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Y. Lee

Online detection of phase resistance of switched reluctance motor by sinusoidal signal injection

Introduction. *Switched reluctance motors (SRMs) are widely used in various applications due to their simplicity, robustness, and cost-effectiveness. However, the performance of SRMs can be significantly influenced by variations in their phase resistance, especially under high current and saturated conditions. Accurate knowledge of this parameter is crucial for optimal control and efficient operation.* ***Problem.*** *During operation, SRM parameters, particularly phase resistance, can vary considerably. These variations pose challenges to control strategies that rely on precise parameter values, leading to potential inefficiencies and degraded performance. There is a need for an effective method to monitor and identify these changes in real-time.* ***Goal.*** *This paper aims to develop and validate a method for the online detection and identification of phase resistance in SRMs. The method should work under varying operational conditions without requiring additional hardware, thereby maintaining the system's simplicity and cost-effectiveness.* ***Methodology.*** *The proposed method injects a sinusoidal signal into the inactive phase of the SRM using Sinusoidal Pulse Width Modulation (SPWM) via the main converter. The phasor method is then applied to determine the impedance of the phase circuit, from which the phase resistance can be identified. This approach eliminates the need for extra circuits, making it an efficient solution.* ***Results.*** *Simulations were conducted to evaluate the proposed method. The results demonstrate that the method can accurately track the variation in phase resistance under different operational conditions, validating its effectiveness.* ***Originality.*** *The originality of this work lies in its innovative use of the phasor method combined with SPWM for online phase resistance detection in SRMs, without the need for additional hardware components.* ***Practical value.*** *This method provides a practical solution for real-time phase resistance identification in SRMs, enhancing the reliability and performance of control strategies in various industrial applications.* References 17, table 1, figures 6.

Key words: **parameter identification, signal injection, switched reluctance motor.**

Вступ. *Вентильні реактивні двигуни (SRMs) широко використовуються в різних сферах завдяки своїй простоті, надійності та економічній ефективності. Однак на продуктивність SRMs можуть суттєво впливати зміни їх фазового опору, особливо в умовах сильного струму та насичення. Точне знання цього параметра має вирішальне значення для оптимального управління та ефективної роботи.* ***Проблема***. *Під час роботи параметри SRM, зокрема фазовий опір, можуть значно змінюватися. Ці зміни створюють проблеми для стратегій управління, які покладаються на точні значення параметрів, що призводить до потенційної неефективності та погіршення продуктивності. Існує необхідність ефективного методу моніторингу та ідентифікації цих змін у режимі реального часу.* ***Метою*** *статті є розробка та перевірка методу онлайн-виявлення та ідентифікації фазового опору у SRMs. Метод повинен працювати в різних робочих умовах без необхідності використання додаткового обладнання, тим самим зберігаючи простоту та економічну ефективність системи.* ***Методологія***. *Пропонований метод вводить синусоїдальний сигнал у неактивну фазу SRM за допомогою синусоїдальної широтно-імпульсної модуляції (SPWM) через головний перетворювач. Потім застосовується метод векторів визначення імпедансу фазового кола, з якого можна визначити опір фази. Такий підхід усуває потребу у додаткових колах, що робить його ефективним рішенням.* ***Результати***. *Для оцінки запропонованого методу було здійснено моделювання. Результати показують, що метод може точно відслідковувати зміну опору фази у різних робочих умовах, підтверджуючи його ефективність.* ***Оригінальність*** *цієї роботи полягає в інноваційному використанні методу векторів у поєднанні з SPWM для визначення опору фази в режимі реального часу SRMs без необхідності використання додаткових апаратних компонентів.* ***Практична цінність***. *Цей метод забезпечує практичне рішення для визначення опору фази SRMs в реальному часі, підвищуючи надійність і продуктивність стратегій управління в різних промислових застосуваннях.* Бібл. 17, табл. 1, рис. 6.

Ключові слова: **ідентифікація параметрів, подача сигналу, вентильний реактивний двигун.**

Introduction. In recent years, the switched reluctance motor (SRM) has experienced significant development and has become increasingly popular due to its robust structure and low cost, making it appealing for both industrial and domestic applications [1–3]. However, during motor operation, key parameters such as phase inductance and phase resistance can vary significantly. Parameters measured at standstill may differ from those when the motor is running, necessitating real-time identification of these values to ensure optimal performance [4, 5].

