Intelligent Control and Automation, 2026, 17(1), 1-18
https://www.scirp.org/journal/ica
ISSN Online: 2153-0661
ISSN Print: 2153-0653

Optimizing Star-Delta Starter Transitions for Induction Motors with Particle Swarm Algorithm

Jacob Owusu Ansah[1], Ernest Smith Mawuli[2*], Enoch Boateng Adomako[2]

[1]Department of Electrical and Electronic Engineering, Faculty of Engineering, Sunyani Technical University, Sunyani, Ghana
[2]Department of Electrical and Electronic Engineering, Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED), Kumasi, Ghana
Email: *esmawuli@aamusted.edu.gh

How to cite this paper: Ansah, J.O., Mawuli, E.S. and Adomako, E.B. (2026) Optimizing Star-Delta Starter Transitions for Induction Motors with Particle Swarm Algorithm. *Intelligent Control and Automation*, **17**, 1-18.
https://doi.org/10.4236/ica.2026.171001

Received: October 30, 2025
Accepted: December 19, 2025
Published: December 22, 2025

Abstract

Induction motors are widely employed in industrial applications due to their robustness, speed consistency, and cost efficiency. However, during startup, they draw a high inrush current that distorts electromagnetic torque and speed, causing overheating, prolonged transient periods, and noise. To address this, the closed transition star-delta starter (CTSDS) is often used as a baseline technique. This study proposes a Modified Particle Swarm Optimization (MPSO) algorithm to enhance CTSDS performance by optimally determining the transition parameters that minimize starting current and transient duration. A MATLAB/Simulink model was developed to analyze motor behavior under transient conditions, evaluating speed, torque, voltage, and current characteristics. The MPSO-based method was compared with conventional CTSDS and timer-based (TB) transition schemes. Results show that the proposed MPSO approach achieves 5.3 sec in settling time with only 0.4% voltage overshoot, outperforming TB (9.16 sec settling time, 30% overshoot) and CTSDS (21 sec settling time, 129.82% overshoot). The findings demonstrate that the MPSO-controlled starter enables faster and smoother transitions with significantly reduced switching transients and inrush currents, making it an efficient alternative for induction motor control systems.

Keywords

Closed Transition Star-Delta Starter, Induction Motor,
Switching Transient Time, Particle Swarm Optimization Algorithm,
Starting Current

1. Introduction

The starting behaviour of induction motors is very crucial to their performance, as it impacts not only their lifespan but also the power quality. During start-up, induction motors draw a high starting current, which affects electromagnetic torque and speed [1] [2]. When induction motors are started, high current surges cause disturbances in the supply voltage. To mitigate this problem, star-delta and autotransformer starting methods are employed to regulate the starting voltage [3]. While the autotransformer starter is suitable for high-voltage motors, the star-delta starter is the opposite, utilizing transformer taps to lower the supply voltage. However, the disadvantages of this solution are reduced torque, a long transition period, and a lack of speed control [4] [5]. Concerning the star–delta starter, it has the drawback of causing long transients and high vibration during the switchover. This causes damage to the induction motor and increases maintenance costs. A more advanced starting control method, such as a closed transition star-delta starter (CTSDS), offers a smooth transition without transient effects. However, its effectiveness depends on factors like motor size, load characteristics, and control parameters [6]. When it operates, the large initial current requires further investigation for optimal control of the induction motor. This could be reduced by optimizing the motor stator windings using a star-connection configuration [6]. To achieve this, the star and delta connection to a motor can be reconfigured to obtain voltage tolerance, as the delta-star and star-delta configurations of the stator winding connection reveal varying performance in phase voltage and current imbalance [3]-[6]. In related development, the core saturation difference between winding connections in the delta and star stators using reconfigurable induction motors at different saturation levels has been analyzed to be effective [5]. In support of this, a stator winding that supports both delta and star connections was developed [6] and also introduced to facilitate magnetizing flux adjustment and a soft-starting method for motors [1]-[7]. Additionally, a rapid acceleration technique for an inter-winding machine drive system [8] was reported to enhance the starting torque by introducing the delta star switching process, yet it induces a high inrush current. These developments over the years have made the Star-Delta starters for induction motors increasingly vital in the industrial sectors. To automate the starting technique, automatic star-delta, also known as soft starting, was introduced [3]-[9]. Nevertheless, controlling the high transient and starting current has remained a challenge. Therefore, it has necessitated a paradigm shift, where the optimisation of starting techniques has become crucial to achieve optimal conditions for induction motor control strategies, thereby enhancing performance, improving energy efficiency, and reducing losses. This involves the particle moving along the path of the current optimum particle. For instance, the Particle Swarm Optimisation (PSO) technique has been reported for estimating real-time motor resistance and inductance [10], as well as its utilisation in identifying parameters of a double-cage induction motor [11]. The integrated PSO with a sensor fault detection and diagnosis algorithm demonstrates that this combined approach enhances the accuracy of parameter estimation in the presence of sensor faults. However, the reported technique demonstrated its effectiveness in accurately estimating the parameters of an induction motor model. A hybrid algorithm that combines PSO with a fuzzy clustering algorithm was proposed for estimating the speed, torque, and starting current of an induction motor model [12]. The authors demonstrated that their proposed method outperformed traditional PSO algorithms in terms of accuracy and convergence speed. Hence, a modified PSO algorithm was proposed for parameter estimation of an induction motor model in the presence of uncertainties [12] [13]. The authors incorporated the PSO algorithm to account for uncertainties in the model parameters and showed that the proposed method improved the robustness of parameter estimation. In the same vein, a multi-objective PSO algorithm was developed for parameter estimation of an induction motor model [14]. The parameter estimation problem was formulated as a multi-objective optimisation problem, and the PSO algorithm was employed to search for Pareto-optimal solutions. This method illustrated better trade-offs between accuracy and convergence speed compared to single-objective PSO algorithms. To account for noise, a PSO technique for parameter estimation of an induction motor model was presented [15]. The authors proposed a noise-assisted PSO algorithm that incorporated a noise term into the velocity update equation of the PSO algorithm and demonstrated that their method improved the accuracy of parameter estimation in the presence of noise. Regarding the rotor flux and torque, a PSO was used to optimise the fuzzy logic controller for an induction motor drive [12]-[16]. Concerning motor speed and voltage control, the PSO technique has been reported to achieve appreciable speed control by adjusting the voltage and frequency of the motor [10]. The proposed technique resulted in an improved speed control performance with reduced overshoot and settling time, indicating the effectiveness of PSO for optimising the speed control of induction motors. In addition to speed control, PSO has been used to optimise the torque performance of induction motors. Reducing the stator current of an induction motor by adjusting the voltage and current levels has also been reported [2]. The results illustrated an improved torque performance with reduced harmonic distortions in the stator current, demonstrating the potential of PSO for optimising the torque characteristics of induction motors. Furthermore, PSO has been used to analyse the starting performance of the AC voltage controller-fed induction motor drive to investigate an optimum firing angle for the AC voltage controller [17]. Regarding motor current evaluation, a PSO-based defect diagnostic method for induction motors was presented [10]-[15]. In the report, the control of induction motors involves optimising multiple objectives, such as improving speed, energy efficiency, reducing losses, and achieving desired performance characteristics. Multi-objective optimisation techniques have gained significant attention due to their ability to handle multiple conflicting objectives simultaneously. A PSO-based approach for optimising both torque and efficiency of an induction motor, where the PSO algorithm was used to search for the optimal values of motor parameters [11]-[18].

