Switched Reluctance Motor Speed and Torque Control using ACO and PSO Algorithms

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Abstract: - A Switched Reluctance Machine (SRM) is an electric motor that operates based on the principle of magnetic reluctance. In addition, SRMs have several advantages over other types of electric motors. However, SRMs also have some disadvantages. They can produce high noise and vibration levels, especially at high speeds. This paper describes the torque and speed controller for SRM using two techniques, Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) combined with a PI corrector. The conventional PI controller is nowadays used in most engineering, being acknowledged for their ability to give up superior control in power electronic systems. Moreover, finding appropriate values for the PI controller is not easy. A solution based on ACO and PSO is used to overcome this problem and simplify tuning the PI controller parameters. Simulation in MATLAB-Simulink was used to demonstrate the effectiveness of the suggested controllers.

Key-Words: - SRM; Speed Controller; Torque Controller; Proportional-Integral (PI); ACO; PSO

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1 Introduction

Nowadays, the SRM has unique features like simple structure, high efficiency, high operating temperature, low cost, simple geometry, and high torque, [1]. As a result of its special features, the SRM has extreme multivariable, nonlinear coupling and ripples in torque, [2]. Recently, research on various aspects of SRMs has also become a hot spot. Overall, SRMs are a promising technology for electric vehicles, renewable energy, and other applications where high efficiency, low cost, and compact size are important factors, [3]. In fact, SRMs have several advantages over other types of electric motors. They are relatively simple in design and construction, with fewer parts compared to other motor types, [4]. This makes them potentially more cost-effective and easier to maintain. Additionally, they have a high power density, meaning that they can provide a lot of power in a relatively small package. They are also highly efficient, with low losses in the magnetic circuit. However, SRMs also have some disadvantages. They can produce high noise and vibration levels, especially at high speeds. They also have a limited speed range, making them less suitable for some applications that require a wide range of speeds, [5]. Ongoing research and development efforts are focused on improving the performance and reducing the limitations of SRMs to make them even more competitive with other motor types.

Many techniques have been proposed in the literature for torque ripple and speed control of SRM drives. However, a fuzzy logic technique is used for torque ripple in SRM, [6]. Another technique used an adaptive turn-on angle technique with direct instantaneous torque control to minimize the torque ripple is developed in, [7]. Also, for ideal speed control of switched reluctance motors, the traditional Proportional Integral (PI) controller is the most favored controller because of its effectiveness and simplicity in use. In addition. Engineers choose the Classical (PI) controller because of its dependability, structural simplicity, and the complementing relationship between price and performance, [8]. Moreover, some authors used Ant Colony Optimization (PSO) and Genetic Algorithm (GA) techniques for tuning the PID controller to reduce torque ripple and speed control in, [9], [10]. In, [11], Fuzzy logic and neural networks are used to reduce the error between the desired speed and true speed in SRM. Based on fuzzy logic, a highly efficient speed controlling of SRM is used in, [12]. Furthermore, the Ant Lion-based cascaded Fractional Order PID controller (FOPID) was designed to enhance the speed and torque profile of a 6/4 SRM drive, [13]. Additionally, an adaptive control algorithm for optimum turn-on and turn-off angles of SRM is proposed in, [14]. Other researchers, however, have used a simpler approach where numerous optimization techniques have been applied to PID controllers to achieve optimal speed and torque, [15]. Additionally, advanced control techniques, such as predictive or adaptive controls, have also been reported in the literature, [16]. In fact, an adaptive control algorithm for optimum turn-on and turn-off angles of SRM over a wide range of speed control is proposed in, [17]. The optimal turn-on and turn-off angles for minimizing the torque ripple in SRM have been described in, [18]. In, [19], a direct torque control based on the Lyapunov function was selected to minimize the torque ripples. In, [20], The innovative approach integrated machine design with control algorithms, enabling the profiling of phase currents to effectively minimize torque ripples in the SRM. However, another approach for torque optimization using a fuzzy adaptive controller and off-line Transfer sharing function is discussed respectively in, [21], [22]. A TSF-based controller is proposed in, [23], [24]. The TSF can achieve a minimized torque ripple with reduced copper losses by imposing optimal profiling for phase currents.

