Journal of Kryvyi Rih National University
Journal homepage: https://journal-knu.com.ua/en
Article's History: Received: 02.07.2025 Revised: 14.10.2025 Accepted: 24.12.2025 Published: 28.12.2025
Vol. 23, No. 2, 2025
ISSN 2306-5451
e-ISSN 2519-2736

UDC 621.313.333
DOI: 10.31721/2306-5451-2025-2-23-137-143

Prospects of applying switched reluctance drives with outer rotor in unmanned aerial vehicles

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Abstract. This work addressed the relevance of utilising a switched reluctance drive in unmanned aerial vehicle (UAV) designs. This approach aimed to enhance the reliability of the electric drive system and reduce its cost by eliminating expensive permanent magnets. The objective of this study was to compare various motor types as power drives for electric-powered UAVs. This comparison was based on key operational characteristics of the motors and their reliability levels. The stated goal was achieved using mathematical analysis methods and subsequently implementing the developed models in specialised software. The switched reluctance motor model is based on a magnetic field model of its magnetic system, which in turn relies on the integral equations method. The results of the mathematical modelling were used to generalise the potential applications of this type of drive for specific traction purposes. The paper presented a mathematical model of an external rotor switched reluctance motor designed within the dimensions of a standard brushless DC motor. This model was implemented in specialised software. The obtained characteristics of the developed motor satisfy the necessary requirements for drone propulsion system parameters. The proposed approach for evaluating the feasibility of using switched reluctance motors as traction drives in UAV systems, along with the analysis performed using the developed mathematical model, demonstrated the prospects of such a solution. The results obtained in this work can be used in the development of an alternative drone electric drive system based on reluctance machines without the use of permanent magnets

Keywords: electric-powered drones; operational characteristics; reluctance motors; alternative to permanent magnet motors

Introduction

Electric-powered unmanned aerial vehicles (UAVs) are rapidly developing and gaining popularity in various fields. These include aerial photography, scanning of the Earth's surface and geotechnical objects, monitoring of engineering structures, communications, transport routes, cargo transportation, military reconnaissance, search and rescue operations, territory surveillance, monitoring, and processing of agricultural land, among many others. For this reason, the development of a highly efficient and reliable UAV drive with

Suggested Citation:
Tytiuk, V., & Vlasenko, V. (2025). Prospects of applying switched reluctance drives with outer rotor in unmanned aerial vehicles. *Journal of Kryvyi Rih National University*, 23(2), 137-143. doi: 10.31721/2306-5451-2025-2-23-137-143.

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improved characteristics compared to current solutions is a pressing task.

In the field of aircraft drive applications, switched reluctance motors (SRMs) can fully compete with BLDC motors. SRMs offer the advantage of eliminating the need for neodymium magnets while retaining the core benefits of DC motors, which SRMs also possess. Numerous studies compare switched reluctance motors and brushless DC motors for diverse applications. For instance, between 2020 and 2025, the use of such motors for vehicles-cars, trams, scooters, etc. has been actively explored. For example, G. Watthewaduge & B. Bilgin (2023) presented work detailing the methodology and results of designing a switched reluctance motor for the NASA Maxwell X-57 aircraft drive. The paper reported high performance indicators based on calculated characteristics using a magnetic equivalent circuit. Y. Lan *et al*. (2021) noted the high potential of using SRMs for vehicle drives, provided relevant mathematical models, and investigated the design of a segmented motor for an automotive drive. S. Patil *et al*. (2023) conducted a study comparing various motor types, including SRMs, in laboratory conditions for use as an electric vehicle drive. The main drawback of known research is the lack of theoretical and practical results for external rotor SRMs, which presents a significant specific consideration for SRM use in UAVs. X. Sun *et al*. (2024) proposed product design optimisation methods centred around the product's intended application. These methods were based on the idea that product design should be tailored to the specific requirements of its intended use, rather than being optimised for a general set of specifications. This work presented an application-oriented design optimisation method for drive systems with SRMs, considering various operating modes. An example of an SRM applied in an electric vehicle and a UAV is discussed. For specific applications, additional optimisation concepts, such as multi-mode optimisation and correlation analysis regarding numerous motion cycles, were introduced.