In addition to standard PSO, researchers have also proposed various improved variants of PSO for multi-objective optimisation in induction motor control [19] [20]. A modified PSO (MPSO) algorithm with an improved update equation for controlling the stator current of an induction motor [17]. The results showed that the MPSO algorithm achieved better convergence performance compared with standard PSO, though PSO algorithms is suited for motor control optimization due to its ability to efficiently search complex, non-linear spaces and handle multiple local optima, common in motor control problems, while also being relatively simple to implement and computationally efficient compared to other algorithms like genetic algorithms and ant colony optimization. Consequently, literature review revealed that PSO has been extensively utilized for various applications in induction motor control, including parameter estimation, control strategy optimisation, fault diagnosis, and multi-objective optimisation. However, MPSO has shown promising results in improving motor performance, energy efficiency, and fault tolerance compared with PSO, but has not been used to investigate transient characteristics. Besides, despite the numerous advantages of star-delta starters over the other starting methods, not much work has been done in optimizing the switching transition of these starters. Therefore, this study examines the switching characteristics of CTSDS and develops an optimal motor starter capable of minimising switching transients, such as starting current and voltage, transition period, vibration, and motor torque, using the MPSO algorithms.

The proposed MPSO algorithm is capable of minimizing the high-starting current and high-switching transient, and it eventually improves the overall performance of the induction motor. To achieve these objectives the MPSO has been used to: 1) estimate the motor parameters of an induction motor, 2) model the transient period characteristics of the star-delta starting method of an induction motor using MATLAB/Simulink model, 3) optimize the CTSDS method of an induction motor, 4) conduct a performance analysis with other methods to evaluate the robustness of the proposed method.

The study is organized into four sections. The introduction captures the study background, which includes the research problem and the proposed innovative solution. Following the introduction is the presentation of the proposed model, the main objective and the flow chart of the design procedure. The conceptualization of the proposed method and modelling of the novel technique that yielded outstanding results are also presented. Comparative analysis and discussion of the proposed method and results have been discussed, as well as the main contribution of this study to knowledge. Finally, a summary of the research results, a conclusion and recommendations are presented.

The innovations of this paper are:

- Reduced starting current and torque transients.

- Improved motor performance and lifespan.
- Optimized transition strategies via MPSO.

2. Method

2.1. The Proposed Model Design

This section presents the MPSO model for minimising transient problems of induction motors. The proposed MPSO is an optimised starting technique implemented in the MATLAB/SIMULINK model simulation interface. The proposed model seeks to reduce switching transient duration and its associated problems, which impact the performance of induction motors.

2.1.1. The Main Objective

The optimization aims to minimize the transition period (T) and starting current I_{start} of a closed transition star-delta starter (CTSDS) for a three-phase squirrel cage induction motor, while maintaining vibration (V) within acceptable limits. The decision variables are the time parameters governing the switching sequence:

t_{sd}: duration in star configuration before transition,

t_{star}: delay time of the star contactor, and

t_{δ}: delay time of the delta contactor.

The objective function is expressed as:

$$\text{Minimize}: Obj = w_1 T + w_2 I_{start} \tag{1}$$

Subject to the following constraints:

$$P_{motor} = \sqrt{3} V_{rated} I_{start} \cos\phi = 9.25\ \text{kW} \tag{2}$$

$$T = t_{sd} + t_{star} + t_{\delta} \leq 0.04\ \text{s} \tag{3}$$

$$V \leq 0.05\ \text{mm/s} \tag{4}$$

where, w_1 and w_2 are the weighting factors that define the trade-off between transition period and starting current reduction. The Modified Particle Swarm Optimization (MPSO) algorithm is used to determine the optimal set of decision variables satisfying these conditions.

2.1.2. The Design Process

The design process of the proposed model follows the flow chart illustrated in Figure 1. The process algorithm is simple to follow, hence reducing all complexity. The design process starts with the preliminary analysis of the specifications of the squirrel cage induction motor (SCIM), which aims to initialise the model parameters. The system then generates ‘N’ number of the population, in accordance with the objective function to obtain an optimal solution in terms of minimal vibration, low starting current and rapid closed transition period from the generated population.

The functional algorithm for the MPSO can therefore be developed for an efficient and optimal star-delta starting and switchover scheme by following the methodological constraints illustrated in Figure 1.