Due to the saturation, nonlinearity, and time-varying nature of switched reluctance motors, it is challenging to develop a precise current-torque relationship. So, the control strategy of a switched reluctance motor based on torque and current has certain limitations.

The aim of this work is to develop a new control of SRM for minimizing the torque ripple, less vibration, and mitigating the error between the desired speed and true speed. By addressing these aspects, the research aims to enhance the overall performance, efficiency, and reliability of the SRM in various practical applications. Thus, the statement indicates that the main objective of the ongoing research project is to create an innovative control. To evaluate the proposed controller by simulation, a specific SRM 8/6 model in MATLAB is adopted. Test results demonstrate the proposed controller's effectiveness, robustness, and accuracy when load torque and speed vary. In addition, according to the simulation, the proposed controller such as ACO-PI can minimize the torque ripple and the error between the desired speed and the true speed.

While I can offer insights on the potential impacts of research in power systems and optimization methods. Generally, the impact of my paper in these fields could be significant for various reasons:

- Advancements in Power Systems: Research findings in power systems often contribute to the development of more efficient, reliable, and sustainable energy solutions. Your paper's contributions may include improved control strategies for power systems, enhancing the stability, torque ripple, error and performance of various components within the system.
- Optimization Techniques: Modern optimization methods are crucial for enhancing the efficiency of complex systems. my paper findings might introduce novel approaches to optimize the performance of power systems, including the fine-tuning of control parameters and the improvement of overall system efficiency.

2 SRM Functioning and Mathematical Model

2.1 Mathematical Model of SRM

The Switched Reluctance Motor (SRM) is a type of synchronous electric motor that operates based on the principle of reluctance torque. Unlike other types of motors, SRMs do not have any windings on the rotor, which simplifies the construction and reduces the manufacturing cost. (As shown in Figure 1), [25]. Switched Reluctance Machines offer several advantages that make them suitable for various applications. In addition, these benefits include having a simple structure, robust, high efficiency, high-speed range, Silent Operation, and Regenerative Braking**.** The unique combination of these advantages makes SRMs a viable choice for various industrial and commercial applications, including electric vehicles, appliances, industrial automation, and more. Moreover, SRMs operate based on the principle of minimizing the reluctance of the magnetic circuit, leading to the rotor aligning itself with the stator poles. The stator and rotor are typically made of ferromagnetic materials, and the rotor has salient poles. By energizing the stator windings in a sequence, the rotor is compelled to rotate to minimize the reluctance. The direction of the torque can be changed by altering the phase sequence of the stator winding current.

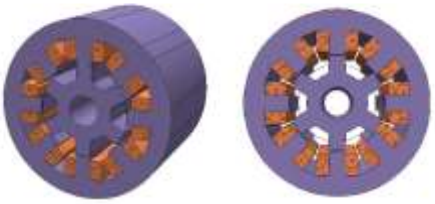

Fig. 1: 3D projection of 8/6 SRM obtained by FEM analysis.

The introduction noted that magnetic saturation is necessary to improve SRM performance. This can be achieved by expressing SRM parameters as functions of phase current and rotor position. By using the fundamental laws of dynamics and the usual electrical laws, one can develop the following dynamic system equation:

An equation for the voltage of a phase winding can be written as follows:

$$U(t) = Ri + \frac{d\varphi(\theta,i)}{dt} \tag{1}$$

Where R is the resistance per phase and φ is the flux linkage per phase given by:

$$\varphi(\theta,i) = L(\theta,i).i \tag{2}$$

Finally, the voltage equation is given by:

$$U(t) = \frac{di}{dt}\left(L(\theta,i) + i\frac{\partial L(\theta,i)}{\partial i}\right) + Ri + i\omega\frac{\partial L(\theta,i)}{\partial \theta} \tag{3}$$

