Reliability study for traction electrical equipment of urban electric transport

L S Sabitov 1, A E Aukhadeyev 2, R G Idiyatullin 2, R S Litvinenko 2, L N Kisneeva 2, A N Khusnutdinov 2 and O V Ilyushin 1,2

1Kazan (Volga Region) Federal University 18 Kremlyovskaya Str., Kazan 420008, Russia
2Kazan State Power Engineering University 51 Krasnoselskaya str., Kazan 420061, Russia

rr-088@mail.ru

Abstract. The paper discusses the matter of reliability of the windings of the asynchronous traction motors being part of the urban electrically powered vehicles, contains the characteristic curve of the stator failure-free operation probability, and refers to experimental data on the failure rate. The results can be used both at the design stage of asynchronous traction motors and while in operation to optimize the preventive maintenance.

Generally, the companies of urban electric transport (UET) operate rolling stock (RS), providing efficient transport services to the urban population, namely: maximum reduction of time spent on movement and reduction of transport fatigue; maximum release of RS for utilization, high regularity of movement and transport comfort of passenger traffic [1-4].

The reliability of traction electric equipment of RS, providing the healthy operation in a given period, when there is an impact of operational factors, directly or indirectly influences the high quality performance of UET [5-7].

Taken together, the influence of design quality and deviations from the specifications for operation leads to failures and malfunctions of the RS traction components [5, 6].

Nowadays, traction electric equipment based on squirrel-cage asynchronous traction motors (ATM) is actively used on the existing RS. This motor type demonstrates increased reliability as determined by its simple design. In this case, the most typical cause of failure (up to 80% of all cases) for ATM is the destruction of the stator insulation due to its overheating. The main types of insulation failures are turn-to-turn short circuit, coil insulation failure, coil short circuit to frame. With a continuous load on the ATM and deviations in the process of operating the RS, the load current increases, resulting in overheating of the insulation, and, as a result, its accelerated aging [8, 9].

Currently, the existing RS is required to increase the operating speed, causing the traction electric equipment to run longer in traction mode, and, consequently, it increases the heating time of the ATM insulation. The allowable amount of heating of the traction motor components is calculated at the design stage. The permissible heating of the traction motor components is set so that the insulation in contact with them or located in the immediate vicinity of them can perform during the estimated
lifetime. With this in mind, the ultimate level of heating of the ATM components depends on the heat resistance class of the insulation [3, 6].

The probability of failure-free operation of the stator components as a function of the RS run was determined to analyze their reliability based on the statistical data of failures of the traction electric equipment. In this case, $\lambda_k = 0.08$, where the failure rate of the coil insulation and the housing insulation of the traction motor stator winding slot is summed. The failure rate $\lambda_e = 0.24$ for the previous value of the overheating of the winding, equal to $10^\circ$C [10, 11].

Design and technological solutions that determine the value of $\lambda_k$ also influence the operation of stator insulation. As the number of in-service defects increases, the failure rate climbs as well, i.e. becomes more than the value specified in the design specifications. If the load conditions of the ATM in operation exceed the specifications limits, then this will cause an increase in the value of $\lambda_k$. The failure rate $\lambda$ depends on the quality of design, manufacturing technology and the influence of external operational factors $\lambda_e$, i.e. $\lambda = \lambda_k + \lambda_e$. If we accept the condition that the failure flow obeys the Poisson stationary flow, then the equation for the reliability of the ATM stator slot will be as follows [12, 13]:

$$P(t) = e^{-(\lambda_k + \lambda_e)t}$$

where $\lambda_e$ is the flow of failures caused by design and technological factors; is the flow of failures caused by operational factors.

Figure 1 shows the various factors vs. the RS run characteristic curves. The highest failure-free operation probability is determined by factors contingent on the quality of the design. Lower reliability is caused by in-service factors – in this event, failure to comply with the specifications for operation leads to overloading of the ATM, overheating of the insulation, its thermal breakdown, and, as a result, to failure [13, 14].

The constructed characteristic curves demonstrate the probability of failure-free operation as a function of time. As is seen from the above curves, the influence of operating conditions on the reliability of the traction electric equipment is stronger compared to failures caused by the quality of design and workmanship [10, 14, 15]. In view of the above, the following important features can be noted:

First, if there is $\lambda_k < \lambda_e$, then the influence of design and technological defects on the reliability of the ATM will be lower [16,17,18]. This is a case where the high quality of design and workmanship is ensured, but at the same time the specifications is not met in operation. Based on the results of the data obtained, it can be noted that the operational reliability of the ATM insulation, taking into account the effect of factors at the design and fabrication stages $P_k(t) = 0.45$, taking into account the effect of operational factors $P_e(t) = 0.09$. Thus, it can be said that the reliability of the ATM insulation is lower when exposed to operational factors and higher when exposed to design and production factors.
Fig. 1 The failure-free probability of traction motor components vs. the run:

\[ P_k(l) \] - design factors; \[ P_e(l) \] is the operational factors;

\[ P_r(l) \] - resulting reliability

The second option is the release of defective ATM to operation if \[ \lambda_k > \lambda_e \] (i.e. due to insufficient design quality and workmanship). Moreover, let us assume that the specifications are strictly observed in operation.