A neural network-based method for SRM parameter identification was proposed in [6–12], utilizing a more precise circuit model that includes an extra RL branch connected in parallel to account for saturation and losses. This method, however, requires complex modeling and does not directly address the need for real-time resistance identification without additional hardware.

Modulation techniques, such as phase and amplitude modulation, have been employed to detect rotor position without using encoders or Hall sensors [13–17]. These techniques leverage phase inductance information but assume constant phase resistance, requiring additional circuitry such as signal generators, amplifiers, and resistors, which add bulk and complexity to the motor drive. While effective, these methods are not ideal for applications where compactness and cost are critical concerns.

Purpose of the work. This paper proposes a novel method for detecting variations in the phase resistance of SRMs in real time. Unlike previous approaches, our method does not require additional hardware; instead, it utilizes the existing main converter to inject a small sinusoidal signal during the negative inductance slope region of the unenergized phase. By adjusting the signal frequency to make the inductive reactance comparable to the phase resistance, this method enhances the sensitivity of resistance detection.

Proposed online detection method of phase resistance of SRM. The phase resistance of a SRM is typically measured when the motor is not in operation. This is done by connecting the phase terminals to a dedicated instrument. After obtaining the phase resistance, the winding is disconnected from the instrument and reconnected to the main converter to drive the motor. Knowing the phase resistance is crucial for various applications, including calculating copper loss, determining flux linkage, and performing sensorless control. However, this offline measurement method cannot be applied while the motor is running. Moreover, the phase resistance may change significantly during operation, especially under high load conditions. Relying on the value measured at standstill may lead to inaccurate calculations, as the resistance might have varied. Therefore, it is essential to measure the phase resistance online.

To achieve online detection of the phase resistance, a low-amplitude sinusoidal voltage is injected into the inactive phase of the motor – meaning the phase that is not currently contributing to torque during the inductance falling region. The resulting small current in the inactive phase produces a minimal negative torque, which has negligible impact on the overall motor performance. Assuming that the self-inductance and resistance of the phase remain constant over a short period, the circuit model of a motor phase can be represented as a first-order RL circuit with an alternating voltage source, inductor, and resistor in series (Fig. 1).

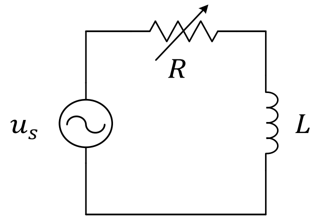

Fig. 1. One-phase model of SRM

The voltage equation for a single-phase circuit can be expressed as:

$$u(t) = Ri(t) + \mathrm{d}\psi/\mathrm{d}t\,, \qquad (1)$$

where u is the phase voltage; R is the phase resistance; i is the phase current; ψ is the flux linkage. Under unsaturated conditions, the flux linkage can be expressed as:

$$\psi(t) = Li(t)\,, \qquad (2)$$

where L is the phase self-inductance. Substituting (2) into (1), the voltage equation becomes:

$$u(t) = Ri(t) + L\frac{\mathrm{d}i}{\mathrm{d}t}\,. \qquad (3)$$

If a sinusoidal voltage is applied, it can be described as:

$$u_s(t) = \sqrt{2}U_s\cos\left(2\pi \cdot f \cdot t + \varphi_{u_s}\right), \qquad (4)$$

where U_s, f, φ_{us} are the RMS value, the frequency and the phase angle of u_s, respectively.

Since the voltage u_s is chosen as the reference, φ_{us} equals 0. It should be noted that, in practice, the actual voltage applied to the phase is a pulse width modulated voltage, whose effect is equivalent to that of the sinusoidal voltage described above. The resulting current in the circuit is expected to take the form:

$$i(t) = \sqrt{2}I\cos\left(2\pi \cdot f \cdot t + \varphi_i\right), \qquad (5)$$

where I and φ_i are the RMS value and phase angle of i, respectively.

The magnitude of the circuit's impedance Z is given by:

$$|Z| = U_s/I = \sqrt{R^2 + X_L^2}\,, \qquad (6)$$

where $X_L = 2\pi f L$ is the inductive reactance.

The phase resistance R can be determined as:

$$R = \sqrt{\frac{U_s^2}{I^2} - X_L^2}\,. \qquad (7)$$

Alternatively, the resistance can also be calculated using the impedance angle φ as follows:

$$R = |Z|\cos\varphi\,, \qquad (8)$$

where φ is the phase shift between the applied voltage and the resulting current.