Where: ω is the motor speed $(\mathrm{rad/s})$. And the equation of motion is as follows:

$$\mathrm{J} * \frac{\mathrm{d}\omega}{\mathrm{dt}} = \mathrm{T} - \mathrm{T}_{\mathrm{load}} - \mathrm{B}_{\mathrm{r}} * \omega \tag{4}$$

J is the rotor moment of inertia $(\mathrm{Kg.m}^2)$, $\mathrm{T}_{\mathrm{load}}$ is the torque of the load $(\mathrm{N.m})$, B_{r} is the rotor friction force $(\mathrm{N.m.s})$ and T is the motor torque $(\mathrm{N.m})$.

2.2 SRM's Mode of Operation

Switched reluctance motors are unique in that they do not have any permanent magnets, and their rotor is made up of steel or iron poles. The motor operates by energizing the stator windings in a specific sequence to create a magnetic field that attracts the rotor poles. As the rotor poles align with the stator poles, the magnetic field is then de-energized, and the rotor poles move to the next set of stator poles. This process is repeated continuously, causing the rotor to rotate. In fact, the SRM is another type of engine, this latter presents several advantages with respect to other engines. However, among these advantages low-power because this machine is functioned when we are excited each phase in depend on others. For this asymmetrical converter is used (as shown in Figure 2), [26]. An asymmetrical converter is a type of power converter that is commonly used to drive switched reluctance motors. The converter is designed to convert DC voltage into a form that can be used to drive the motor. The asymmetrical converter is designed to deliver the necessary power to the motor in a specific pattern to ensure optimal motor performance. The converter consists of several components, including diodes, capacitors, and transistors, that work together to regulate the voltage and current supplied to the motor. One of the key features of the asymmetrical converter is its ability to deliver a variable voltage and current to the motor. This allows the motor to operate at optimal efficiency and speed, depending on the load and other factors. In summary, an asymmetrical converter is a specialized power converter that is commonly used to drive switched reluctance motors. It is designed to deliver a variable voltage and current to the motor, allowing for optimal motor performance and efficiency. In addition, in this work, we are utilized a converter with 8 switches and 8 diodes to energize the 8/6 SRM. In addition, each phase is excited by three steps; excitation mode, freewheeling mode, and De-energizing mode.

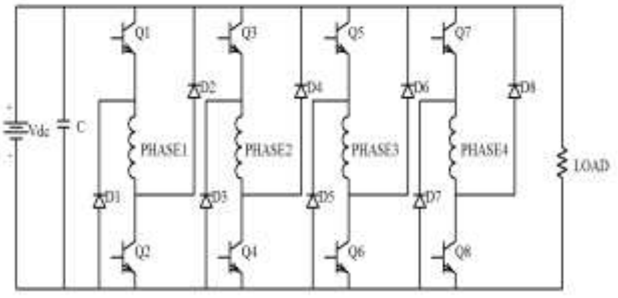

Fig. 2: Asymmetrical converter to feed SRM 8/6

Unlike the present boost converter, this converter has a few key differences. Based on the operating conditions of the SRM, the converter discussed here can calibrate the demagnetization voltage and excitation voltage.

3 Description of SRM Controller

3.1 Description of the ACO Algorithm

The Ant Colony Optimization (ACO) algorithm is a type of metaheuristics optimization algorithm that is inspired by the behavior of ants in finding the shortest path to a food source. ACO is a population-based algorithm that uses a collection of ants to explore the search space and find the optimal solution, [27]. In fact, the algorithm starts by initializing a population of artificial ants, which are used to search the solution space. Each ant moves through the solution space by selecting a candidate solution based on a probability function. The probability function is based on a combination of pheromone trails and heuristics, which guide the ants towards promising solutions. As the ants move through the solution space, they deposit pheromone trails that signal the quality of the solutions they have found. These pheromone trails are used by the other ants to guide their search, with ants more likely to select a path with a higher concentration of pheromones, [28]. Over time, the pheromone trails converge towards the optimal solution, as the ants favour the paths that lead to the best solutions. To prevent the algorithm from getting stuck in local optima, ACO uses a mechanism called pheromone evaporation. This mechanism reduces the concentration of pheromones over time, making it less likely for the ants to follow suboptimal paths. ACO has been successfully applied to a wide range of optimization problems, including the traveling salesman problem, the quadratic assignment problem, and the vehicle routing problem. The algorithm is known for its ability to find high-quality solutions in a reasonable amount of time, and for its ability to handle large and complex optimization problems. The steps of the proposed algorithm are summarized in Figure 3.

