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Salp swarm algorithm–based optimal vector control scheme for dynamic response enhancement of brushless double-fed induction generator in a wind energy conversion system

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Summary

Considering the superior performance and comparatively lower maintenance cost of the brushless double-fed induction generator (BDFIG) than the conventional double-fed induction generator (DFIG), this article explores its application in wind energy conversion systems (WECS) with a novel control strategy. The proposed control strategy utilizes the intelligence of the Salp swarm algorithm (SSA)–based vector control scheme to optimally regulate the speed, torque, current, active, and reactive power of the proposed WECS during the sharp changes in the wind speed and load. To overcome the demerits associated with the conventional “trial and error” method of PI regulator tuning, the SSA is utilized to optimally select their proportional and integral gains automatically. SSA accomplishes the mentioned task by iteratively minimizing the considered error integrating objective function through an offline optimization method; thus, it provides the least error and consequently optimal dynamic response of the proposed BDFIG-based WECS at the end of the optimization process. The effectiveness and performance of the proposed control strategy are validated in terms of optimal speed, torque, and active and reactive power regulation and is compared with the internal model control and particle swarm optimization algorithm–based vector control schemes under identical operating conditions and system configurations. The proposed control scheme for the considered BDFIG-based WECS obtains the best optimal dynamic response among the considered control schemes; thus, it proves its efficacy and essence.

List of Symbols and Abbreviation: λ_p , PW Flux; V_p, V_c, V_r , PW, CW, RW voltage; I_p, I_c, I_r , PW, CW, RW current; R_p, L_p, M_{pr} , PW resistance, PW inductance, mutual inductance; R_c, L_c, M_{cr} , CW resistance, CW inductance and mutual inductance; R_r, L_r , RW resistance and RW inductance; $\omega_p, \omega_c, \omega_r$, angular frequencies of PW, CW, RW; I_m , magnetizing inductance; P_p, P_c, P_r , PW, CW, rotor pole-pairs; Q_p , reactive power of PW; $e_1(t), e_2(t), e_3(t)$, error values fed to the PI-1, PI-2 and PI-3; $K_1^{1:n}$, initial position of the Salps; $rand(\dots)$, MATLAB command; ub_j, lb_j , upper bound and lower bound; K_j^i , position of the i th leader salp in j th dimension; M_i , food target; c_1, c_2, c_3 , random numbers; $\frac{l}{L}$, ratio of Iteration to the maximum iterations; BDFIG, brushless double-fed induction generator; BDFIM, brushless doubly-fed induction machines; DFIG, double-fed induction generator; FF, fitness function; IMC, internal model control; IAE, integral absolute error; ISE, integral square error; ITAE, integral time absolute error; LVRT, low voltage ride-through; MSC, machine side converter; PI, proportional-integral; PSO, particle swarm optimization; PW, CW, RW, power winding, control winding and rotor winding; RES, renewable energy sources; SSA, Salp swarm algorithm; VC, vector control; WECS, wind energy conversion system.

KEYWORDS

brushless doubly fed induction generator, dynamic response enhancement, optimization, Salp swarm algorithm, vector control scheme

1 | INTRODUCTION

The continuous growth in energy demand and depletion of fossil fuels has moved the attention of researchers to extract the maximum possible energy from renewable energy sources (RES).¹ These energy sources are cheaper, environment-friendly, and easily accessible. Among RES wind energy is one of the most reliable and abundantly available sources of energy.² To generate the controlled amount of electrical energy from wind energy, a wind energy conversion system (WECS) is essentially required. A block diagram of a typical WECS is depicted in Figure 1.

To design an efficient WECS, the selection of an appropriate machine for power generation and an intelligent control strategy is of utmost importance.³ One of the most widely used machines in WECS is the double-fed induction generator (DFIG) because of its excellent speed and power control characteristics.⁴ However, the major disadvantage associated with the DFIG is the usage of slip rings and brushes for supplying the generated power to the load. The inclusion of brushes not only limits the rating of the machine but also increases its maintenance cost due to continuous wear and tear in mentioned circuitry.⁵ To avoid these issues, the modern WECS are employing the brushless doubly fed induction generator (BDFIG). Due to the robust brushless rotor design, the BDFIG provides enhanced reliability, multiple operating modes, lower cost of power electronics converters, crowbar-less low voltage ride-through (LVRT), smooth control of active and reactive power, and lower maintenance cost.^{6,7} Owing to the mentioned merits of the BDFIG, this research work attempts to design an optimal control strategy to improve the system in terms of dynamic response.

Appropriate design of an intelligent control strategy is a very vital aspect of any WECS design.⁸ Since the wind speed is changing in nature, consequently, the output power, shaft speed, and torque of the machine vary during the operating hours of the wind turbine.⁹ Under such conditions, the BDFIG needs to be precisely controlled in order to achieve a smooth operation of the considered power system at fixed voltage and frequency. Several control strategies such as scalar control scheme,¹⁰ super-twisting sliding mode direct power control,¹¹ indirect torque control scheme,¹² and indirect stator-quantities control¹³ have been utilized in literature to accomplish the control objectives. The mentioned control strategies successfully regulated the speed, torque, and power output of the machine; however, they were unable to suppress the heavy transients and long oscillations in active power, reactive power, torque, and speed during the starting and abrupt load changes. Besides, independent control over active and reactive power was lagging due to the unavailability of quadrature and the direct current within their structures. Furthermore, compared to the scalar control, the direct power control scheme provides a faster dynamic response; however, it consumes more power due to faster switching frequency and is dependent on system parameters. On the other hand, the direct torque control is simple and less sensitive to machine parameters but causes high ripples and harmonics especially in the low-speed range, which consequently distorts the output power quality.