Despite the fairly wide range of research on the application of switched reluctance motors in UAVs, the issue of external rotor SRM investigation, which is necessary for UAVs, is concluded to have not been sufficiently covered. The purpose of this work was to develop a mathematical model of external rotor switched reluctance motors as a UAV traction drive and to substantiate the possibility of ensuring the required operating characteristics.

Materials and Methods

Developing a mathematical model of an external rotor SRM involves several steps. First, the dependence of the phase inductance on the angular position of the external rotor is determined by analysing the electromagnetic fields in the cross-section of the SRM's magnetic system. For the investigation of the designed motor, the electromechanical processes were modelled using the methodology proposed by S. Tolmachov *et al*. (2010).

To study the electromagnetic field of the SRM's magnetic system, the integral equations method was used. This method was chosen due to its distinct advantages over others: limiting the calculation area to only the magnetic core, which significantly simplifies computation, and allowing for a relatively straightforward consideration of crucial magnetic system factors such as nonlinear anisotropy, vector hysteresis, magnetic viscosity, and more. A key design criterion for the reluctance motor in this study was adhering to the mass and size specifications of a permanent magnet BLDC motor, which served as the original benchmark. The reference BLDC motor was the T-Motor model MN3510-15, widely used in multicopter construction. The main characteristics of this motor are presented in Table 1.

Table 1. Characteristics of the permanent magnet brushless DC Motor MN3510-15

Rotor Type	External
Type Designation	3,510
KV Rating (RPM/Volt)	630
Configuration	12N14P
Stator Diameter	35 mm
Stator Stack Length	10 mm
Shaft Diameter	4 mm
Motor Casing Dimensions	41.8 mm × 28.5 mm
Supply Voltage	11.1 – 14.8 V
Max Continuous Current (3 min)	22 A
Max Continuous Power (3 min)	495 W
Internal Resistance	65 MOhm
Weight	97 g

Source: authors' development based on MN3510: Introduction of MN series (n.d.)

The development of the SRM mathematical model and the investigation of the dynamic properties of the external rotor SRM were performed using MATLAB/Simulink/Simscape/Electrical. Calculations of the electromagnetic fields using the integral equations method were implemented in MATLAB with the PDE Toolbox.

Results and Discussion

A number of technical requirements are imposed on UAV electric drives, which, according to M.E. Abdollahi *et al*. (2023), include high reliability, satisfactory mass-dimensional characteristics, high energy performance, and high-speed responsiveness in regulating rotational speed. Currently, the primary electric drive for UAVs is the synchronous motor with permanent magnets (BLDC, PMSM). However, the use of BLDC also has its drawbacks. The failure of even one phase in the converter leads to motor shutdown and causes the loss of the entire UAV. The application of permanent magnets in UAV drive motors introduced risk factors that negatively affect UAV reliability. For instance, high operating temperatures of the motor and current overloads reduce the service life of the magnets or even lead to their complete demagnetisation. Furthermore, the neodymium magnets used in brushless motors are expensive, which increases the overall cost of the motor.

Within the framework of developing switched reluctance electric drive systems for aircraft, the following range of tasks becomes relevant: field analysis of electromagnetic processes in switched reluctance machines; construction of mathematical models for reluctance electric drives, considering various factors under certain adopted assumptions; and experimental confirmation of the reliability of the developed mathematical models and proposed design solutions. Focusing on the geometric parameters presented in Table 1, a switched reluctance motor was developed in this work. The main characteristics of its magnetic system are presented in Table 2. The field distribution in the cross-section of the external rotor SRM is shown in Figure 1 in the form of flux lines.

Table 2. Characteristics of the Switched Reluctance Motor Magnetic System

Rotor Type	External
Number of Stator Poles	12
Number of Rotor Teeth	16
Stator Diameter	33.4 mm
Outer Rotor Diameter	42 mm
Air Gap	0.3 mm
Stator Stack Length	10 mm
Shaft Diameter	4 mm
Number of Turns per Stator Pole	40
Phase Resistance	0.5 Ohm
Maximum Continuous Power	500 W