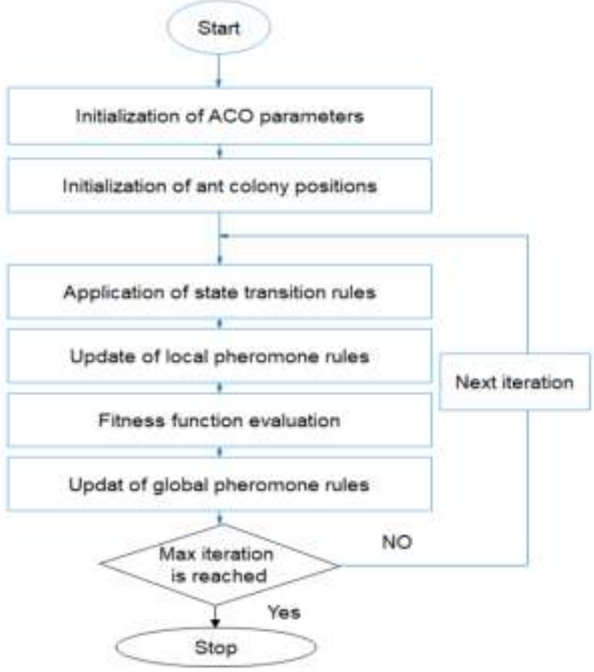

Fig. 3: Flowchart of ACO algorithm

3.2 Description of the PSO Algorithm

Particle Swarm Optimization (PSO) is a computational optimization technique inspired by social behavior, particularly the movement and behavior of bird flocks or fish schools. It is used to solve various optimization problems by simulating the social behavior of individuals, known as particles, within a search space, [29]. PSO's simplicity, ease of implementation, and ability to handle complex optimization problems have made it a popular choice for researchers and practitioners working on a wide range of optimization and search problems in diverse domains.

The PSO algorithm is based on the idea of a swarm of particles moving through the search space, where each particle represents a potential solution to the optimization problem. The position of each particle represents a candidate solution to the problem, and the velocity of the particle determines the direction and magnitude of its movement through the search space. During the optimization process, each particle updates its position and velocity based on the best solution found by itself and the swarm, [30]. This is done using two key components: the cognitive component and the social component. The cognitive component represents the particle's tendency to move towards its own best solution, while the social component represents the particle's tendency to move towards the best solution found by the swarm. The flow chart, shown in Figure 4, illustrates the steps involved in tuning a proportional integral derivative controller using a PSO.