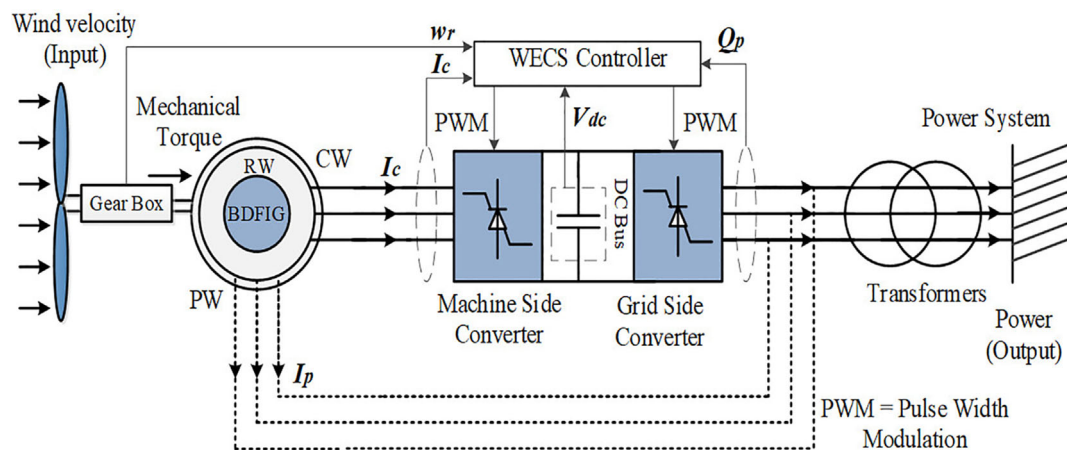


FIGURE 1 WECS and controller

Another important control strategy that has been extensively explored in literature for WECS is the vector control (VC) scheme.^{14,15} VC models are effective tools for independently regulating the speed and reactive power of BDFIM by using dq synchronous frame and by aligning stator flux vector with d axis of the frame. VC schemes are able to provide satisfactory outcomes if their PI regulators are optimally selected.¹⁶ Poza et al¹⁷ developed a mathematical model VC scheme-based BDFIG to regulate the dynamic behavior of the considered WECS. The developed model provided satisfactory outcomes during the normal and transient conditions. A sensor-less-VC scheme¹⁸ and an improved sensor-less BDFIG control¹⁹ were explored to improve the dynamic response of BDFIG-based WECS. The major drawback associated with the referred and several other studies pertaining to BDFIG vector control schemes is that the gains of the PI regulators are chosen manually by using the “trial and error” method.²⁰ The quoted PI tuning method is time-consuming and inefficient and does not provide guaranteed optimal gain selection at the end of the tuning process; thus, it affects the dynamic response of the considered WECS.²¹ To overcome the stated issue and to enhance the dynamic response of the BDFIG-based WECS, the authors in Reference 22 have utilized an internal model control (IMC) technique to select the optimal PI regulator gains in a vector control scheme. The IMC is an analytical PI parameter selection method. It requires the complete mathematical model of the system to compensate its open-loop poles with the zeros of the PI controller. Since most WECS consist of very complex power and control circuits; therefore, it is very hard to derive an accurate mathematical model of such systems. One of the effective methods to overcome this problem is to utilize a PI tuning approach that does not require such extensive modeling of the system and may treat the considered system as a black box.²³ One of such approaches is to select the PI gains with a metaheuristics-based optimization method. The operation of these optimization methods is based on minimizing or maximizing a predefined FF automatically through a stochastic-based searching mechanism, thus reduces the human effort and control system modeling and design constraints.

This article explores the application of one of the most intelligent metaheuristic optimization algorithms called the SSA in achieving the optimal dynamic response in terms of regulating the speed, torque, and reactive power of the BDFIG-based WECS. The SSA intelligence is utilized to achieve the most optimal PI regulator gains in a vector control scheme by minimizing a predefined fitness function automatically.²⁴ One of the significant aspects of this research work is that the current work utilizes the machine-side converter (MSC) for enhancing the dynamic response of the BDFIG system. In order to prove the efficacy of the proposed method, its dynamic response is evaluated under different working conditions such as regulated wind speed, load change, and reactive power change. The proposed controller achieves an excellent dynamic response and robust and efficient operation of the considered BDFIG during all studied operating conditions and provides stable output power at the required voltage and frequency. To examine the performance of the proposed controller, its dynamic response (overshoot, settling time, and rise time) is compared with particle swarm optimization (PSO) algorithm and IMC-based controllers under identical operating conditions and system configurations. The major contributions of this article are listed as follows.

1. A detailed study of VC-based BDFIG WECS is made to regulate its speed, torque, and reactive power.
2. To improve the dynamic response of the considered WECS under different operating conditions, the PI regulators' gains are optimized automatically using the intelligence of SSA.
3. A comprehensive comparative analysis of the proposed control scheme with IMC- and PSO-based VC schemes is made based on few important dynamic response evaluation metrics such as parentage overshoot and settling time to validate the efficacy and essence of the proposed WECS control architecture.

The rest of the article is structured as follows; Section 2 describes the operation and modeling of the machine. The converter along with the proposed SSA gain selection approach is discussed in Section 3. Section 4 describes the proposed VC scheme. The results are presented in Section 5. Finally, Section 6 presents the conclusion of the paper.

2 | MODELING OF BDFIG ALONG WITH THE ARCHITECTURE OF PROPOSED CONTROL

In this section, the mathematical model for the considered BDFIG with the proposed control scheme is discussed in detail. A detailed mathematical model for any WECS is essentially required to design a suitable controller for achieving the control objectives of the studied system. For ease of understanding and modeling, the section is further divided into two subsections.

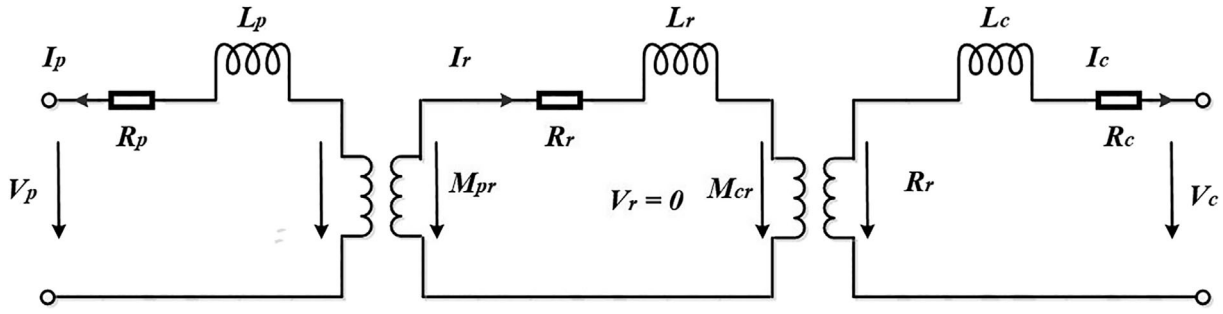


FIGURE 2 Equivalent circuit of BDFIG

2.1 | Mathematical modeling of BDFIG

In this sub-section, a detailed mathematical model for the considered BDFIG is derived. Constructively, the BDFIG has two windings on its stator side, that is, power winding (PW) and control winding (CW). The PW is connected to the load or grid, while CW is connected to the power electronics converters to control the machine according to the required operating condition.²⁵ The rotor is short-circuited; hence no voltage is applied to the rotor. The BDFIG equivalent circuit is shown in Figure 2.