Source: authors' development

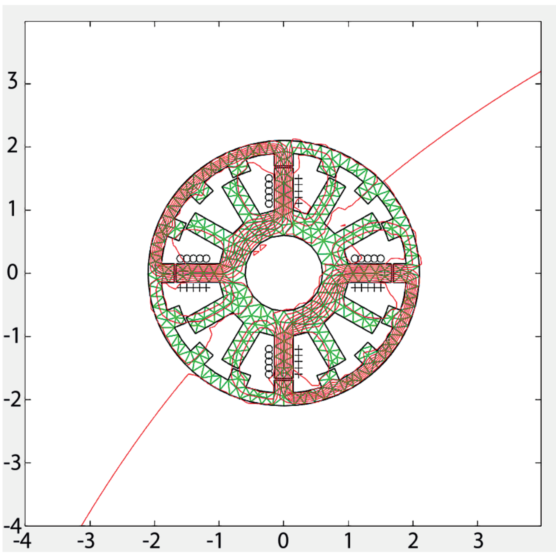

Figure 1. Electromagnetic field distribution in the motor's cross-section
Source: authors' development

Based on the field-oriented mathematical model, the phase inductance was calculated as a function of the rotor's angular position, which is presented in Figure 2. The calculation of phase inductance was performed according to the expression:

$$L = \frac{\Psi}{I} = \frac{2\Phi w}{I}, \quad (1)$$

where $\Phi = \int B dl$ – magnetic flux passing through the cross-section of the stator pole; B – magnetic induction in the cross-section of the stator pole; w – number of turns per phase; I – current value in the phase coil.

The calculated values of phase inductance were approximated by a Fourier series and are presented as an analytical relationship $L(\theta)$. This relationship was then used in the motor's mathematical model in the form of a system of differential equations:

$$\begin{cases} u_k = R_k i_k + L_k(\theta_k)\frac{d i_k}{dt} + \omega \frac{\partial L_k(\theta_k)}{\partial \theta_k} i_k \\ M_e = \sum_{k=1}^{m} \frac{\partial L_k(\theta_k)}{\partial \theta_k} \cdot \frac{{i_k}^2}{2} \\ \frac{d\omega}{dt} = \frac{1}{J} \cdot (M_e - M_c) \\ \frac{d\theta}{dt} = \omega, \end{cases} \quad (2)$$

where $k = 1 \ldots m$ – phase number; u_k, i_k – correspondingly, the voltage and current of the k-th phase; θ_k – angular position of the rotor relative to the k-th ph ase; R – Active resistance of the phase winding; M_c – static load torque; M_e – electromagnetic torque of the motor; J – moment of inertia; ω – angular rotational speed of the rotor.

It is worth noting that this system of equations, in its principle, corresponds to mathematical models presented by many researchers, notably V. Tkachuk (2006). The implemented mathematical model is shown in Figure 3.

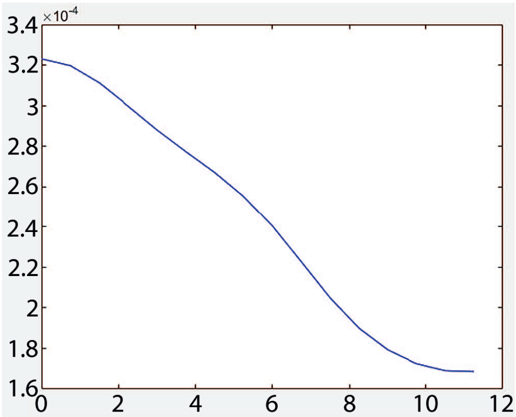

Figure 2. Phase inductance as a function of rotor angular position
source: authors' development