It is important to note that the variable resistor in the circuit model (Fig. 1) indicates that the resistance may differ from the value measured at standstill, though it is assumed to be constant while solving the sinusoidal circuit. The response current in this time-invariant circuit will also take on a sinusoidal form.

As illustrated in Fig. 2, both the amplitude and angle of the impedance will change if the phase resistance varies during motor operation.

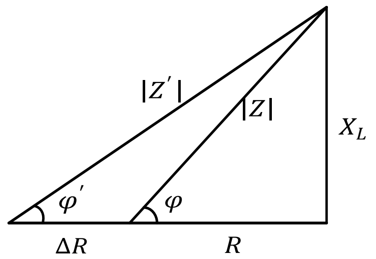

Fig. 2. Change in impedance due to variation in phase resistance

The phasor diagram of the circuit (Fig. 3) highlights that any change in phase resistance during motor operation will result in variations in the angle and amplitude of the response current vector.

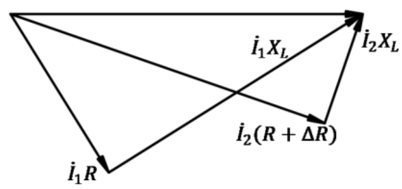

Fig. 3. Phasor diagram of the single-phase circuit

The sinusoidal voltage injection can be performed using the main converter. In this study, a full-bridge converter is employed to drive the SRM, as depicted in Fig. 4. This converter allows phase current to flow in both directions. The sinusoidal voltage is injected using Sinusoidal Pulse Width Modulation (SPWM) technique, where a bipolar triangle wave serves as the carrier wave and the desired sinusoidal voltage acts as the signal wave.

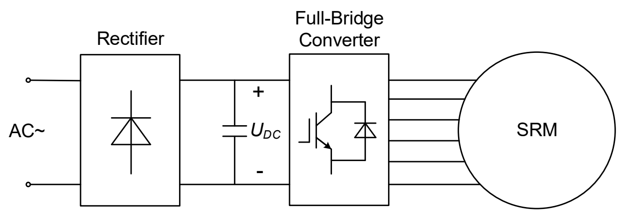

Fig. 4. SRM drive system utilizing a full-bridge converter

The selection of the sinusoidal voltage frequency is critical for the effectiveness of the proposed phase resistance detection method. The frequency must be high enough so that the phase self-inductance remains constant, thereby validating the simplified circuit model shown in Fig. 1. However, the frequency should also be chosen such that the inductive reactance is comparable to the phase resistance. This balance ensures that any variation in phase resistance results in a noticeable change in the phase and amplitude of the response current, leading to improved sensitivity in detecting phase resistance changes.

Simulation results and discussion. To validate the effectiveness of the proposed online phase resistance detection method for a SRM, simulations were conducted using MATLAB/Simulink. The motor used in the simulation is an outer rotor type SRM, with key dimensions provided in Table 1.

Table 1
Outer rotor SRM parameters

Parameters	Value
Number of phases	3
Pole combination	6/4
Stator outer radius	51 mm
Stator inner radius	20 mm
Stator yoke	15 mm
Stator pole arc	28°
Rotor outer radius	95 mm
Rotor inner radius	52 mm
Rotor yoke	15 mm
Rotor pole arc	32°
Stack length	50 mm
Turn number/pole	150

The motor operates at a low speed during the simulation. Once the tail current diminishes completely to zero, a 100 Hz SPWM voltage is injected into the phase during the negative inductance slope region. The reference signal for this injection is a 100 Hz sinusoidal wave with a RMS value of 5.55 V. Initially, the phase resistance is set at 2.56 Ω.

Before any change in resistance, the simulation results are depicted in Fig. 5. As expected in an inductive circuit, the response current lags behind the applied voltage. The current is small, with an RMS value around 1.15 A, producing only a negligible amount of negative torque. The rotor position is approximately 39°, where the inductance is around 6.5 mH. The resistance, calculated using (8), is found to be 2.57 Ω, which is within 1 % of the actual resistance value, demonstrating high accuracy.