To start with the modeling, the d component of the PW flux frame is considered as aligned with PW flux; therefore,

$$\lambda_{pd} = |\lambda_p| \text{ and } \lambda_{pq} = 0 \quad (1)$$

where λ_{pd} and λ_{pq} symbolize the d and q components of PW flux, respectively. The voltage and flux equations for the PW are represented as²⁶,

$$V_{pd} = I_{pd}R_p - j\omega_1\lambda_{pq} + \frac{d\lambda_{pd}}{dt} \quad (2)$$

$$V_{pq} = I_{pq}R_p - j\omega_1\lambda_{pd} + \frac{d\lambda_{pq}}{dt} \quad (3)$$

$$\lambda_{pd} = L_p I_{pd} + M_{pr} I_{rd} \quad (4)$$

$$\lambda_{pq} = L_p I_{pq} + M_{pr} I_{rq} \quad (5)$$

The d and q components of PW voltage are represented as V_{pd} and V_{pq} where I_{pd} and I_{pq} show the d and q component of PW currents, PW resistance, PW inductance, mutual inductance between the rotor and PW, d component of rotor current, and d component of rotor current are represented as R_p , L_p , M_{pr} , I_{rd} , and I_{rq} , respectively. Similarly, the mathematical representation for the CW voltage and flux can be represented as;

$$V_{cd} = I_{cd}R_c - j(\omega_1 - N_r\omega_r)\lambda_{cq} + \frac{d\lambda_{cd}}{dt} \quad (6)$$

$$V_{cq} = I_{cq}R_c - j(\omega_1 - N_r\omega_r)\lambda_{cd} + \frac{d\lambda_{cq}}{dt} \quad (7)$$

$$\lambda_{cd} = L_c I_{cd} + M_{cr} I_{rd} \quad (8)$$

$$\lambda_{cq} = L_c I_{cq} + M_{cr} I_{rq} \quad (9)$$

where V_{cd} and V_{cq} represent the d and q components of CW voltage, the d and q components of the CW currents are symbolized as I_{cd} and I_{cq} , R_c is CW resistance, λ_{cd} and λ_{cq} denote the d and q component of CW flux, respectively, L_c is

the CW inductance, M_{cr} represents the mutual inductance between rotor and CW. Finally, the rotor winding (RW) voltage and flux can be presented mathematically as provided in Equation (10) to (13).

$$V_{rd} = I_{rd}R_r - j(\omega_1 - P_p\omega_r)\lambda_{rq} + \frac{d\lambda_{rd}}{dt} \quad (10)$$

$$V_{rq} = I_{rq}R_r - j(\omega_1 - P_p\omega_r)\lambda_{rd} + \frac{d\lambda_{rq}}{dt} \quad (11)$$

$$\lambda_{rd} = M_{pr}I_{pd} + M_{cr}I_{cd} + L_rI_{rd} \quad (12)$$

$$\lambda_{rq} = M_{pr}I_{pq} + M_{cr}I_{cq} + L_rI_{rq} \quad (13)$$

where V_{rd} and V_{rq} represent the d and q component of rotor winding voltage, R_r is rotor winding resistance, λ_{rd} and λ_{rq} denote the d and q component of rotor winding flux, respectively, while L_r denotes the rotor winding inductance. Similarly, the generated machine torque is given as;

$$T_e = -\frac{3}{2}P_pI_m[\lambda_p^*I_p] - \frac{3}{2}P_cI_m[\lambda_c^*I_c] \quad (14)$$

where T_e denotes the torque, while I_m represents the magnetizing inductance.

The reactive power supplied by PW can be calculated by using Equation (15).²⁷

$$Q_p = -\frac{3}{2}\omega_1|\lambda_p|I_{pq} \quad (15)$$

The q component of the current in the vector control scheme is responsible to regulate the reactive power in the current study. However, the PW flux λ_p is kept constant throughout the simulation run. It is important to mention here that the regulation of reactive power is needed to inject a controlled amount of reactive power at the time of fault so that the unwanted disconnection of the machine from the grid system may be prevented.²⁸

It may be noted that the current research work considers the synchronous operation of BDFIG machine. The rotational speed (ω_r) for the synchronous operation of the machine can be calculated by using Equation (16).

$$\omega_r = \frac{\omega_p + \omega_c}{P_p + P_c} \quad (16)$$

where, ω_p and ω_c represent the excitation angular frequencies supplied by the two stator-windings, that is, PW and CW, respectively. The BDFIG keeps the supply frequency of the PW winding constant (50 Hz) by regulating the frequency of CW through the inverter despite the variation in rotational speed (ω_r) of the shaft. At $\omega_c = 0$, the rotor rotates at natural speed, that is, 52 rad/s, which is referred as the natural or synchronous speed of the BDFIG machine.²⁹

2.2 | Proposed SSA-based vector control scheme

Considering the independent regulation of speed and reactive power, the vector control scheme is utilized in this article to control the behavior of BDFIG-based WECS.³⁰ It enables the machine to remain stable over the wide range of speed regulation as compared to its competitors. The VC scheme consists of PI regulator-based inner and outer control loops. The performance of these regulators depends on the selection of their gains. Generally, the “trial and error” method is utilized to select these gains.³¹ The mentioned method of selecting the PI gains is a manual tuning process and depends on the experience and expertise of the control designer. Besides, it is time-consuming and does not yield optimal outcomes generally. Thus, the WECS may experience an inappropriate overshoot and settling time. To avoid this issue, the