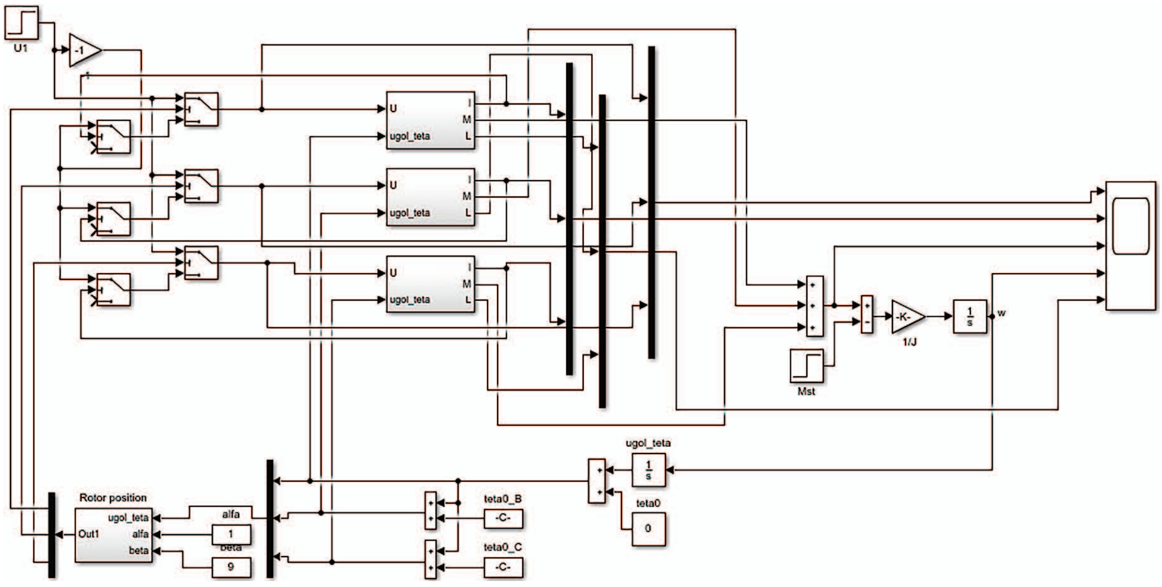

Figure 3. Structural diagram of the SRM mathematical model in the simulink matlab environment
Source: authors' development

The results of the motor's modelling process in steady-state operation are shown in Figure 4. The phase inductance corresponds to the graph calculated based on the field model (Fig. 2).

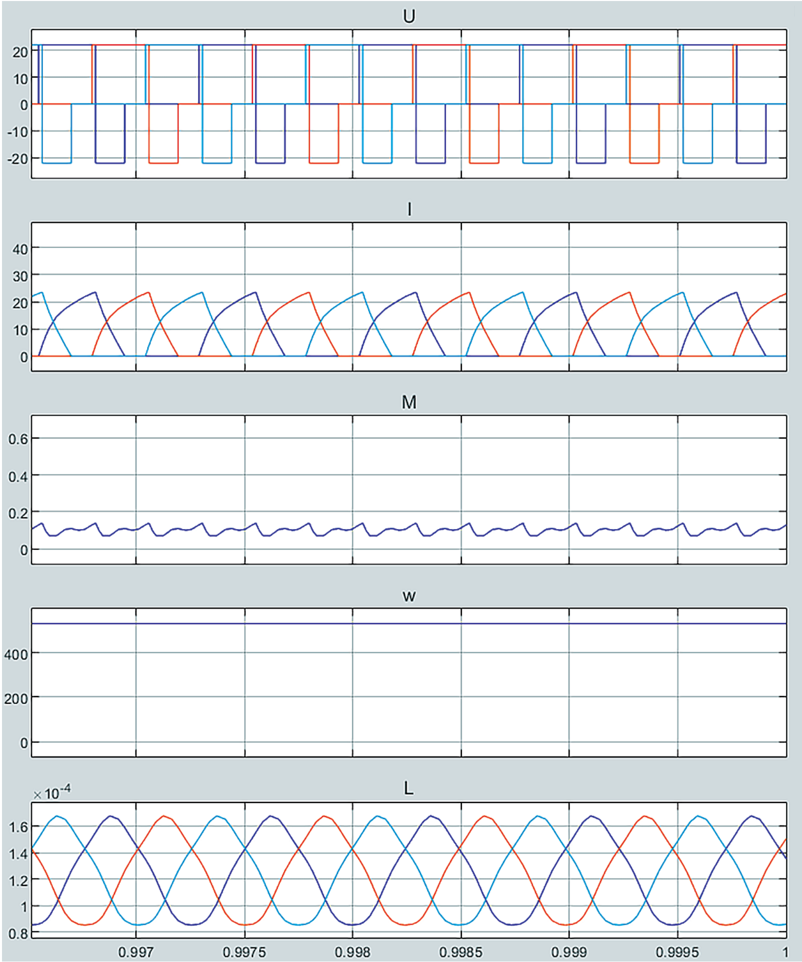

Figure 4. Diagrams of motor voltage, current, torque, angular speed, and inductance at a static load of 0.1 Nm
Source: authors' development

Using the developed SRM mathematical model in the form of a generalised electromechanical converter, the start-up and steady-state operating modes of the external rotor SRM were calculated. The electromagnetic torque developed by the motor exhibits a pulsating periodic nature with an average value equal to the static load torque. The currents in the motor phases are symmetrical, showing distinct rising and falling sections, which is characteristic of this power supply mode. The rotational speed of the motor rotor is stable at 530 rad/s, with minor pulsations.