When the phase resistance is doubled to 5.12 Ω, the simulation is repeated at the same rotor position of 39°. The results are shown in Fig. 6. Due to the unsaturated state of the circuit and the unchanged rotor position, the inductance remains constant at 6.5 mH. The impedance change is solely due to the increase in the resistive component. The figure reveals that the response current exhibits a smaller phase shift relative to the applied voltage and a reduced RMS value of approximately 0.85 A, compared to the previous simulation. This reduction in current amplitude indicates a change in phase resistance. The resistance calculated from (8) is 5.11 Ω, closely matching the actual resistance value.

These simulation results clearly demonstrate that the phase resistance information is effectively encoded in the sinusoidal response current. Consequently, the proposed method is capable of accurately extracting this information to detect and monitor variations in phase resistance in real-time.

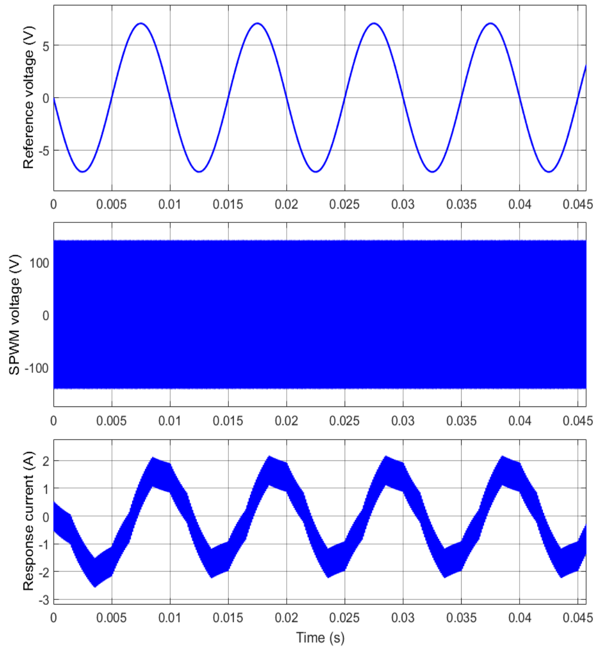

Fig. 5. Simulation results with the initial resistance

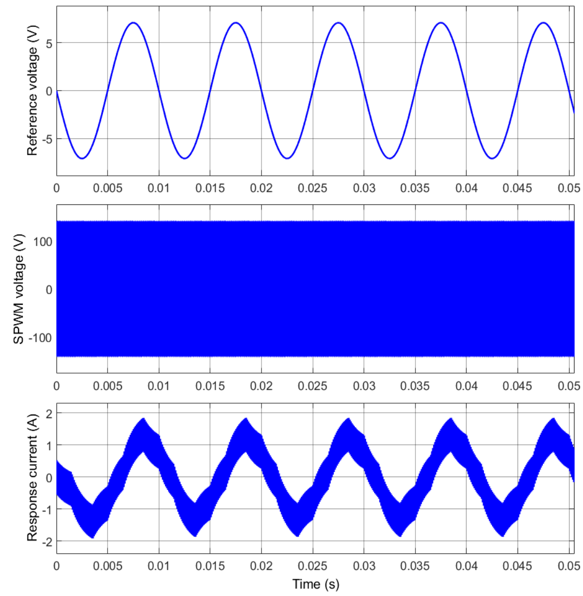

Fig. 6. Simulation results with the modified resistance

Conclusions. This paper presents a method for detecting phase resistance in switched reluctance motors (SRMs) using sinusoidal voltage injection via the main converter. Unlike conventional methods that require external instruments and can't monitor resistance changes during operation, this approach enables real-time detection, especially in high-current and saturated conditions.

By injecting a finely tuned sinusoidal-equivalent PWM voltage into the inactive phase, the method accurately identifies phase resistance through impedance or current analysis, without the need for additional circuitry.

Future prospects. Further research could focus on optimizing frequency tuning for greater detection accuracy under varying conditions and validating the method experimentally on physical SRM systems.

Additionally, integrating this detection method with advanced control strategies and expanding it to monitor other parameters like phase inductance could significantly enhance the performance and reliability of SRMs in industrial applications.

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Conflict of interest. The author declares no conflicts of interest.

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Yongkeun Lee[1], *PhD, Professor,*
[1] Seoul National University of Science and Technology,
Seoul 01811, South Korea,
e-mail: yklee@seoultech.ac.kr (Corresponding Author)

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