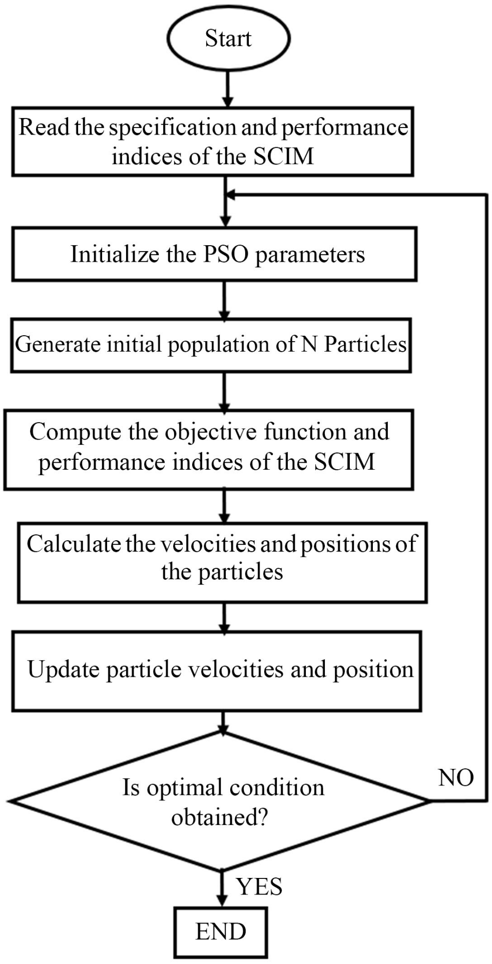

Figure 1. Flow chart of the proposed MPSO technique.

Step 1: Initialize the PSO parameters:

- Set the number of particles (agents) in the swarm, N.
- Set the maximum number of iterations, Max_{iter}.
- Set the inertia weight, w.
- Set the acceleration constants, c_1 and c_2.
- Initialize the position and velocity of each particle randomly within the search space.
- Set the initial best position P_{best} and the best fitness value $P_{best_{fitness}}$ for each particle, the current position and its corresponding fitness value.
- Set the global best position g_{best} and the best fitness value $g_{best_{fitness}}$ as the best position and fitness value among all particles.

Step 2: Define the fitness function:

- Calculate the fitness value of each particle based on the performance of the closed transition star delta starter using appropriate performance metrics, such as the time taken to complete the transition, the efficiency of the transition, and vibration.

MPSO: For each particle, compute the fitness using the combined objective function:

$$\text{Min}: Obj = w_1 T + w_2 I_{start}$$

subject to the constraints $T \le 0.04\ \text{s}$, $V \le 0.05\ \text{mm/s}$ and the motor rating condition $P_{motor} = \sqrt{3} V_{rated} I_{start}$. This formulation enables simultaneous minimization of the transition period and starting current while enforcing vibration and system constraints.

Step 3: Update the velocity and position of each particle

For each particle, update its velocity using the following equation, where rand () is a random number between 0 and 1. But first, update inertia weight dynamically.

At each iteration, compute the adaptive inertia weight as:

$$w = w_{\max} - \left(\frac{w_{\max} - w_{\min}}{Max_{iter}} \right) * iter \tag{5}$$

This modification balances exploration and exploitation by gradually reducing inertia as the swarm converges.

$$\begin{aligned} \text{velocity} = {} & w \times \text{velocity} + c_1 \times \text{rand}(\ ) \times (P_{best} - \text{position}) \\ & + c_2 \times \text{rand}(\ ) \times (g_{best} - \text{position}) \end{aligned} \tag{6}$$

Step 4: Update the position of each particle using the following equation

$$\text{Position} = \text{position} + \text{velocity} \tag{7}$$

where rand() generates a random number in [0, 1].

The inclusion of adaptive w, c_1 and c_2 constitutes a key modification enhancing convergence and stability.

Step 5: Update the personal best and global best positions

- For each particle, calculate the fitness value of the new position using the fitness function.
- If the fitness value of the new position is better than the current personal best fitness value, update the pbest and pbest_fitness for that particle.
- If the fitness value of the new position is better than the current global best fitness value, update the gbest and gbest_fitness for the entire swarm.

Step 6: Repeat steps 3 and 4 until the maximum number of iterations (max_iter) is reached or a termination condition is met, such as reaching a satisfactory fitness value or a predefined time limit.

Step 7: Return the best solution found, which corresponds to the gbest position, as the optimal closed transition star delta starter configuration.

2.2. Selection of Fitness Function

The criteria for measuring the performance of a good controller are the selection of a good objective function. The Fitness function used for this research is the Integral of Time multiplied by Absolute Error (ITAE) performance criterion. The

ITAE performance index has the advantage of producing smaller overshoots and oscillations than the Integral of Absolute Error (IAE) and Integral Square Error (ISE) performance indices. It is the most sensitive of the three, *i.e.*, it has the best selectivity. The Integral Time Square Error (ITSE) index is somewhat less sensitive and is not computational. However, to demonstrate the efficiency and robustness of the proposed MPSO star delta starter, different performance indices such as IAE, ISE, ITAE and ITSE were investigated. The objective functions are defined in Equations (8)-(11).

$$J = \mathrm{IAE} = \int_0^t \left| ACE_i(t) \right| \mathrm{d}t \tag{8}$$

$$J = \mathrm{ISE} = \int_0^t ACE_i^2(t) \mathrm{d}t \tag{9}$$

$$J = \mathrm{ITAE} = \int_0^t t \left| ACE_i(t) \right| \mathrm{d}t \tag{10}$$

$$J = \mathrm{ITSE} = \int_0^t t \left(ACE_i \right)^2 (t) \mathrm{d}t \tag{11}$$

2.3. Simulink Model of the Optimized Closed Transition Star-Delta Starter (CTSDS)

The Simulink model of a CTSDS of an induction motor using timers is shown in **Figure 2**. Three scenarios were modelled, analyzed and compared. These are the base case (raw star delta starter), the timer-based close transition star delta starter and the PSO-based closed transition star delta starter.

