Research of options for maintaining the operability of the traction switched reluctance motors in emergencies

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Abstract.

The switched reluctance machines (SRM) in most cases of their application do not have a galvanic connection between the phase windings. It is widely known when one phase fails, SRM as a short circuit in the coil of one of the phases, the others continue to work. This gives you the ability to retain partial performance of the engine. This is especially important for transport systems: an electric car can drive to a depot on its own, and an electric car can drive to a service station. And for some transport systems, such as manned underwater vehicles, maintaining partial performance in emergency situations is a priority requirement-the life support of the crew depends on it.

For using a widely applied semi-bridge power supply scheme, the SRM with two transistors for each of the phases of the electric motor, it is not possible to maintain partial performance of the SRM if the only power source fails. To ensure the performance of the type, in the case of a short circuit in the source, a new power supply scheme for the SRM is proposed, containing one transistor for each of the phases of the engine (patent No. 2704494). Each phase is electrified charged from a separate source. For transport systems that have batteries in their composition, the total battery is divided into components by the number of phases. At the same time, the entire electrical circuit of the SRM phase, including the source, is backed up.

A simulation of the proposed new power supply circuit was performed in order to confirm its performance and evaluate its functionality. The analysis of the existing Converter circuits used for SRM is carried out, which allows to evaluate the advantages and disadvantages of the proposed circuit solution.

1. Introduction

The traction electric drives are used in a wide class of transport systems of the railway, automobile, surface and underwater transports. Electric drives are also used for transport robots.

The requirements for reliability and survivability of transport systems are usually high. Nevertheless, special requirements are placed on reliability and survivability. This means that movement in ultra-low or ultra-high temperatures in remote areas. This category also includes autonomous inhabited vehicles for servicing underwater communications, carrying out rescue and research work at various depths. To create such traction electric drives, it is advisable to use switched-reluctance electric machines (SRM) which have a simple design and high energy performance.
SRM cannot work independently, such as asynchronous motors, but only as part of an electric drive. The study of options for maintaining the operability of traction switched-reluctance drives (SRD) in emergency situations was carried out by analyzing the reliability of the functioning of the components of the entire electric drive. SRD consists of the following components: SRM; converter's, which in turn consists of a power part and a control system including a rotor position sensor; power source. An emergency here means a complete failure without the possibility of further use of the SRD. The possibility of an automatic (without human participation) conversion of a complete failure to a partial one, in which a SRD can be partially used with incomplete power, is being investigated. It does not address the obvious cases in which a faulty unit can be repaired on site or replaced with a new one.

SRM possesses design features, such as a winding-free rotor and concentrated stator windings without intersecting frontal parts, which makes it more reliable among the closest competitors.

As a power source in traction electric drives of autonomous vehicles, batteries or supercapacitors are often used, which are low-voltage elements connected in series until the required voltage level and energy supply are achieved. For example, a Tesla S battery has 2100x1500x150mm dimensions and a weight of 540kg, which is about 25% of the total weight of the car and consists of 16 blocks, each of which in turn consists of 74 elements. A large number of elements with an equal probability of failure, connected in sequence, form a system whose reliability may not correspond to what is desired. For this reason, for traction drives with increased requirements for reliability and survivability, the power source is duplicated or divided into several independent parts and is used in circuits that allow to maintain the partial operability of the traction drive in the event of failure of one of the parts of the power source.

2. The objectives of the investigation

The power part of the converter and the SRD control system have a fairly high degree of reliability, taking into account the current level of quality of semiconductor devices and microprocessor technology. However, there are still reserves for improving circuitry solutions to improve the reliability and survivability of SRD in emergency situations.

Currently, the most common circuit of the power part of the converter for powering the SRD phases is an asymmetric half-bridge circuit, which contains a source, two transistors and two reverse diodes, a capacitor that acts as a filter and an energy storage device for exchanging it with the winding through reverse diodes (fig. 1) [1-9].

![Figure 1. The power circuit diagram of an asymmetric converter in 3-phase design](image_url)

The main properties of the converter:
1. Provides greater flexibility in management, as the converter can realize the following circuits: positive - connecting the full voltage of the source to the phase winding, zero - gradually reducing the current and dissipating the energy stored in the phase on the internal resistance of the circuit elements, negative - applying the phase voltage with negative polarity to the motor winding and the energy...
conservation circuit — the energy conservation of the residual current of the phase winding in the capacitor or source for its further use at the next switching cycle [6].

2. All phases are connected to the source independently, and it is possible to disconnect the damaged phase without affecting the operation of the others.

3. The converter can be performed on any number of phases.

4. The converter can implement the motor and generator operating modes of the SRM.

The power part of the converter has two semiconductor switches for one phase SRM. To reduce the cost of the power part and increase the reliability of the SRD, the search for circuit solutions such that the number of power semiconductor switches for one phase of the SRM will be less than two, while maintaining the quality of operation, does not stop. By the number of switches per phase, the existing power part of the converters are divided into several groups [1-5]:

- single-switches converters: a converter with a power dissipating resistor [2-4, 6-9]; converter with bifilar winding [1-3, 6, 8-9]; converter with separation of the DC link [1-4, 6, 8-9]; converters with one switch and two diodes per phase with adjacent phases [2, 10] and with independent phases [2]. These power parts of the converters have a lower cost due to the use of a single switch, but do not satisfy several basic requirements for the effective operation of the SRD such as: independent operation of the phases, it is not possible to form all 4 operating modes of the circuits (positive, zero, negative circuits, energy conservation circuit), have low energy efficiency, and also some of them have a limit on the number of phases.

