15440} + P_2^{SS_3}(t)z^{7720} + P_3^{SS_3}(t)z^0, P_1^{GB}(t)z^{15440} + P_2^{GB}(t)z^0\right). \\ &= P_1^{SS_4}(t)z^{15440} + P_2^{SS_4}(t)z^{7720} + P_3^{SS_4}(t)z^0 \end{aligned} \quad (17)$$

where

$$P_1^{SS_4}(t) = P_1^{SS_3}(t)P_1^{GB}(t),$$
$$P_2^{SS_4}(t) = P_2^{SS_3}(t)P_1^{GB}(t),$$
$$P_3^{SS_4}(t) = P_3^{SS_3}(t)P_1^{GB}(t) + P_2^{GB}(t)$$

- L_Z-transforms for the DGD system

$$\begin{aligned} L_z\left\{G^{DGD}(t)\right\} &= \Omega_{f_{ser}}\left(L_z\left\{G^{SS_4}(t)\right\}, L_z\left\{G^{VPP}(t)\right\}\right) \\ &= \Omega_{f_{ser}}\Big(P_1^{SS_4}(t)z^{15440} + P_2^{SS_4}(t)z^{7720} + P_3^{SS_4}(t)z^0, \\ &\qquad P_1^{VPP}(t)z^{15440} + P_2^{VPP}(t)z^0\Big) \\ &= P_1^{DGD}(t)z^{15440} + P_2^{DGD}(t)z^{7720} + P_3^{DGD}(t)z^0 \end{aligned}. \quad (18)$$

where

$$P_1^{DGD}(t) = P_1^{SS_4}(t)P_1^{VPP}(t),$$
$$P_2^{DGD}(t) = P_2^{SS_4}(t)P_1^{VPP}(t),$$
$$P_3^{DGD}(t) = P_3^{SS_4}(t)P_1^{VPP}(t) + P_2^{VPP}(t)$$

3.4. Calculation of the reliability indices of Multi-Power Source Traction Drive

Using expression (3), the instantaneous availability for constant demand level *w* may be presented as follows:

- Winter period - 75% demand level

$$A_{w\geq 11580kW}^{DGD}(t) = \sum_{g_i^{DGD}\geq 11580} P_i^{DGD}(t) = P_1^{DGD}(t). \quad (19)$$

Summer period - 50% demand

$$A_{w\geq 7720kW}^{DGD}(t) = \sum_{g_i^{DGD}\geq 7720} P_i^{DGD}(t) = P_1^{DGD}(t) + P_2^{DGD}(t). \quad (20)$$

The instantaneous power performance for Multi-Power Source Traction Drives can be obtained in the following manner:

$$E^{DGD}(t) = \sum_{g_i^{DGD}>0} g_i^{DGD} P_i^{DGD}(t) = \sum_{i=1}^{2} g_i^{DGD} P_i^{DGD}(t) = 15440 \cdot P_1^{DGD}(t) + 7720 \cdot P_2^{DGD}(t). \quad (21)$$

The instantaneous power deficiency of Multi-Power Source Traction Drives for the winter period can be obtained in the following manner:

$$D^{DGD}(t) = \sum_{i=1}^{3} P_i^{DGD}(t) \cdot \max(11580 - g_i, 0) = 3860 \cdot P_2^{DGD}(t) + 11580 \cdot P_3^{DGD}(t). \quad (22)$$

The instantaneous power deficiency of Multi-Power Source Traction Drives for the summer period can be obtained in the following manner:

$$D^{DGD}(t) = \sum_{i=1}^{3} P_i^{DGD}(t) \cdot \max(7720 - g_i, 0) = 7720 \cdot P_3^{DGD}(t).. \quad (23)$$

The failure and repair rates (per year^{-1}) for each system's elements are presented in the Table 1.

Table 1. Failure and repair rates of elements in Norilsk-type ships (year^{-1})

System's elements	Failure rates	Repair rates
Diesel engine	1.5	230
Gear box	0.11	195
Coupling	0.15	398
Clutch	0.11	467
Variable pitch propeller	0.11	92

The calculated reliability indices of Multi-Power Source Traction Drive in Norilsk-type ships after a year of operations are presented in Figures 4-6 and Table 2.