And the last, third option, if \( \lambda_\delta = \lambda_k = \lambda_e \), i.e. there are practically no cases of releasing the defective ATM to operation providing that the specifications for operation are met. This option is the most favorable, the reliability characteristics of the ATM correspond to the design \( \lambda_\delta \) that were specified in the design specifications.

Studies show that in practice the most likely option is the first, although the second and third options cannot be excluded. This can be explained by the fact that specialists with a high level of education and experience are engaged in the stages of designing the specifications, sketch design, detailed drawings, fabrication and finalization of the design of ATM.

Although the failure rate is regarded constant during the period of steady wear of ATM components, insulation aging occurs due to operational factors. Therefore, for \( \lambda_e \), it is necessary to take an average value, which is the arithmetic mean sum of the initial and final values.

The characteristic curves show how the failure rate can bias the ATM failure-free operation probability: with increasing \( \lambda_e \), the failure-free operation probability of motor components reduces. Then, at the design stage, for a specific value of \( P_f(t) \) (Fig. 1), the measure \( \lambda_e(t) \) (Fig. 2) can be determined. The in-service failure rate of insulation may depend on both external factors, such as temperature, humidity, vibration, etc., and internal factors, such as load, number of starts and stops, etc.
Of course, these factors increase the failure rate if the operating modes of the ATM can vary over wide ranges.

Calculations of the reliability parameters show that in the design and operation of ATM it is necessary to ensure that the failure rate asymptotically tends to zero. In this event, with the Poisson flow of failures, it can be assumed that the failure-free operation probability will be close to 0.98.

References

[1] Kashapov N F, Sabitov L S, Auhadeev A E, Litvienko R S and Gatiyatov I Z 2019 Description of a complex technical system of urban electric transport from the standpoint of synergistic methodology IOP Conference Series: Materials Science and Engineering. vol. 570(1). – 012040

[2] Kashapov N F, Sabitov L S, Litvinenko R S, Auhadeev A E and Gatiyatov I Z 2019 The approach to the study of the reliability of the electric transport system of the city as a complex technical system IOP Conference Series: Materials Science and Engineering. vol. 570(1). – 012043

[3] Sabitov L S, Gatiyatov I Z, Kashapov N F, Gilmanshin I R and Kiyamov I K 2018 Increase of reliability of contact networks of electric transport, due to increase of strength of the joint unit of pipes of different diameters IOP Conference Series: Materials Science and Engineering. Vol. 240, № 012058

[4] Hizbullin Rob and Hizbullin Rad 2019 Ways to improve safety in the power industry: an automated hardware complex for pre-shift inspection of personnel of power enterprises E3S Web of Conferences. vol. 124. – 05037

[5] Auhadeev A E, Litvinenko R S, Fandeev V P, Pavlov P P, Butakov V M and Litvinenko A R 2019 Research of reliability of urban electric transport system E3S Web of Conferences. vol. 124. – 05078

[6] Auhadeev A E, Idiyatullin R G, Pavlov P P, Butakov V M, Kisneeva L N and Tukhbatullina D I 2019 Improving the theory for calculating the rational modes of traction electrical equipment. E3S Web of Conferences. vol. 124. – 05077

[7] Nechiporenko V I 1977 Structural analysis of systems (Moscow. Sovetskoye radio) p 214

[8] Khafizov I I, Nurullin I G and Sadykov Z B 2018 Problems of development of electrochemical production of Russia and possibility of their decision IOP Conference Series: Materials Science and Engineering Vol. 412, Iss. 1, № 012042

[9] Biryukov V V and Porsc E G 2018 Traction electric drive (Moscow. Yurait) p. 315

[10] Idiyatullin R G 1987 Reliability of traction electric machines (Tashkent. MekhNAT) p. 152
[11] Kotelenets N F and Kuznetsov N L 1988 Tests and reliability of electric machines (Moscow. Vysshaya shkola) p. 232
[12] Barlow R and Proschan F 1984 Statistical Theory of Reliability and Reliability Tests (Moscow. Nauka) p. 326
[14] Popov A V, Idiyatullin R G and Aukhadeev A E 2016 Calculation method of reliability of winding of high-voltage asynchronous electric motors. Izvestiya vuzov. Problemy energetiki. No. 5-6. pp. 94-98
[13] Popov A V, Idiyatullin R G and Aukhadeev A E 2016 Experimental study of load modes of asynchronous electric motors under operating conditions. Energetika Tatarstana. No. 2 (42). pp. 76-79
[15] Pavlov P P, Fandeev V P, Aukhadeev A E, Litvinenko R S, Butakov V M 2019 Technique for optimization of diagnostic parameters composition for power systems objects IOP Conference Series: Materials Science and Engineering. vol. 643(1). - 012013.
[16] Filina O A and Tsvetkov A N 2019 Evaluation of the operational life of direct current motors IOP Conference Series: Materials science and engineering Vol. 489 № 012016
[17] Filina O A and Salmikova O.V. 2020 Construction of verification and diagnostic tests for the functional diagram of the object of diagnosis IOP Conference Series: Materials Science and Engineering. Vol. 747, № 012111
[18] Kashapov R N, Kashapov L N, Kashapov N F, 2017 Formation of cracks in the selective laser melting of objects from powdered stainless steel 17-4 PH IOP Conference Series: Materials Science and Engineering. Vol. 240, Is.1 № 012074