- converters with \((q + 1)\) switches for \(q\) phases: a converter with double demagnetization [2, 6]; a converter with a common switch for 2 phases [2, 4, 6, 8]; converter with storage capacitor - classic [1-5, 7-9, 11], modified [2, 4, 7, 12] (with storage capacitor and zero circuit), energy-efficient [12]; Miller Converter [1, 4-6]; a converter with a minimum number of switches and an increased input voltage [2]; a converter with a minimum number of switches and an increased pulse input voltage [2]; resonant converter (developed on the basis of a converter with a storage capacitor) [9]. These converters have one or several drawbacks compared to the circuit (fig 1): they do not provide independent operation of the phases, they do not implement one or several operating modes, they have voltages higher than the source voltage, they have a complex and not flexible control system, high torque ripples, long time dispersion and, consequently, low switching speeds, have generally lower efficiency and, often, quite high cost (due to the use of additional diodes, inductors, capacitors).

- converter with 1.5q switches for q phases and independent phase current control [2, 4, 13], provides independent control and allows you to implement all operation algorithms, but is suitable only for SRD with an even number of phases, some of the switches work for two phases, which increases the load on them and reduces the reliability of the drive.

According to the power section of the converter (fig. 1), the SRM phases receive power from a single source. This does not ensure the survivability of the entire electric drive system in case of failure of the power source (fig. 2a).
3. The solution of the problem

It is proposed to use SRD with a converter containing a smaller number of power switches and allowing full backup of all components of each phase, including power sources, as a traction drive for autonomous vehicles [14-15]. Full redundancy involves the creation of independent channels in phases, including the source. The batteries used in autonomous transport batteries can be divided into groups, each of which feeds a separate phase. Failure of one group of batteries, for example, with an internal circuit or other cause of loss of operability, will deenergize only one phase, and the rest will remain in operation. In the proposed technical solution, the operation of the SRD power supply circuit with one power switch (transistor) for switching each phase is illustrated in fig. 2b.

The single-switch circuit for powering the phase of the SRD [14-15] contains two sources $E_1$ and $E_2$, two capacitors $C_1$ and $C_2$, a reverse diode $V_{D1}$, a semiconductor switch $V_T$, and a phase winding divided into two half-windings $L_1$ and $L_2$ located on diametrically opposite teeth stator (fig. 3a). This single-switch scheme works when the parameters of the sources $E_1$ and $E_2$ are equal. If the sources $E_1$ and $E_2$ have unequal parameters, then diodes $V_{D1}$, $V_{D2}$ are used to exclude equalizing currents (fig. 3b). Using the proposed single-switch SRD phase power circuit, multi-phase SRD converters can be implemented, as shown in fig. 3c [15].
Figure 3 Single-switch scheme of the SRM converter:

a – with voltage sources having the same parameters;
b – with voltage sources having different parameters; c – three-phase design

The scheme (fig. 3b) allows the SRD to work according to the following algorithm. In the initial state, the $V_T$ switch is closed, the current in the half-windings $L_1$ and $L_2$ is zero, the capacitors $C_1$ and $C_2$ are charged. The $V_T$ switch open field through the half-windings $L_1$ and $L_2$ flows current – circuits $E_1 - V_{D1} - L_1 - V_T - L_1 - V_{D1} - C_1, E_2 - V_T - V_{D2} - L_2 - E_2, C_2 - V_T - V_{D2} - L_2 - C_2$. In this case, the electromagnetic energy is converted into mechanical energy in the SRD (the positive voltage circuits work). After closing the $V_T$ switch, the energy accumulated in the half-windings $L_1$ and $L_2$ charges the capacitors $C_1$ and $C_2$ – circuits $L_1 - C_2 - V_{D3} - V_{D1} - L_1, L_2 - V_{D3} - C_1 - V_{D2} - L_2$ (energy conservation circuits work). Next, the cycle repeats. When the $V_T$ switch is opened, the $V_D$ diode opens and a negative voltage is applied to the half windings of the phase (negative voltage circuits work).