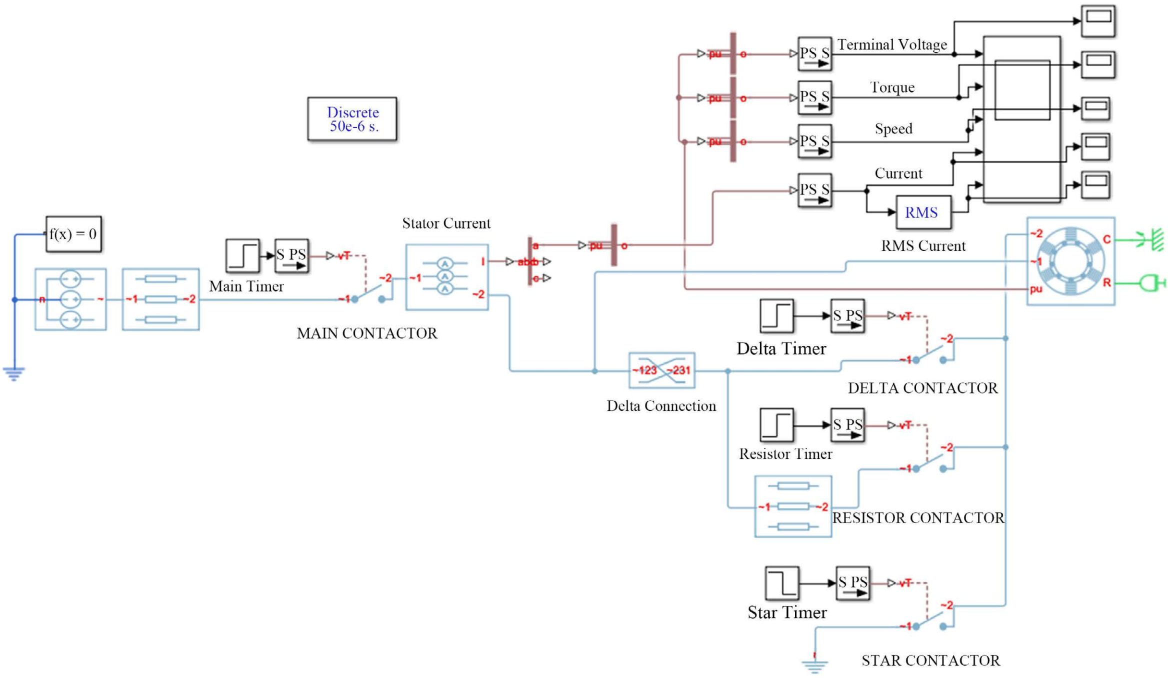

Figure 2. Simulink model of optimized closed transition star delta starter.

2.4. Parameter Setting for System Model and Optimization

The effectiveness of optimization algorithms, MPSO, is highly dependent on the appropriate configuration of their parameters. In the context of optimizing a system model, the selection of suitable algorithmic parameters becomes a critical step in achieving optimal results. Table 1 shows the parameters used for the system model and optimization.

Table 1. Parameters for the system model.

SN	Parameters	Value
1	Population (N)	30
2	Iter$_{max}$	50
3	Learning factor (c_1)	2.8
4	Learning factor (c_2)	1.3
5	Inertia weight (w_{max})	1.2
6	Inertial weight (w_{min})	0.9
7	Power rating (3-Φ SCIM)	9.25 kW
8	Rated voltage	415 V
9	Rated current	22 A
10	Rated speed	1400 rpm
11	Frequency (Hz)	50 Hz
12	No. of Poles	4

2.5. Conceptual Framework of the Proposed Model Implementation

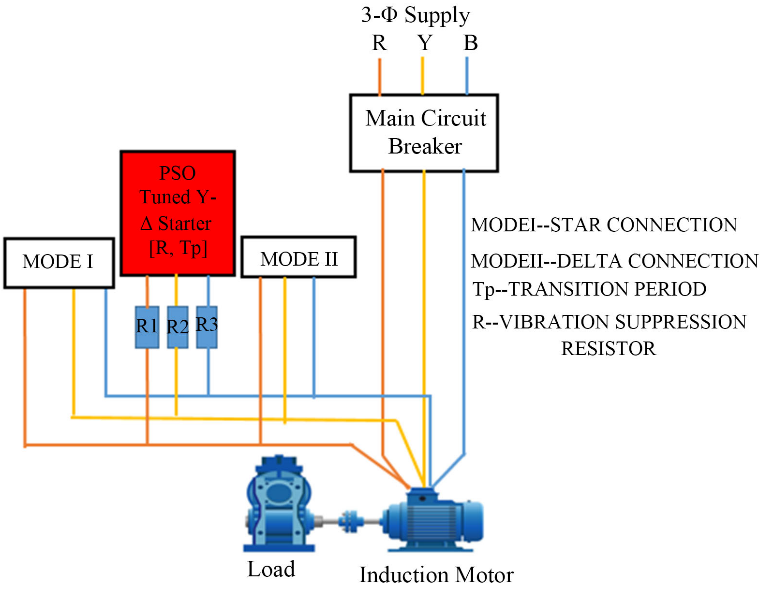

Figure 3. Conceptual design of the proposed method.

Figure 3 illustrates the switching sequence of the proposed model, which employs star-delta starter features. The induction motor is supplied with power from the 3-phase supply. Depending on the starting condition, the motor switches from the star (Mode I) to the Delta (Mode II). In between these two switching states are usually switching transients (high current and excessive vibration). However, the MPSO is used to select an optimal resistance value to suppress the switching transients to effectively control the induction motor and the connected load, as shown in **Figure 3**.

2.6. Optimal Value of Vibration Suppression Resistor

The expression in Equation 12 calculates the appropriate resistance value for the starting resistor in a star-delta starter, which is used to gradually limit the starting current of a motor during the transition from star to delta connection. The resistance value is determined based on the phase voltage of the motor, the short-circuit current of the motor, and the resistance values of the starting resistor and motor winding. Proper selection of the resistance value is important to ensure a smooth and safe motor starting in a star-delta starter configuration [5].

$$R = V_{ph}\left(\frac{1}{\left(\sqrt{3}\times I_{sc}\right)\times\frac{R_t}{R_t+R_s}}\right) \tag{12}$$

where, R is the optimal value of the resistance for suppressing starting vibrations,

V_{ph} is the phase voltage of the motor,
I_{sc} is the short-circuit current of the motor,
R_t is the resistance value of the starting resistor in ohms,
R_s is the resistance value of the motor winding in ohms.