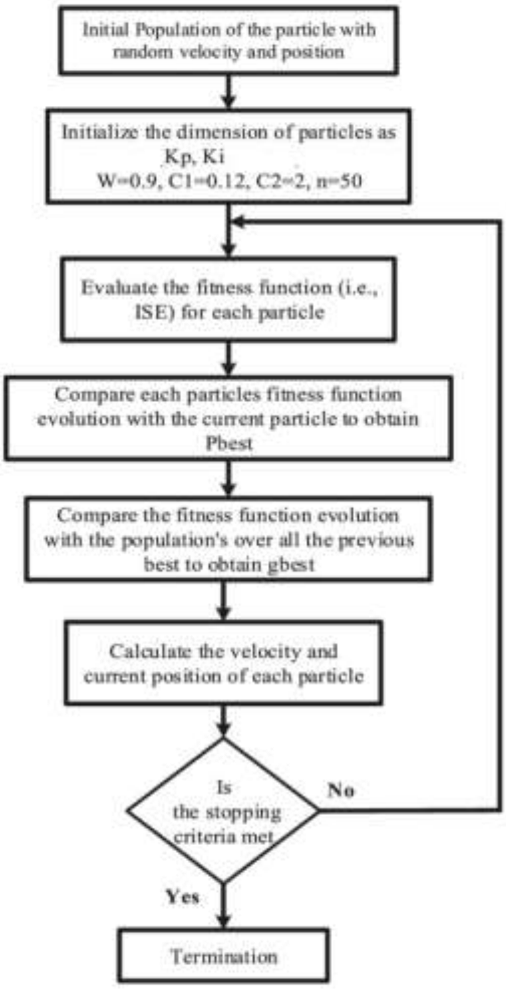

Fig. 4: Flowchart of PSO algorithm

4 Results and Simulation

To demonstrate the effectiveness of the proposed methods, examples of simulations are presented. In addition, the main problem with the PI corrector is to find the best parameters K_i and K_p. A solution based on ACO and PSO is used to overcome this problem and simplify the process of tuning the PI controller parameters for reduce the torque ripple and minimize the error between the desired speed and the true speed.

Figure 5, shows the diagram for controlling the SRM using closed-loop control. The controller parameters are optimized by PSO and ACO algorithms. This approach allows for the efficient fine-tuning of the controller's parameters, leading to improved system performance, stability, and responsiveness in achieving the desired control objectives. Firstly, the PSO or ACO methods generate initial values of two parameters K_p and K_i. after, each iteration, the proposed algorithms give the best values of parameters such as the minimum value of the objective function.

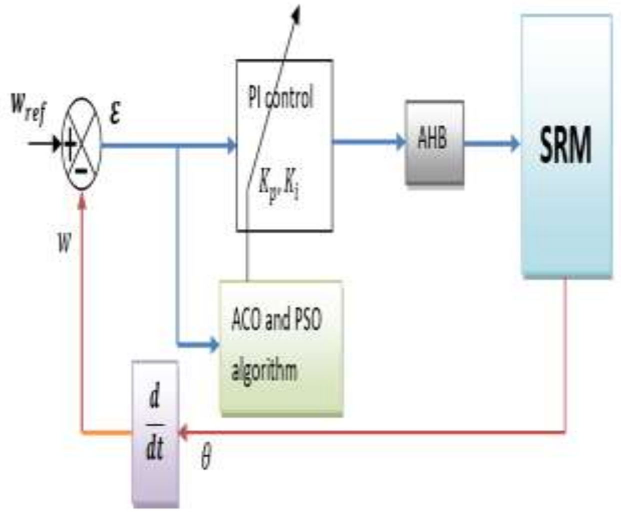

Fig. 5: SRM control via PI controller implementation in ACO and PSO

The proposed method is tested in several cases:

- **For variable speed**

The comparison is performed when the two controllers are applied to SRM 8/6 simulator. In Figure 6, the speed responses of the two controllers are shown when the reference speed is a signal that changes over time (from 2000 to 2500 rpm). As can be seen, both controllers achieve the reference speed, but the PI controller requires more time to stabilize, which warrants the significant overshoot. In addition, the control ACO presents fast convergent and also the best accuracy vs PSO algorithm.

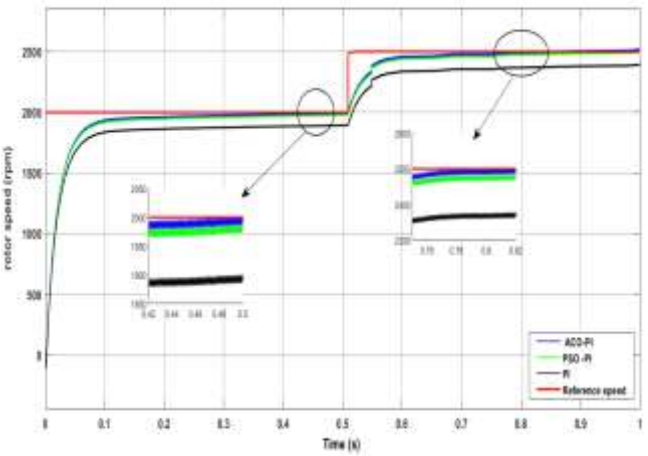

Fig. 6: Speed response using proposed controllers.