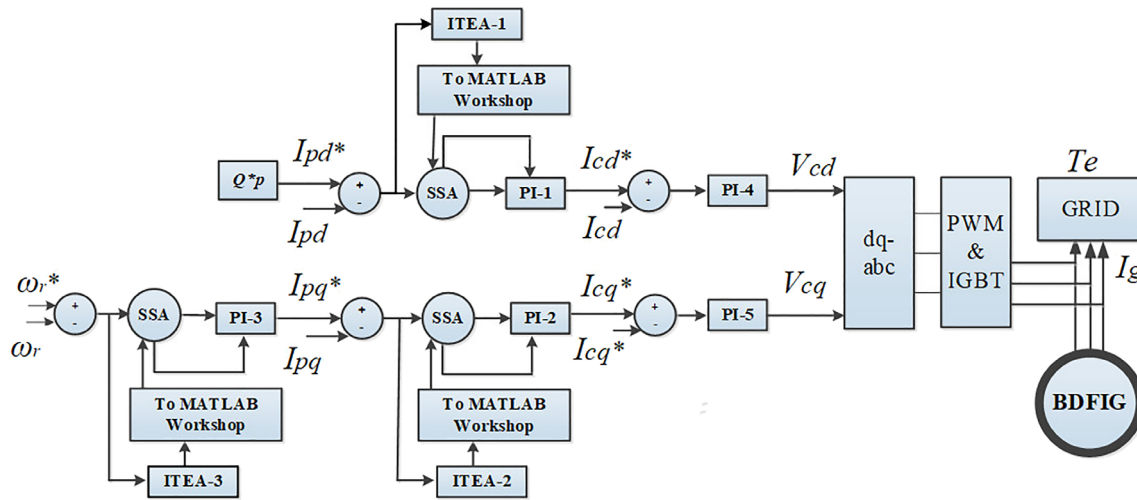


FIGURE 3 Proposed SSA-based Vector Control Scheme. Asterisk “*” sign represents the reference values of the corresponding parameter. It can be seen from Figure 2 that the d component of PW and CW current regulates the reactive power Q_p , while its q component regulates the speed of the machine according to the set control objectives. The gains for the PI regulators PI-1, PI-2, and PI-3 are optimized using SSA as depicted in Figure 3. SSA is utilized to select the most optimal PI gains automatically through an iterative optimization procedure to optimize the dynamic behavior of the developed BDFIG-based WECS. It may be noted that the gain values for PI-4 and PI-5 are not opted as optimization variables. This is to avoid unnecessary complexity in the optimization process and to limit the search space dimensionality for achieving an efficient global optimization

current research work utilizes an automatic PI tuning procedure using swarm intelligence-based metaheuristic techniques called the SSA. The SSA intelligence is utilized to choose the most optimal PI regulator gains by minimizing a predefined error integrating fitness function. The block diagram representation of the BDFIG with the proposed control scheme is given in Figure 3.

3 | OPTIMIZATION AND ITS NECESSITY IN PROPOSED CONTROL DESIGN

The optimization process performs the searching of the most suitable solution among all the feasible solutions for a given optimization problem.³² It accomplishes the mentioned task by minimizing or maximizing a predefined fitness function (FF). Since the current study aims to obtain the most optimal dynamic response of the BDFIG-based WECS using a vector control scheme; the gains of all the PI regulators need to be optimized. In this context, the current study utilizes a swarm intelligence-based optimization technique called SSA in order to achieve the most optimal dynamic response of the considered system. The fitness function opted for the current study is an error integrating expression called integral time absolute error (ITAE) and is given by Equation (17).³³

$$\text{ITAE} = \int_0^t t|e_1(t)| dt + \int_0^t t|e_2(t)| dt + \int_0^t t|e_3(t)| dt \quad (17)$$

where $e_1(t)$, $e_2(t)$, and $e_3(t)$ are the corresponding error values fed to the PI-1, PI-2, and PI-3, respectively.

One of the most widely employed performance evaluation metrics in control applications is integral absolute error (IAE). However, the ITAE tuning makes the controlled systems settle more quickly than the IAE.^{21,34} This is because the inclusion of time in the expression provides an added weight and thus provides a faster corrective action compared to its counterpart. In addition, integral square error (ISE) is also a good performance evaluation criterion for control systems; however, it penalizes the large errors due to error squaring. Contrary to that the ITAE penalizes errors that persist for longer periods of time, thus provides more optimal outcomes. Since the minimization of the ITAE has been opted as a fitness function, its minimum value corresponds to the most optimal dynamic response (least overshoot and settling time) of the proposed BDFIG-based WECS. The magnitude of the ITAE is calculated and updated through an automatic iterative process by using the intelligence of SSA. The algorithm measures the value of formulated fitness function

(ITAE) during each iteration and compares it with the already stored values of ITAE for the previous iteration. If the current value of the fitness function is less than the previous value, it replaces the previous value with the newer one; else it keeps the previous value of the fitness function. Thus, the least possible value of ITAE is achieved at the end of this optimization process, which corresponds to the least area under the curve for the studied variable that consequently corresponds to the least value of overshoot and settling time; thus optimal dynamic response is achieved.

3.1 | Salp swarm optimization algorithm

Contrary to the previously explored manual error minimizing methods such as “trial and error” and internal model control, the current research work utilizes an automatic searching mechanism called SSA to accomplish the mentioned task with reduced complexity and enhanced accuracy.