3. Results and Discussion

An extensive assessment of the closed transition star-delta starter control method's efficacy and performance in induction motor applications is given in this section. It aims to describe the outcomes obtained from simulated data, elaborating on the important discoveries. By examining various parameters and performance metrics, such as motor starting time, starting current waveform characteristics, torque ripple, and energy efficiency, a thorough assessment of the star-delta starter's operation is conducted. Additionally, comparisons with alternative starting methods or theoretical predictions will be explored to ascertain the robustness of the proposed method.

3.1. Evaluation of Fitness Functions

The effectiveness of the modified PSO algorithm can be evaluated by comparing different control strategies and parameter settings for closed transition in Star-Delta starters for induction motor control. The choice of fitness function depends on the specific requirements of the control system, such as desired performance criteria, transient response characteristics, and control effort considerations. Through iterative optimization, ITAE-MPSO converges quickly to a solution with the least number of iterations as compared to IAE, ISE, and ITSE fitness functions, as illustrated in **Figure 4**. Hence, ITAE is selected as the best fitness function in this work. The control parameters can be fine-tuned to achieve optimal system performance while considering stability, robustness, and energy efficiency.

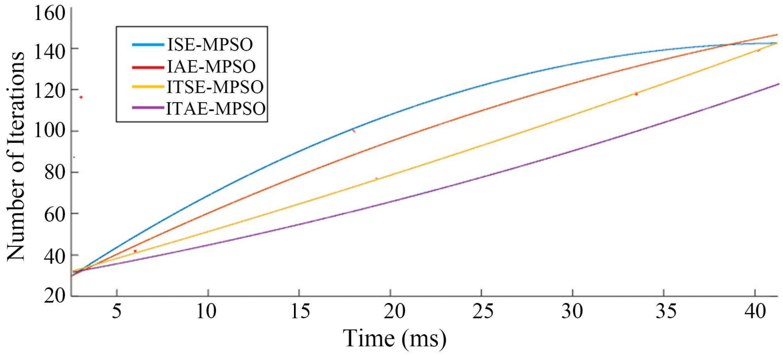

Figure 4. Analysis of fitness function for optimal SCIM starter design.

3.2. Analyzing the Robustness of the Proposed Method on the Starting Current of an Induction Motor

Figure 4 depicts a comparison of fitness functions utilized in the control of an induction motor's starting current, showcasing the performance of the proposed ITAE-MPSO technique against other commonly used fitness functions: ISE, IAE, and ITSE-MPSO methods. The horizontal axis represents time, while the vertical axis represents the starting current of the induction motor, measured as a unit of its rated current.

Figure 5 exhibits the starting current characteristics of induction motors. At the initial stage, the starting current exhibits a sharp rise, indicating the typical high inrush current associated with motor startup. As the motor transitions from the star to the delta configuration, significant switching transients are observed, resulting in fluctuations in the starting current. However, the proposed ITAE-MPSO technique demonstrates superior performance compared to other methods, effectively suppressing these transients and maintaining the starting current within acceptable limits.

Remarkably, the ITAE-MPSO technique showcases its ability to dampen the switching transients and rapidly stabilize the starting current. Within a short period of approximately 10 milliseconds, the starting current settles around 5% of the rated current, signifying a significant reduction from the initial high inrush current. This rapid stabilization highlights the effectiveness of the proposed method in achieving smooth and controlled motor startup, minimizing stress on electrical components, and enhancing overall system reliability.

However, the ISE-MPSO, IAE-MPSO, and ITSE-MPSO methods exhibit comparatively slower response times and less effective suppression of switching transients. While these methods eventually settle at the rated current, they exhibit prolonged settling times of 30 ms, 35 ms and 15 ms, respectively, and less precise control over the starting current during the transition period.

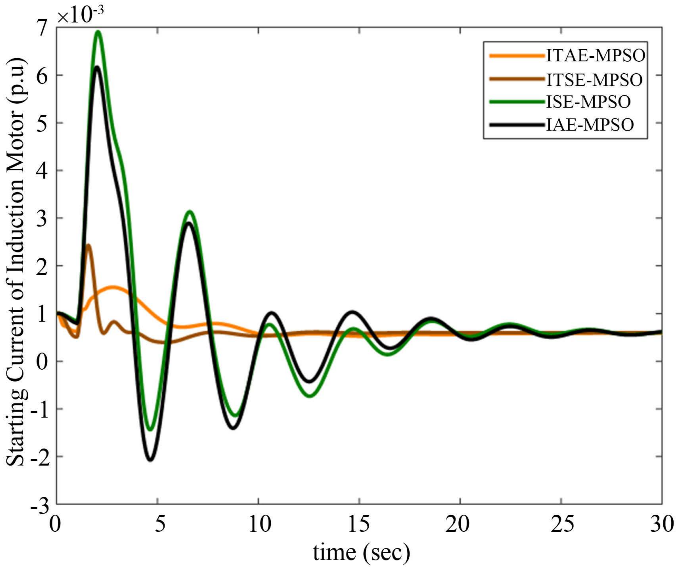

Figure 5. Starting current behaviour of induction motor.

Table 2 presents the results of performance indices for four different methods, ITAE-MPSO, ITSE-MPSO, ISE-MPSO, and IAE-MPSO, across different iterations of a particle swarm optimization algorithm. ITAE-MPSO shows a general decreasing trend as iterations increase, with the smallest value at iteration 50 (0.000125), indicating better performance in minimizing the time-weighted absolute error as compared to the other methods, making the proposed ITAE-MPSO the best candidate for optimizing the operations of the induction motor.

Table 2. Comparing error minimization of four performance metrics.

Iterations	Performance indices			
	ITAE-MPSO	ITSE-MPSO	ISE-MPSO	IAE-MPSO
20	**0.000496**	0.049649	1.02490	0.120850
30	**0.000767**	0.011150	1.54170	0.188230
40	**0.000243**	0.017278	1.28130	0.157070
50	**0.000125**	0.006246	1.62660	0.196280

3.3. Simulation and Analysis of Speed of an Induction Motor

Figure 6 depicts the speed of an induction motor over time, comparing the performance of the MPSO method against a timer-based closed transition starter and a conventional star-delta starter.