- **torque controller in variable speed**

The torque waveforms obtained by both controllers are shown in Figure 7. It is clear that the proposed controller reduces torque ripples, such as the ACO algorithm. In fact, in case of the speed is changed (at 0.5s) we observe the torque is changed, but one moment torque follows the load torque. Figure 7, justify that the control using ACO presents best accuracy and low ripple torque.

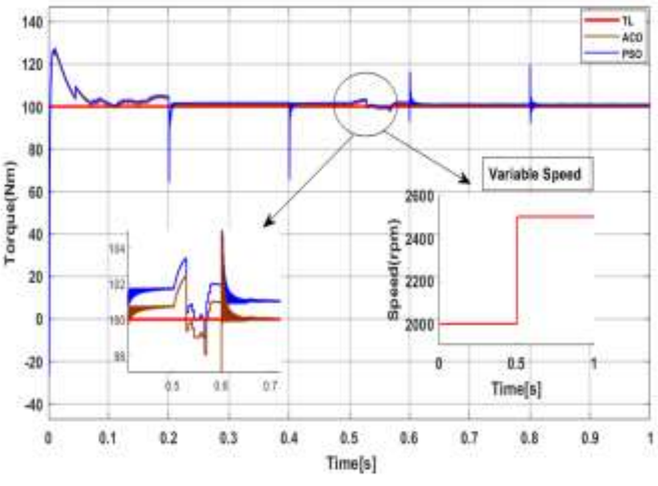

Fig. 7: Torque waveform of controllers for a 100Nm fixed loa

- **for load variable and speed constant**

In order to evaluate the robustness of the proposed controller, we applied a variable load torque with a constant speed of 2000rad/s. Figure 8 depicts the torque response when the load torque control law considered takes these values 100Nm and 150Nm. The proposed controller always maintains the speed to its reference despite variations in the load torque while guaranteeing minimum torque ripples, regardless of load torque variations. Moreover, the control using ACO gives good results at the level of accuracy and torque ripple.

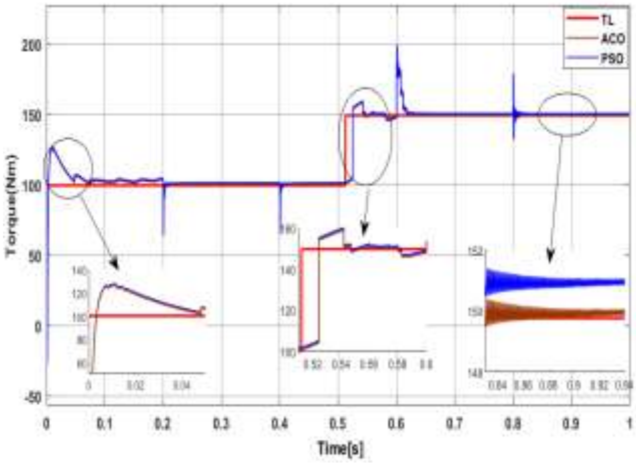

Fig. 8: Torque waveform of controllers for variable load

According to simulation results, even with a high torque value, the proposed controller efficiently regulates speed and reduces torque ripples. In summary, the statement emphasizes the positive findings of simulation results, highlighting the effectiveness of the proposed controller in achieving efficient speed regulation and reducing torque ripple, even in scenarios involving high torque values. This suggests the controller's suitability for applications where precise speed control and stable motor performance are essential, particularly in challenging operating conditions. Furthermore, its robustness to load torque changes is proven.