Salps are related to the family member of the Salpidae group with a translucent barrel-shaped body. To model their movement behavior into an optimization algorithm, their initial positions are initialized randomly as provided in Equation (18).

$$K_1^{1:n} = rand(...) * (ub_j - lb_j) + lb_j, \forall j \in \text{no. of variables} \quad (18)$$

where $K_1^{1:n}$ presents the initial position of the salps, $rand(...)$ is the Matlab command to generate the random number within the upper bound (ub_j) and lower bound (lb_j). In SSA, based on the value of the FF, the complete swarm is divided into two groups, that is, leaders and followers. The leader salps position is updated with Equation (19).

$$K_j^i = \begin{cases} M_i + c_1((ub_j - lb_j)c_2 + lb_j); c_3 \geq 0.5 \\ M_i - c_1((ub_j - lb_j)c_2 + lb_j); c_3 < 0.5 \end{cases} \quad (19)$$

where K denotes the position of the i th leader salp in j th dimension. M_i denotes the food target, while c_2 and c_3 show the random numbers between 0 and 1. The c_1 is a very crucial parameter that helps the salps to catch the food sources efficiently and is given by;

$$c_1 = 2e^{-\left(\frac{4t}{T}\right)^2} \quad (20)$$

where $\frac{t}{T}$ is the ratio of present iteration to the maximum iterations number. Since the minimization of the fitness function is utilized as the optimization problem in current research work, half of the total salps with the least fitness function value are considered as leaders, while the remaining are treated as followers. The follower salps position is updated by using the Equation (21).

$$K_j^i = \frac{K_j^i + K_j^{i-1}}{2} \quad (21)$$

It is important to note that the salp chain searches for the best solution by exploring and exploiting the search space during each iteration to constantly move toward the food source (global best). The motivation for opting for SSA to solve the current optimization problem lies in its diversified searching mechanism, reduced complexity, only one controlling parameter (c_1), and superior exploration and exploiting properties.³⁵

3.2 | Implementation of studied optimization methods for optimal PI parameter selection

This research employs three different optimization techniques (IMC, PSO, and SSA) to enhance the dynamic response of the considered BDFIG-based WECS. IMC is an analytical PI parameter selection method that considers the system parameters for compensating its open-loop poles with the zeros of the PI controller, thus provides the desired closed-loop bandwidth and time constant. A detailed mathematical description of IMC can be found in Reference 22. On the other hand, PSO and SSA are swarm intelligence-based optimization techniques that provide the optimized solution

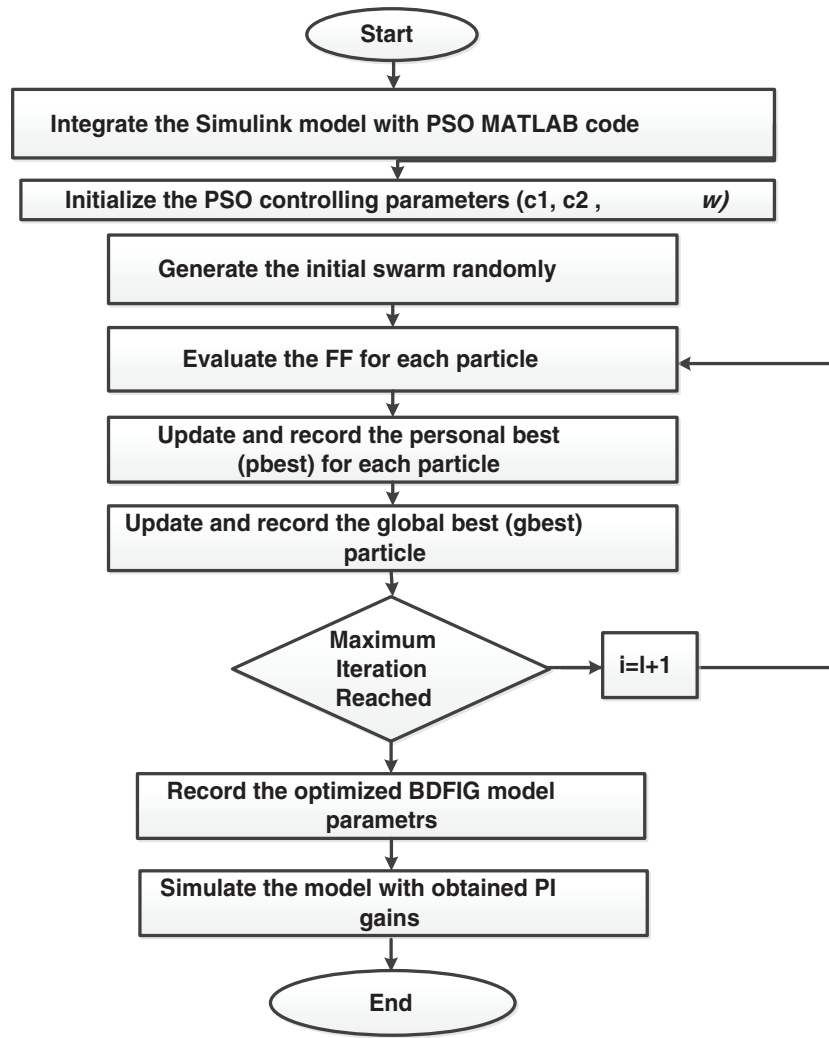


FIGURE 4 Flow chart for PSO-based vector control scheme

through an iterative process. Unlike the IMC, swarm intelligence–based methods do not require a complete mathematical model of the system. These optimization methods employ a random number generation within the bounded search space at their very initial stage of operation. Afterward, the fitness of each search agent is calculated, and their position is updated based on the governing equations of the algorithm iteratively until the required number of iterations are completed. A complete flowchart for the implementation of the PSO- and SSA-based vector control scheme is provided in Figures 4 and 5, respectively.

It is worthwhile to mention that, finding the optimal gains for several PI controllers through the IMC method accurately is a quite tedious and time-consuming job. This is because of the reason that the mentioned method requires complex calculations using a detailed mathematical model of the studied control system which may not be feasible in certain large and complex systems. On the other hand, the swarm intelligence–based optimization methods such as PSO and SSA does not require complete information of the system to be optimized since they can treat the system as a black box, and only a little information such as fitness function and optimized variable is required to perform the optimization task.²³ In terms of computational burden, the IMC is better than PSO and SSA since the latter utilizes an iterative procedure to reach an optimized solution, which puts an additional burden on the controller.