Initially, the motor's speed exhibits a gradual increase from 0 seconds to 6 seconds, reaching full speed within this timeframe. Notably, the speed experiences a slower rise between 0 and 3.8 seconds when the motor is started in a star configuration, followed by more rapid acceleration to full speed between 3.7 and 6 seconds upon transitioning to a delta connection. An important observation is the ability of the proposed MPSO technique to dampen motor vibration within the time interval of 3.6 to 3.9 seconds, achieving this with a closed transition period of 20 milliseconds. In contrast, both the timer-based and conventional star-delta starters exhibit longer transitional periods, taking 30 seconds and 40 seconds, respectively, to dampen vibration and stabilize motor operation.

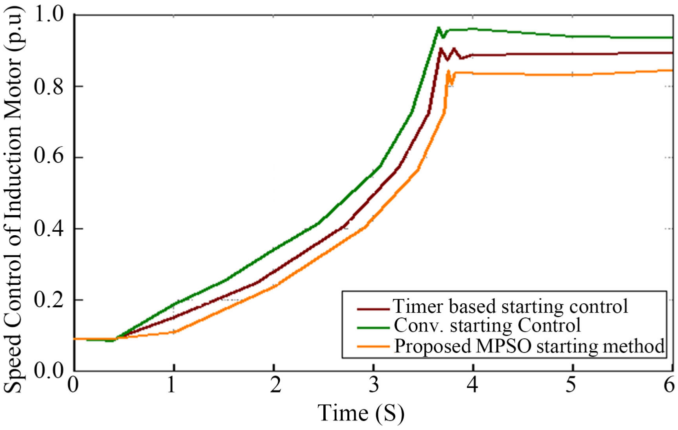

Figure 6. Speed of the induction motor.

3.4. Control of Starting Current of Induction Motor

Figure 7 provides a comparison of various starters for controlling the high inrush current of an induction motor, highlighting the robustness of the proposed MPSO-based closed transition star-delta starter technique. The graph illustrates the starting current, transition period, and switching transients associated with each starter method. The proposed MPSO-based technique demonstrates robustness in reducing the starting current, achieving a level of approximately 0.6 p.u. This reduction is achieved within a rapid transition period of 20 milliseconds, showcasing the method's ability to swiftly transition from star to delta configuration. Furthermore, the starting current stabilizes at the rated current of approximately 0.21 p.u., with minimal switching transients observed during the transition process.

In contrast, the timer-based star-delta starter achieves a slightly higher starting current of approximately 0.73 A during the star connection phase. The transition period for this method extends to 40 milliseconds, and the final settling current in the delta connection is approximately 30 A. While this method is effective, it exhibits a longer transition period compared to the proposed MPSO-based technique. Conversely, the conventional star-delta starter exhibits poor performance, with a significantly higher starting current of 80 A observed during the star connection phase. The transition period for this method is even longer, spanning 50 milliseconds. Furthermore, the settling current in the star connection is notably higher at 42 A, indicating less effective control over the motor's operation.

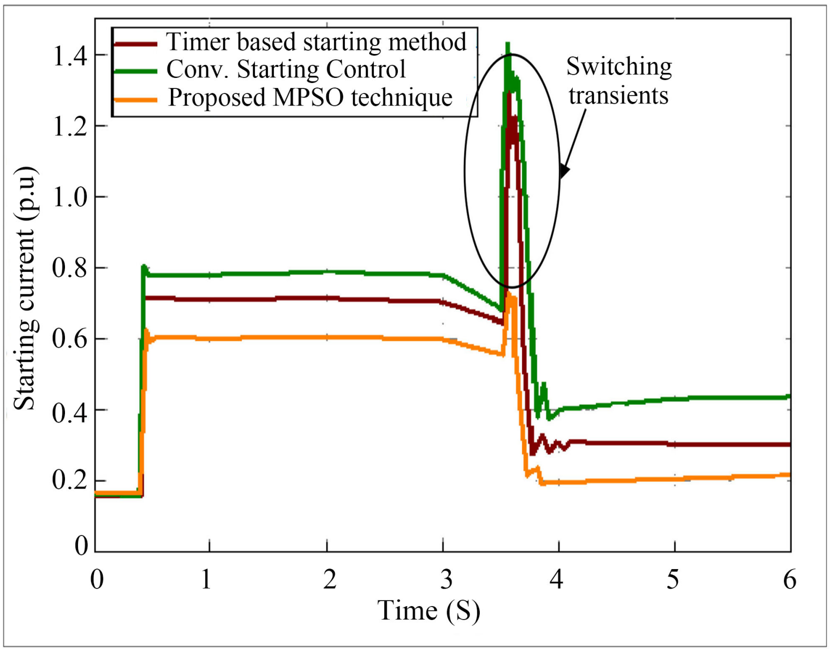

Figure 7. Starting current of the induction motor with a different closed transition star-delta starter.

3.5. Sensitivity Analysis of the Proposed Method under Transient Faults

Sensitivity analysis of the proposed MPSO closed transition star-delta method under transient faults in induction motor control entails a detailed examination of the method's robustness and responsiveness to variations and disturbances in the system, particularly during transient fault conditions. This analysis aims to assess the method's ability to maintain stable motor operation and mitigate adverse effects caused by transient faults.

In induction motor control, transient faults refer to sudden and temporary deviations from normal operating conditions, such as voltage fluctuations, sudden load changes, or disturbances in the power supply. These faults can lead to undesirable effects such as motor stalling, increased vibration, or torque fluctuations, which can compromise system performance and reliability.

Figure 8 shows the system response after being subjected to a 1% and 5% step load change.

Percentage load variation in the power system implies a transient response of the system after a disturbance. Sudden load changes create frequency oscillations, which are diminished with time to normalise the system stability. It is clear that with the proposed MPSO starter, system deviations settle quickly, and the dynamic responses are less oscillatory with a low amplitude of switching transients in the system. The proposed MPSO controller illustrated better disturbance responses as compared to the timer-based star delta and the classical star delta starter.