5 Conclusion

In this study, the torque and speed of SRM are controlled by a PI regulator with optimization algorithms ACO and PSO. In fact, finding appropriate values for the PI controller is not an easy task. A solution based on ACO and PSO is used to overcome this problem and simplify the process of tuning the PI controller parameters. This approach enables the study to optimize the performance of the PI controller for better control of the system, particularly in the context of managing the torque and speed of the SRM. The obtained results show that the proposed controller using ACO-PI given the best results in terms of torque ripples and speed tracking error. This finding suggests the effectiveness of the ACO-PI controller configuration in achieving better control and stability for the SRM in the context of the study.

References :

[1] A. Ouannou, A. Brouri, L. Kadi, Hafid Oubouaddi. Identification of switched reluctance machine using fuzzy model. *International Journal of System Assurance Engineering and Management*, 2022, vol. 13, no 6, p. 2833-2846

[2] H. Oubouaddi, A. Ouannou, L. Kadi and A. Brouri. Identification of switched reluctance machine inductance using artificial neuronal network. *2022 2nd International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET). IEEE*, 2022. p. 1-6. DOI: 10.1109/IRASET52964.2022.9737988

[3] Bostanci E, Moallem M, Parsapour A, Fahimi B. Opportunities and challenges of switched reluctance motor drives for electric propulsion: a comparative study. *IEEE Trans. Transportation Electrification* 2017;3(1):58–75.

[4] Diao, Kaikai, Sun, Xiaodong, Gerd Bramerdorfer, Yingfeng Cai, Gang Lei, Long Chen, Design optimization of switched reluctance machines for performance and reliability enhancements: A review. *Renewable and Sustainable Energy Reviews*, 2022, vol. 168, p. 112785. https://doi.org/10.1016/j.rser.2022.112785.

[5] Kadi, Laila, Brouri, Adil, Ouannou, Abdelmalek. Frequency-geometric identification of magnetization characteristics of switched reluctance machine. *Advances in Systems Science and Applications*, 2020, vol. 20, no 4, p. 11-26.

[6] M. Rodrigues, P.J. Costa Branco, W. Suemitsu, Fuzzy logic torque ripple reduction by turn-off angle compensation for switched reluctance motors, *IEEE Trans. Industrial Electronics*, 48 (2001) 711–715.

[7] Al Quraan Laith, Szamel Laszlo. Torque ripple reduction of switched reluctance motor using direct instantaneous torque control and adaptive turn-on technique for electric vehicle applications. *IET Electric Power Applications*, 2023.

[8] Ibrahim H.E-SA, Ahmed M.S.S., Awad K. M. Speed control of switched reluctance motor using genetic algorithm and ant colony based on optimizing PID controller. *ITM Web of Conferences*, vol. 16, 2018, p. 01001.

[9] Nimisha KK, Senthilkumar R. Optimal tuning of PID controller for switched reluctance motor speed control using particle swarm optimization. *2018 International Conference on Control, Power, Communication and Computing Technologies (ICCPCCT). IEEE*, 2018.

[10] Saha Nutan, Panda Sidhartha. Speed control with torque ripple reduction of switched reluctance motor by Hybrid Many Optimizing Liaison Gravitational Search technique. *Engineering science and technology, an international journal*, 2017, vol. 20, no 3, p. 909-921.

[11] H. Oubouaddi, A. Brouri and A. Ouannou, "Speed control of Switched Reluctance Machine using fuzzy controller and neural network," 2022 *International Conference on Intelligent Systems and Computer Vision (ISCV)*, 2022, pp. 1-6, DOI: 10.1109/ISCV54655.2022.9806121.

[12] Zhang C., Ming Z., Su Z., Cai Z.. An advanced robust method for speed control of switched reluctance motor. *Rev Sci Instrum* 2018;89.