4 | RESULTS AND DISCUSSION

In order to examine the efficacy of the proposed SSA-controlled VC scheme based on BDFIG-WECS in regulating torque, reactive power, and speed, its modeling is simulated in MATLAB/SIMULINK version 2018b, while the codes for

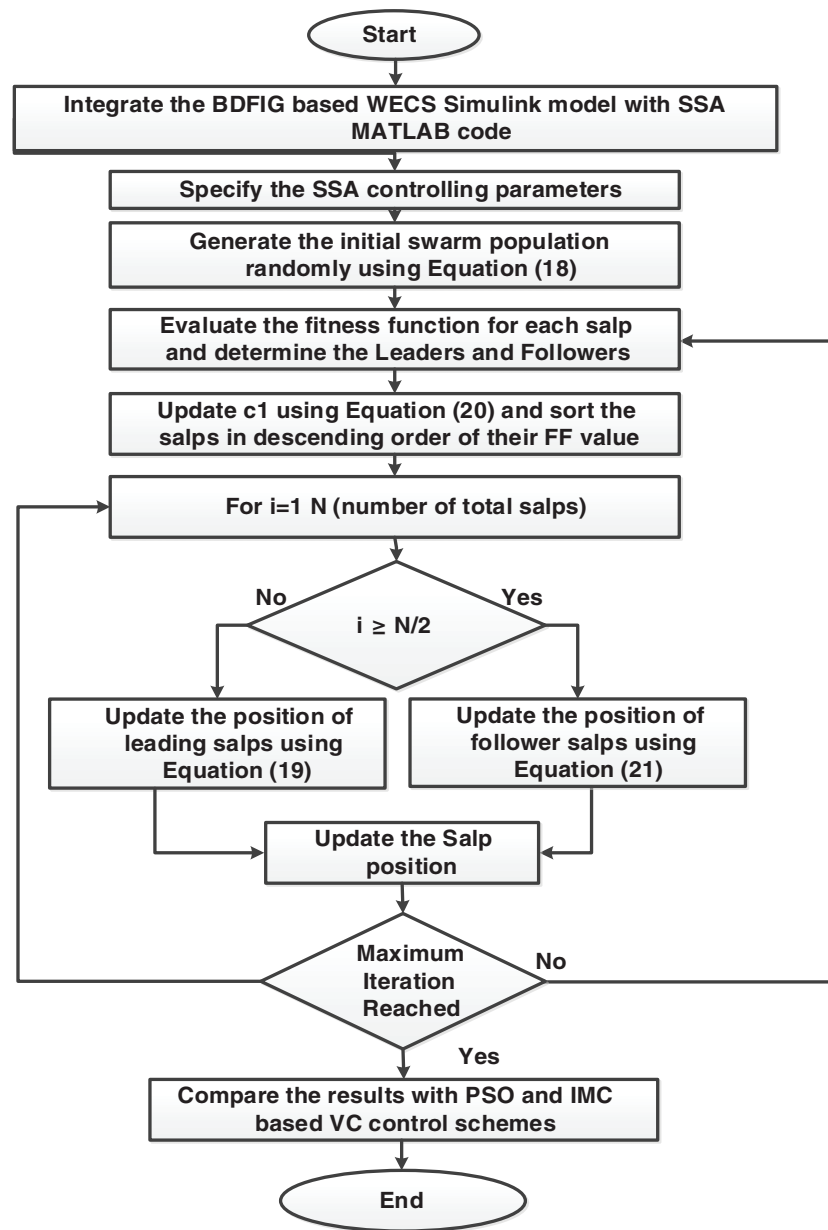


FIGURE 5 Flow chart for proposed SSA-based vector control scheme

TABLE 1 Optimization parameters

Parameters	PSO	SSA
Maximum number of iterations (i)	50	50
Population size (N)	50	50
Upper boundary of PI gains (ub_j)	50	50
Lower boundary of PI gains (lb_j)	0.001	150
Number of dimensions (D)	06	06
PSO cognitive constant (C_1)	2	—
PSO social constant (C_2)	2	—
inertia weight (ω)	0.9-0.4	—
Random numbers (C_1, C_2)	—	Random (0-1)

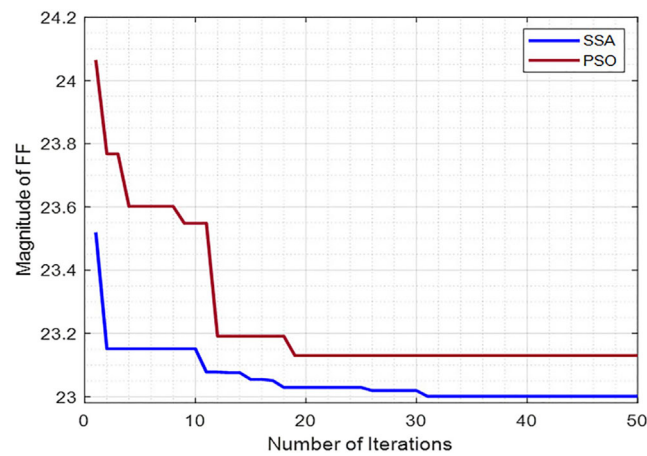


FIGURE 6 Convergence curve

TABLE 2 Machine parameters

Parameter	Value	Parameter	Value
PW pole pairs (pp)	2	Power winding resistance (R_{sp})	2.3 Ω
CW pole pairs (pc)	4	Control winding resistance (R_{sc})	4 Ω
PW voltage	240 V	Rotor winding resistance (R_r)	1.2967e ⁻⁴ Ω
CW voltage	240 V	Self-inductance of PW (L_{sp})	0.3498 H
PW current	8 A	Self-inductance of CW (L_{sc})	0.3637 H
CW current	8 A	Self-inductance of RW (L_r)	4.4521e ⁻⁵ H
Rated torque	100 Nm	Mutual inductance between PW and RW (L_{hp})	0.0031 H
Grid frequency (f_p)	50 Hz	Mutual inductance between CW and RW (L_{hc})	0.0022 H
Synchronous speed	52 rad/s	Rotor moment of inertia (J)	0.4 kg m ²

TABLE 3 Optimal PI regulator gain values for studied techniques

	Controller	Gain	Value
IMC	PI-1	K_{P1}	15.9624
		K_{i1}	146.1958
	PI-2	K_{P2}	9.6479
		K_{i2}	0.0022
	PI-3	K_{P3}	1.7667
		K_{i3}	8.8331
PSO	PI-1	K_{P1}	12.5343
		K_{i1}	141.9568
	PI-2	K_{P2}	7.9052
		K_{i2}	0.0122
	PI-3	K_{P3}	2.5843
		K_{i3}	9.3160
SSA	PI-1	K_{P1}	9.2309
		K_{i1}	137.4510
	PI-2	K_{P2}	6.7590
		K_{i2}	0.0187
	PI-3	K_{P3}	3.7822
		K_{i3}	9.8246