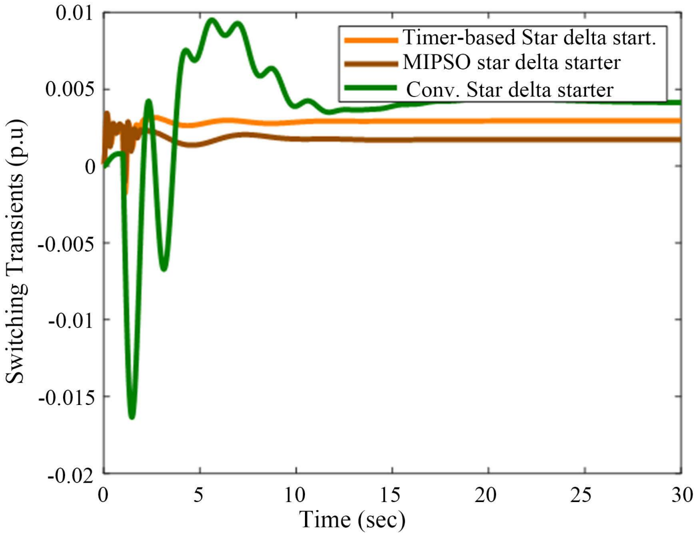

Figure 8. Sensitivity analysis of the proposed MPSO method under transient fault.

Table 3. Settling time and transient overshoot with step load change.

Starter	Settling Time		Switching transients' overshoot	
	Settling Time 1% load change (Sec.)	Settling Time 5% load change (Sec.)	Overshoot 1% load change (%)	Overshoot 5% load change (%)
Timer-based star delta starter	9.16	9.29	30.20	67.63
Proposed MPSO star delta starter	**5.30**	**5.96**	**0.40**	**6.66**
Conv. Star-delta starter	21.38	21.79	129.82	151.23

The settling time and transient overshoots of all three starters are illustrated in Table 3. The proposed MPSO in all the areas produced tremendous results in terms of settling times of varied load percentage, which are 5.3 sec, 5.96 sec, as compared to timer-based 9.16 sec, 9.29 sec, and Conventional star delta starters 21.38 sec, 21.79 sec. Again, the proposed MPSO produced less transient overshoot, 0.40%, and 6.66%, as shown in Table 3. The conventional star-delta starter performed poorly in terms of settling time and percentage transient overshoot under disturbance. The excellent performance in the proposed technique was due to the adaptive control strategy of the ITAE-MPSO that adaptively tunes the control parameters during the start-up process, allowing it to respond dynamically to changing conditions and disturbances, resulting in more precise control, reduce transient overshoots and achieve a quicker settling time, whiles the ITAE criterion focuses on minimizing the time-weighted absolute error leading to reduced transients overshoots and settling time. However, a conventional star-delta starter uses fixed timing for the transition, which lacks adaptability to varying loads, leading to suboptimal performance.

4. Conclusions

This study presented a Modified Particle Swarm Optimization (MPSO)-based control strategy to optimize the closed transition star–delta starter (CTSDS) for a three-phase squirrel cage induction motor. The objective was to minimize switching transients, starting current, and torque fluctuations during the transition process. The proposed MPSO algorithm was implemented in MATLAB/Simulink and successfully optimized the key switching parameters of the starter.

Simulation results demonstrated that the MPSO-based starter achieved significant performance improvements compared to conventional Timer-based and CTSDS methods. In that the optimized system MPSO exhibited 5.3 sec in settling time and only 0.4% voltage overshoot all in 1% load variation, as the best former, while substantially minimizing starting current and vibration. The induction motor attained its rated speed and torque more rapidly, with smoother transient characteristics and lower mechanical stress during startup. These outcomes confirm that the MPSO-based starter enhances motor performance, efficiency, and operational stability.

Future Work

Further research should focus on developing and testing real-time implementations of the MPSO-based starter under diverse load and environmental conditions to evaluate its robustness and adaptability. Integrating the system with smart grid and Internet of Things (IoT) platforms could enable remote monitoring, adaptive control, and predictive maintenance, leading to more intelligent and energy-efficient motor management systems. Additionally, developing user-friendly interfaces for industrial deployment would facilitate broader adoption of the proposed approach in modern automated systems.

Authorship Credit

Ernest Smith Mawuli: Concept formulation and development, supervision, funding acquisition, writing, reviewing & editing. **Jacob Owusu Ansah:** Concept formulation and development, methodology, investigation, and writing original draft. **Enoch Boateng Adomako:** Data curation, writing, review & editing.

Acknowledgements

This work was supported by the staff of the Electronics and Simulation Lab at the Department of Electrical and Electronics Engineering, Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED).

Conflicts of Interest

The authors declare that this paper is the result of original research. Therefore, we are not aware of any competing financial interests, personal relationships, or official fund support that could have influenced the findings reported in this paper.

References

[1] Yang, D., Kim, T., Oh, T., Kim, Y., Lee, S. and Cho, D.D. (2022) A Current Balancing

Method of Two-Phase Soft Starter for Three-Phase Induction Motor Drive System without Current Sensor. 2022 13*th Asian Control Conference* (*ASCC*), Jeju, 4-7 May 2022, 1309-1314. https://doi.org/10.23919/ascc56756.2022.9828099

[2] Meshcheryakov, V. and Belousov, A. (2021) Development of a Method for Reducing Starting Currents and Electromagnetic Torque of a Two-Phase Induction Motor by Delaying Voltage Supply. 2021 *XVIII International Scientific Technical Conference Alternating Current Electric Drives* (*ACED*), Ekaterinburg, 24-27 May 2021, 1-5. https://doi.org/10.1109/aced50605.2021.9462269

[3] Nazare, C., Chavan, A., Rathod, L., Kumar, G. and Kahandal, S. (2021) Star δ Starter Using Three Phase Induction Motor. *International Journal of Emerging Technologies and Innovative Research*, **8**, f157-f161. https://www.jetir.org/view?paper=JETIR2105685