The calculation of the operation parameters of the single-switch electric drive circuit was made using the example of the operation of one phase in different modes. For this, substitution schemes for the moments of opening (fig. 4a) and closing (fig. 4b) of the power semiconductor switch have been compiled.
According to Kirchhoff’s laws, the equations for 1-4 nodes (fig. 4a) and contours $E_1 - R_{01} - R_{C1} - C_1 - R_{d2} - E_1; E_1 - R_{01} - R_{d1} - R_1 - L_1 - R_4 - R_{d2} - E_1; E_2 - R_{02} - R_{d2} - R_{C2} - C_2 - E_2; E_2 - R_{02} - R_{d2} - R_2 - R_4 - R_2 - L_2$. After converting the obtained equations and reducing them to the Cauchy form, a system of equations is obtained for calculating the electromagnetic and electromechanical processes of the SRD when the transistor is opened. An expression for the electromagnetic moment has been added to this system of equations.

$$\frac{dU_{c1}}{dt} = \frac{E_1 - U_{c1} - i_{a1}R_{01} - i_{a1}R_{d2}}{C_1(R_{01} + R_{d2} + R_{C1})}$$

$$\frac{dU_{c2}}{dt} = \frac{E_2 - U_{c2} - i_{a2}R_{02} - i_{a2}R_{d2}}{C_2(R_{02} + R_{d2} + R_{C2})}$$

$$\frac{di_{a1}}{dt} = \frac{1}{L_g} \left( E_1 - i_{a1}(R_{01} + R_{d1} + R_1 + R_4 + R_{d2}) - C_1 \frac{dU_{c1}}{dt} \right) - \omega \frac{\partial i_{a1}}{\partial \theta}$$

$$\frac{di_{a2}}{dt} = \frac{1}{L_g} \left( E_2 - i_{a2}(R_{02} + R_{d2} + R_2 + R_4 + R_2) - C_2 \frac{dU_{c2}}{dt} \right) - \omega \frac{\partial i_{a2}}{\partial \theta}$$

$$\frac{d\omega}{dt} = \frac{1}{J} \left[ M_d - M_u - B_1 \omega \right]$$

Similar transformations are performed for the transistor closing mode. According to Kirchhoff’s laws, the equations for 1-6 nodes (fig. 4b), and for contours $E_1 - R_{01} - R_{C1} - C_1 - R_{d2} - E_1; L_1 - R_{C2} - C_2 - R_4 - R_{d1} - R_1 - L_1; E_2 - R_{02} - R_{d2} - R_{C2} - C_2 - E_2; L_2 - R_4 - R_{C1} - C_1 - R_{d2} - R_2 - L_2$. After the transformations, a system of equations is obtained:

Figure 4 SRM replacement Circuit with a single-switch converter circuit:

a – the semiconductor switch is open; b – the semiconductor switch is closed
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\begin{align*}
\frac{d U_{c1}}{dt} &= \frac{E_1 - U_{c1} + i_{a2} R_{o1} + i_{a2} R_{d2}}{C_1 | R_{o1} + R_{d2} + R_{c1} |} \\
\frac{d U_{c2}}{dt} &= \frac{E_2 - U_{c2} + i_{a1} R_{o2} + i_{a1} R_{d2}}{C_2 | R_{o2} + R_{d2} + R_{c2} |} \\
\frac{d i_{a2}}{dt} &= -\frac{1}{L_{g2}} \left( U_{c1} + C_1 \frac{d U_{c1}}{dt} R_{c1} + i_{a2} [ R_{d1} + R_{d2} ] + \omega \frac{\partial \psi [ i_{a2}, \theta ]}{\partial \theta} + i_{a1} R_{d} \right) \\
\frac{d i_{a1}}{dt} &= -\frac{1}{L_{g1}} \left( U_{c2} + C_2 \frac{d U_{c2}}{dt} R_{c2} + \omega \frac{\partial \psi [ i_{a1}, \theta ]}{\partial \theta} + i_{a1} [ R_{d1} + R_{d2} ] + i_{a2} R_{d} \right) \\
\frac{d \omega}{dt} &= -\frac{1}{J} [ M_d - M_n - B_i \omega ] \\
M_d &= \frac{\partial}{\partial \theta} \int_0^1 \psi [ i_{a1}, \theta ] \, di + \frac{\partial}{\partial \theta} \int_0^1 \psi [ i_{a2}, \theta ] \, di
\end{align*}
\]

To test the circuit's performance (fig. 3b), a simulated computer simulation of the SRD was performed using the MATLAB (Simulink) program for a 3kW electric motor. From the OrCad v17 program, the IGBT models of the IGW40N60DTP_L2 transistor and the Infineon IR2110 driver were imported into Simulink PSpice, the remaining components of the circuit were selected from the standard Simulink library. As a result of the simulation, the characteristics of the SRD are obtained, similar to the scheme of the power part of the asymmetric Converter (fig. 1). Thus, while maintaining the basic functionality of the most common circuit of the power part of the SRD Converter (fig. 1), the proposed scheme (fig. 3b) can be used for electric drives with full redundancy of each of the phases of the SRD, including the power source. At the same time, the number of semiconductor switches in the power part of the SRD will be reduced by half.

4. Conclusions

As a result of consideration of the various circuitry of the power part of the SRD and save health in emergency situations for cases where the reliability and survivability of SRD is the defining requirement, we can recommend the single-switch circuit power Converter circuit (fig. 3b). For this option, each phase of the SRM is powered from a separate power source, and the number of power semiconductor elements per phase is minimal. In this version of the circuit solution, the SRD phase combines only a common magnetic core and each of the phases can be disabled in an emergency without compromising the performance of the others.

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