Within the scope of this study, a mathematical model of an external rotor SRM was developed and analysed, corresponding to the mass-dimensional parameters of a permanent magnet BLDC motor. The obtained results confirm the feasibility of using SRMs in UAVs as an alternative traction drive. As recommended by R. Sehab *et al.* (2021), this study utilised a two-dimensional field model in the motor's cross-section. However, unlike in the aforementioned work, here an SRM was developed with mass-dimensional indicators matching the original BLDC widely used in UAVs.

The conducted analysis showed that the designed external rotor SRM fully conforms to existing solutions in terms of its dimensional parameters and can be integrated into existing UAV systems. The output power values correspond to the level of traditional BLDCs, confirming the expediency of using SRMs under similar operating conditions. The elimination of neodymium permanent magnets from the design contributes to reduced cost and increased operational reliability of the drive. These aspects were also emphasised in the work by H.K. Shashikiran (2015). The results of the mathematical modelling confirmed the stable operation of the motor with predictable torque fluctuations that do not critically impact UAV functionality at high rotational speeds. The simplified rotor design and the absence of elements sensitive to external factors ensure stable operation even under challenging operating conditions.

Therefore, this work proposed to enhance the reliability of FPV drones by replacing existing BLDC with an external rotor SRM. This SRM offers significantly better reliability indicators compared to BLDC motors, as well as lower cost and improved mass-dimensional characteristics.

Conclusions

In this work, based on the developed model, the feasibility of creating and practically using a SRM that can compete with permanent magnet BLDC motors has been demonstrated. This comparison was made based on the motors' mass-dimensional characteristics, while ensuring compliance with necessary operational parameters such as power level, rotational speed, and so forth. It is important to note that the designed SRM was built to the same dimensions as the original BLDC and features an identical external rotor design. These factors are crucial when seeking the closest possible analogue for replacement. As a result, it can be concluded that this switched reluctance type motor can be used as a drive for unmanned aerial vehicles, such as multicopters, in place of BLDCs. Future research should focus on thermal analysis in various motor operating modes, the development of a power phase commutation module, and a motor control system. These advancements are necessary to ensure a complete and integrated electric drive for UAVs.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Перспективи застосування вентильно-ідукторного привода із зовнішнім ротором в безпілотних літальних апаратах

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Анотація. Актуальність роботи полягає у перспективності використання вентильно-індукторного привода в конструкції безпілотних літальних апаратів задля підвищення надійності системи електропривода та його здешевлення шляхом виключення високовартісних постійних магнітів. Метою даного дослідження було порівняння різних типів двигунів в якості силового привода безпілотних літальних апаратів на електричній тязі. Порівняння виконувалось, базуючись на основних експлуатаційних характеристиках двигуна та рівня його надійності. Досягнення поставленої мети в роботі здійснювалось із використанням методів математичного аналізу з подальшою реалізацією розроблених моделей в середовищі спеціалізованого програмного забезпечення. В основі моделі вентильного-індукторного двигуна закладена модель поля його магнітної системи, що базується на методі інтегральних рівнянь. Результати математичного моделювання використані для узагальнення можливостей застосування даного типу привода як тягового певного призначення. В роботі приведена математична модель вентильно-індукторного двигуна із зовнішнім ротором в габаритах стандартного вентильного безколекторного двигуна, виконано її реалізацію в спеціалізованому програмному забезпечені. Отримані характеристики розробленого двигуна забезпечують необхідні вимоги, що висуваються до параметрів роботи приводних двигунів дронів. Запропонований підхід до оцінки можливості використання вентильно-індукторних двигунів як тягових в системах безпілотних літальних апаратів, а також виконаний аналіз із використанням розробленої математичної моделі демонструє перспективність такого рішення. Отримані в роботі результати можуть бути використані при розробці альтернативної системи електропривода дронів на основі індукторних машин без використання постійних магнітів

Ключові слова: дрони з електродвигунами; експлуатаційні характеристики; реактивні двигуни; альтернатива двигунам з постійними магнітами