[13] Prasad ES, Ram BVS. Ant-lion optimizer algorithm based FOPID controller for speed control and torque ripple minimization of SRM drive system. *2016 International Conference on Signal Processing, Communication, Power and Embedded System (SCOPES). IEEE*, 2016.

[14] M. Hamouda, and L. Szamel, (2017). Optimum excitation angles for switched reluctance motor drives. *XXXIII. Kando Conference*, Obudai University, 128–142.

[15] Ibrahim HE-SA, Ahmed MSS, Awad KM. Speed control of switched reluctance motor using genetic algorithm and ant colony based on optimizing PID controller. *ITM Web of Conferences*, vol. 16, 2018, p. 01001.

[16] Wang J.. Speed-assigned position tracking control of SRM with adaptive backstepping control. *IEEE/CAA Journal of Automatica Sinica,* Vol.5, Issue: 6, November 2018. https://doi.org/10.1109/JAS.2016.7510019.

[17] Hamouda M., Számel László. Optimum excitation angles for switched reluctance motor drives. *XXXIII. Kando Conference*. 2017. pp.128-142.

[18] Hannoun, H.; Hilairet, M.; Marchand, C. Design of an SRM speed control strategy for a wide range of operating speeds. *IEEE Trans. Industrial Electronics,* 2010, 57, 2911–2921.

[19] Sahoo, S.K.; Dasgupta, S.; Panda, S.K.; Xu, J. A Lyapunov function based robust direct torque controller for a switched reluctance motor drive system. *IEEE Trans. Power Electronics,* 2012, 27, 555–564.

[20] Shaked, N.T.; Rabinovici, R. New procedures for minimizing the torque ripple in switched reluctance motors by optimizing the phase-current profile. *IEEE Trans. Magnetics,* 2005, 41, 1184–1192.

[21] Masoudi, S., Soltanpour, M.R., and Abdollahi, H. (2018). Adaptive fuzzy control method for a linear switched reluctance motor. *IET Electr. Power Appl.*, 12(9), 1328-1336.

[22] J. Ye, B. Bilgin, and A. Emadi, ‘‘An offline torque sharing function for torque ripple reduction in switched reluctance motor drives,’’ *IEEE Trans. Energy Convers.*, vol. 30, no. 2, pp. 726–735, Jun. 2015.

[23] Li, H.; Bilgin, B.; Emadi, A. An Improved Torque Sharing Function for Torque Ripple Reduction in Switched Reluctance Machines. *IEEE Trans. Power Electron*. 2019, 34, 1635–1644.

[24] Li, C.; Zhang, C.; Liu, J.; Bian, D. A High-Performance Indirect Torque Control Strategy for Switched Reluctance Motor Drives. *Math. Probl*. Eng. 2021, 2021, 1–15.

[25] A. Brouri, L. Kadi, A. Tounzi, A. Ouannou, J. Bouchnaif, Modelling and identification of switched reluctance machine inductance. *Australian Journal of Electrical and Electronics Engineering*, 2021, vol. 18, no 1, p. 8-20.

[26] Samia M. Mahmoud, Mohsen Z. El-Sherif, and Emad S. Abdel-Al. Studying different types of power converters fed switched reluctance motor. *International Journal of Electronics and Electrical Engineering*, 2013, vol. 1, no 4, p. 281-290.

[27] Dorigo Marco, Stützle Thomas. Ant colony optimization: overview and recent advances. *Springer International Publishing*, 2019.

[28] Dorigo Marco, Blum Christian. Ant colony optimization theory: *A survey. Theoretical computer science*, 2005, vol. 344, no 2-3, p. 243-278.

[29] Jiang Yan, Hu Tiesong, Huang Chong Chao, Xianing Wu. An improved particle swarm optimization algorithm. *Applied Mathematics and Computation*, 2007, vol. 193, no 1, p. 231-239.

[30] Zhou, Fei Hong et Liao, Zi Zhen. A particle swarm optimization algorithm. *Applied*

Mechanics and Materials. Trans Tech Publications Ltd, 2013. p. 1369-1372.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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