[4] Siregar, Y., Rotua Oktaviana Siahaan, Y., Nabila Binti Mohamed, N., Candra Riawan, D. and Yuhendri, M. (2025) Design of Starting a Three Phase Induction Motor Using Direct On-Line, Variable Frequency Drive, Soft Starting, and Auto Transformer Methods. *Indonesian Journal of Electrical Engineering and Computer Science*, **37**, 700-714. https://doi.org/10.11591/ijeecs.v37.i2.pp700-714

[5] Ferreira, F.J.T.E., Silva, A.M., Cruz, S.M.A. and De Almeida, A.T. (2017) Comparison of Losses in Star- and δ-Connected Induction Motors with Saturated Core. 2017 *IEEE International Electric Machines and Drives Conference* (*IEMDC*), Miami, 21-24 May 2017, 1-8. https://doi.org/10.1109/iemdc.2017.8002312

[6] Ferreira, F.J.T.E., Alberto, J., Silva, A.M. and de Almeida, A.T. (2020) Saturation-related Losses in Induction Motors for Star and δ Connection Modes. 2020 *International Conference on Electrical Machines* (*ICEM*), Gothenburg, 23-26 August 2020, 1586-1593. https://doi.org/10.1109/icem49940.2020.9270994

[7] Ferreira, F.J.T.E., Cistelecan, M.V. and De Almeida, A.T. (2014) Comparison of Different Tapped Windings for Flux Adjustment in Induction Motors. *IEEE Transactions on Energy Conversion*, **29**, 375-391. https://doi.org/10.1109/TEC.2013.2296300

[8] Kato, M., Orikawa, K., Itoh, J. and Saitoh, N. (2013) Fast Starting Method Using Both Inverter and δ-Star Starter for Weaving Machine Drive Systems. 2013 1*st International Future Energy Electronics Conference* (*IFEEC*), Tainan, 3-6 November 2013, 211-216. https://doi.org/10.1109/ifeec.2013.6687505

[9] Alsina, E.F., Chica, M., Trawiński, K. and Regattieri, A. (2017) On the Use of Machine Learning Methods to Predict Component Reliability from Data-Driven Industrial Case Studies. *The International Journal of Advanced Manufacturing Technology*, **94**, 2419-2433. https://doi.org/10.1007/s00170-017-1039-x

[10] Abou Omar, M.S., Khedr, T.Y. and Abou Zalam, B.A. (2013) Particle Swarm Optimization of Fuzzy Supervisory Controller for Nonlinear Position Control System. 2013 8*th International Conference on Computer Engineering & Systems* (*ICCES*), Cairo, 26-28 November 2013, 138-145. https://doi.org/10.1109/icces.2013.6707189

[11] Khettache, L., Djeffal, F. and Ferhati, H. (2024) Optimal Speed Control of Dual-Star Linear Induction Motor Based on Particle Swarm Algorithm. 2024 *International Conference on Advances in Electrical and Communication Technologies* (*ICAECOT*), Setif, 1-3 October 2024, 1-5. https://doi.org/10.1109/icaecot62402.2024.10829349

[12] Sayed, M.M., Saad, M.S., Emara, H.M. and Abou El-Zahab, E.E. (2013) A Novel Method for Type-2 Fuzzy Logic Controller Design Using a Modified Biogeography-Based Optimization. 2013 *IEEE International Conference on Industrial Technology* (*ICIT*), Cape Town, 25-28 February 2013, 28-33.

https://doi.org/10.1109/icit.2013.6505643

[13] Martinez-Soto, R., Castillo, O., Aguilar, L.T. and Baruch, I.S. (2012) Bio-Inspired Optimization of Fuzzy Logic Controllers for Autonomous Mobile Robots. 2012 *Annual Meeting of the North American Fuzzy Information Processing Society* (*NAFIPS*), Berkeley, 6-8 August 2012, 1-6. https://doi.org/10.1109/nafips.2012.6291053

[14] Mohammadi, A., Tamaskani, R., Mosayyebi, S.R. and Ajoudani, M. (2015) Parameter Estimation of Induction Motors by PSO Algorithm. *Science International*, **27**, 141-145.

[15] Huynh, D.C. and Dunnigan, M.W. (2010) Parameter Estimation of an Induction Machine Using a Dynamic Particle Swarm Optimization Algorithm. 2010 *IEEE International Symposium on Industrial Electronics*, Bari, 4-7 July 2010, 1414-1419. https://doi.org/10.1109/isie.2010.5637818

[16] Rania, A., Mohamed, B. and Lamine, F.M. (2024) A PSO-Based Type-2 Fuzzy Logic Controller Designed for Quadrotor Systems. 2024 2*nd International Conference on Electrical Engineering and Automatic Control* (*ICEEAC*), Setif, 12-14 May 2024, 1-6. https://doi.org/10.1109/iceeac61226.2024.10576341

[17] Santana, G.A., Goedtel, A., Santana, G.A., Martinez, C.A.P. and Goedtel, A. (2023) Parameter Identecation in Three-Phase Induction Motor Aided by Halton-Chaos-β-PSO Algorithm. https://doi.org/10.21203/rs.3.rs-2491634/v1

[18] Valdez, F., Melin, P. and Castillo, O. (2012) Particle Swarm Optimization for Designing an Optimal Fuzzy Logic Controller of a DC Motor. 2012 *Annual Meeting of the North American Fuzzy Information Processing Society* (*NAFIPS*), Berkeley, 6-8 August 2012, 1-6. https://doi.org/10.1109/nafips.2012.6291051

[19] El-Hassanein, D., Amin, A.A.R., Gouda, E. and Kotb, M.F. (2023) Multi Objective Optimum Design of Squirrel Cage Induction Motor Using Wild Horse Optimizer. 2023 24*th International Middle East Power System Conference* (*MEPCON*), Mansoura, 19-21 December 2023, 1-8. https://doi.org/10.1109/mepcon58725.2023.10462376

[20] Hao, C., Li, G., Wang, Q. and Zhou, R. (2021) Multi-Objective Optimization Design of Spherical Induction Motor. 2021 *IEEE* 16*th Conference on Industrial Electronics and Applications* (*ICIEA*), Chengdu, 1-4 August 2021, 762-767. https://doi.org/10.1109/iciea51954.2021.9516202