Table 2. Reliability indices of Multi-Power Source Traction Drives after a year of operations

Reliability indices	Value
Instantaneous availability of traction drive for winter demand	0.9228
Instantaneous availability of traction drive for summer demand	0.9969
Power performance	14820 kW
Power performance deficiency for winter demand	322 kW
Power performance deficiency for summer demand	24.2 kW

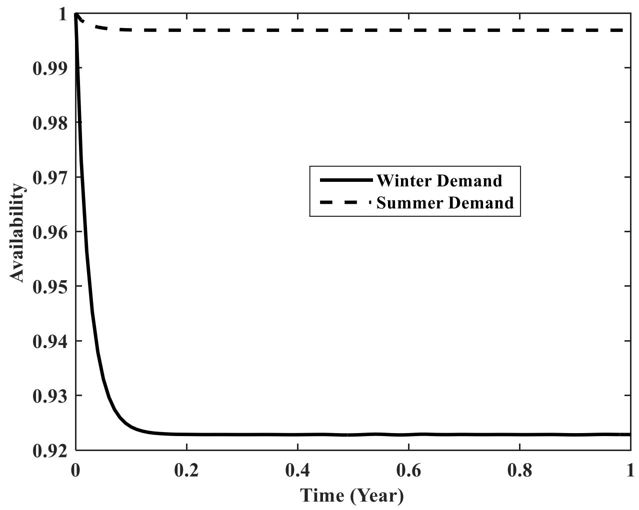

Figure 4. Availability of traction drives in Norilsk-type ship for different constant demand levels

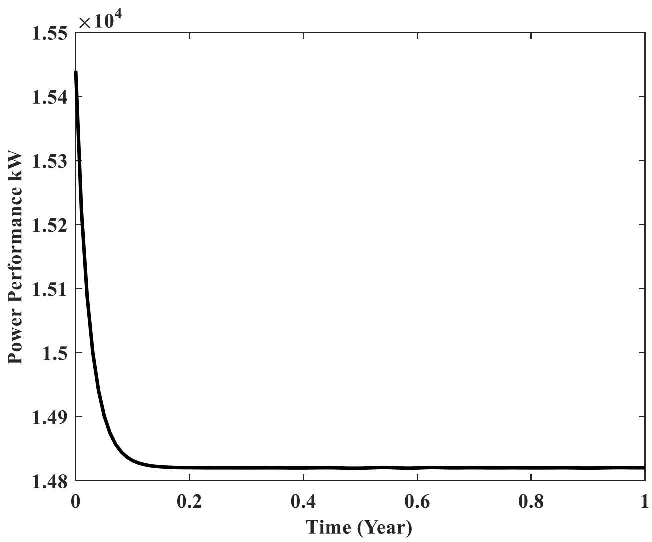

Figure 5. Power performance of traction drive in Norilsk-type ship

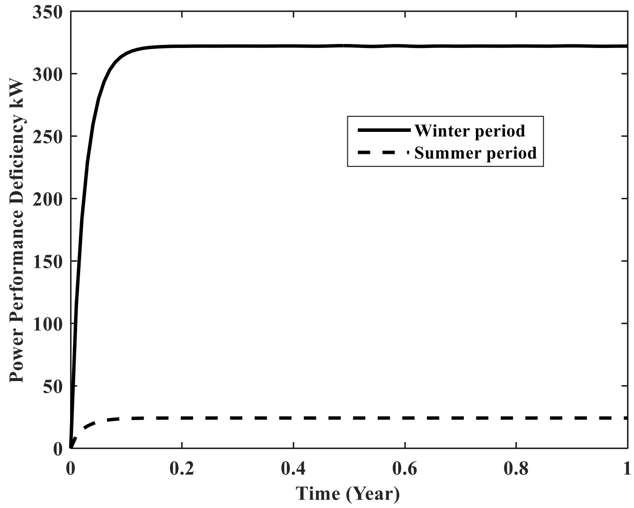

Figure 6. Power performance deficiency of traction drive in Norilsk -type ships

As one can see, the instantaneous availability of the traction drive during summer period is greater than the instantaneous availability of the traction drive in during the winter period. Power performance deficiency for winter demand is much greater the in summer period. Real power performance with respect to availability of the system is 14820 kW.

4. Conclusion

In this paper, the L_Z-transform method was used for the evaluation of important parameters of the vehicle's operational sustainability – the availability, power performance and power performance deficiency of the multi-state Multi-Power Source Traction Drive in the Norilsk icebreaker ships. The results of calculations based on *Lz*-transform correlate with the statistical data on the operational availability of diesel-geared propulsion systems, as discussed in referred literature.

The L_Z-transform approach extremely simplifies the solution, in comparison with the straightforward Markov method, which would have required construction and solution of model with 256 states for Norilsk-type ship.

The obtained results show that taking into account the changes in winter and summer demands, the average value of the ship availability is approximately 93%. The most preferable and advisable way to increase the value of availability of an icebreaker cargo ship and, consequently, its comprehensive operational efficiency, is the use of an electric propulsion system.

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