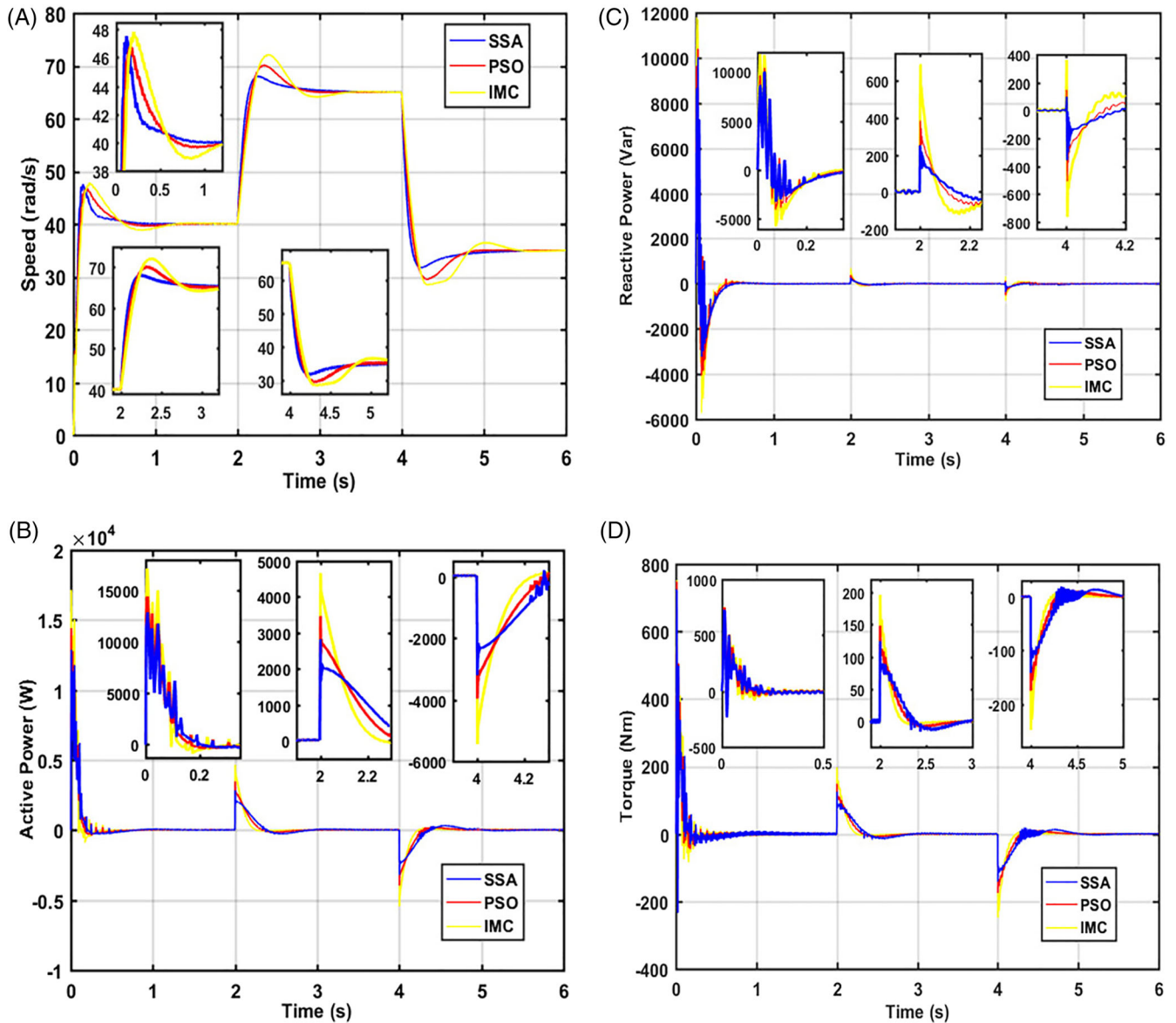


FIGURE 7 (A) Speed regulation, (B) active power, (C) reactive power, and (D) torque

the PSO and SSA are encrypted in MATLAB Editor window. To validate the efficacy of the proposed control scheme, IMC- and PSO-based controllers are compared with the SSA performance under identical system configuration operating conditions. The optimization parameters utilized for the PSO and SSA are provided in Table 1, while the convergence profile for both the studied algorithms is depicted in Figure 6.

As can be observed from Figure 6 that the SSA, due to superior exploration vs exploitation balancing capability and diversified search mechanism, achieves a better solution quality compared to that of the PSO under identical optimization parameters and system operating conditions. The BDFIG-based WECS parameters utilized in current research work are depicted in Table 2, while the optimal PI gains achieved at the end of the optimization process are provided in Table 3.

Based on the objective of the study, the simulated outcomes from the proposed control strategy are divided into three broad categories as discussed below.

4.1 | Case A: Speed regulation

The electrical machines in WECS need to provide consistent power output despite the continuous variations in wind speed. The wind speed decides the amount of power that can be extracted from WECS. Since wind energy is variable in

TABLE 4 Dynamic response evaluation for Speed curve

	Speed		
	SSA	PSO	IMC
Rise time (ms)	50.554	60.475	75.705
Overshoot (%)	6.452	7.059	9.88
Settling time (s)	0.6065	1.1691	1.3491
Peak value (rad/s)	47.52	46.74	47.81

TABLE 5 Dynamic response evaluation for active and reactive power curve

	Active power		
	SSA	PSO	IMC
Rise time (ms)	1.007	1.233	1.554
Overshoot (%)	55.00	66.630	70.487
Settling time (s)	0.7168	0.7528	0.9152
Peak value (W)	1.287e ⁴	1.442e ⁴	1.715e ⁴
	Reactive power		
	SSA	PSO	IMC
Rise time (ms)	3.841	4.253	6.281
Overshoot (%)	12.273	20.363	53.063
Settling time (s)	0.63814	0.8123	0.9241
Peak value (Var)	1.002e ⁴	1.039e ⁴	1.179e ⁴

TABLE 6 Dynamic response evaluation for Torque curve

	Torque		
	SSA	PSO	IMC
Rise time (ms)	1.271	2.910	3.219
Overshoot (%)	41.324	61.127	114.520
Settling time (s)	1.1647	1.5841	1.9417
Peak value (Nm)	713.9	804.2	879.0

nature and is directly associated with the power frequency of the supply, its regulation is of utmost importance for any WECS. The connection of variable frequency source (wind) with fixed frequency source (grid) adds severity to the problem and may cause power flickering, system instability, and disconnection if not controlled properly. To analyze the effectiveness of the proposed control scheme in regulating the wind speed and its impact on the system variables such as active power, reactive power, and torque, the proposed BDFIG machine is made to run at the variable speed from 40 (sub-synchronous speed) to 65 rad/s (super-synchronous speed) under no-load condition. To accomplish this task in the developed simulation model, a step change in the reference speed is made at 2.0 and 4.0 seconds of the simulation run. The equivalent response of the system is shown in Figure 7A, while its impact on active power, reactive power, and torque is depicted in Figure 7B-D, respectively.

It may be noted from the figures that the proposed optimization technique SSA provides a better dynamic response and tracks the reference signal efficiently with the least overshoot and settling time compared to IMC- and PSO-based controllers under identical operating conditions. Since there is no torque applied to the machine as evident from Figure 7D, the active and reactive power remains constant at zero value except for the transient period (at 2.0 and 4.0 seconds) where a sharp change in reference speed causes a corresponding change in mentioned quantities. Tables 4

to 6 quantify the speed, active and reactive power, and torque, respectively, on a few important dynamic response evaluation metrics such as rise time, percentage overshoot, and settling time.

4.2 | Case B: Dynamic response evaluation due to step changes in torque

One of the essential features of a good wind turbine control scheme is to sustain the stability of the system during sharp changes in torque. A well-controlled wind turbine should regulate the speed and reactive power of the machine at a constant value despite the changes in the applied torque. In addition, it should provide a decent transient response during sharp changes in torque. In other words, the speed and active and reactive power curves should follow the variations in torque with the least possible overshoot, rise time, and settling time during the transient period. To evaluate the performance of the proposed controller under severe fluctuations in torque, two-step changes in torque (30-60 Nm and 60-95 Nm) are applied to the BDFIG system at 2.0 and 4.0 seconds of the simulation run. The equivalent response is depicted in Figure 8A, while its impact on the active power, reactive power, and speed are provided in Figure 8B-D, respectively.

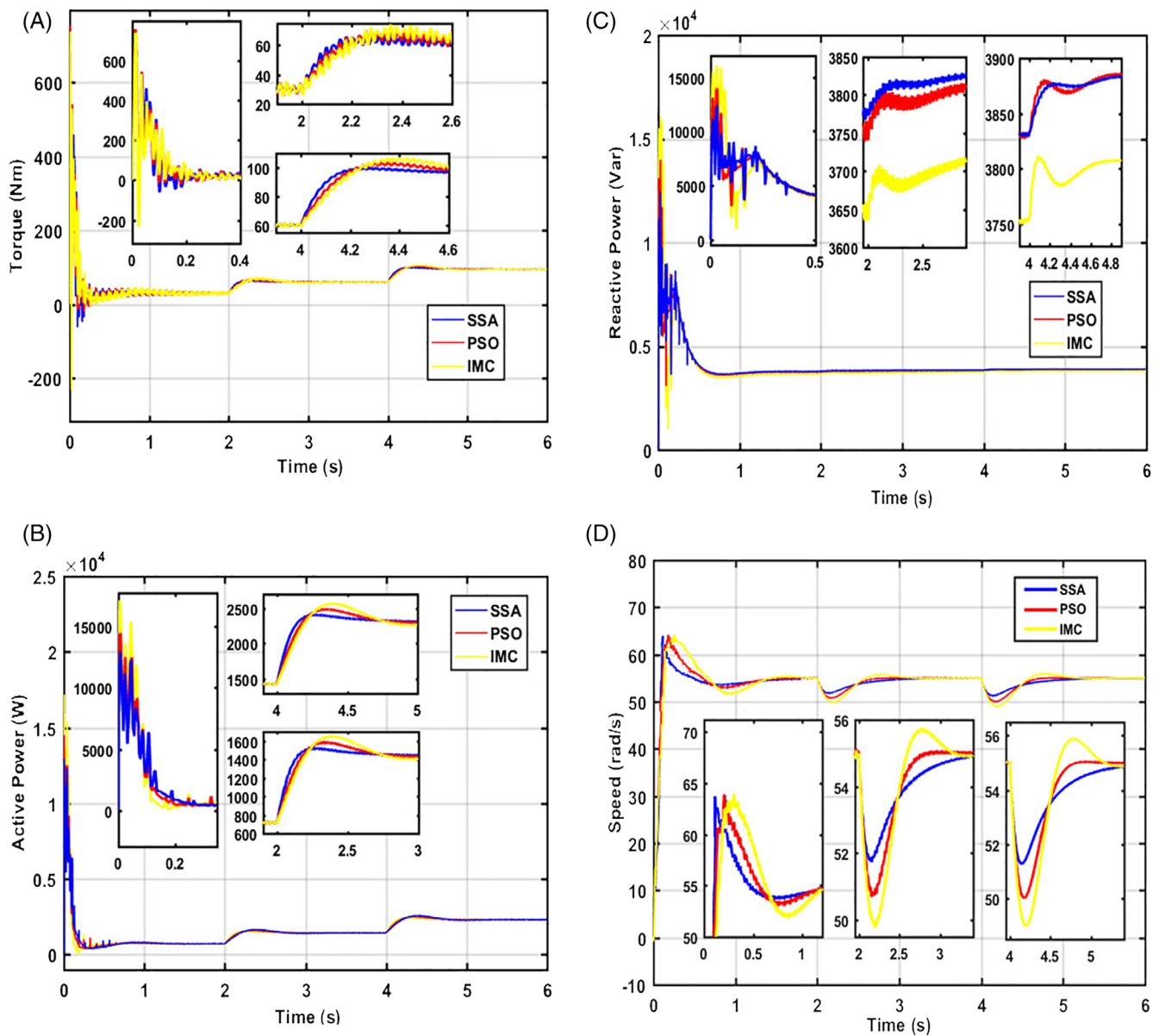


FIGURE 8 (A) Torque effect, (B) active power, (C) reactive power, and (D) speed regulator

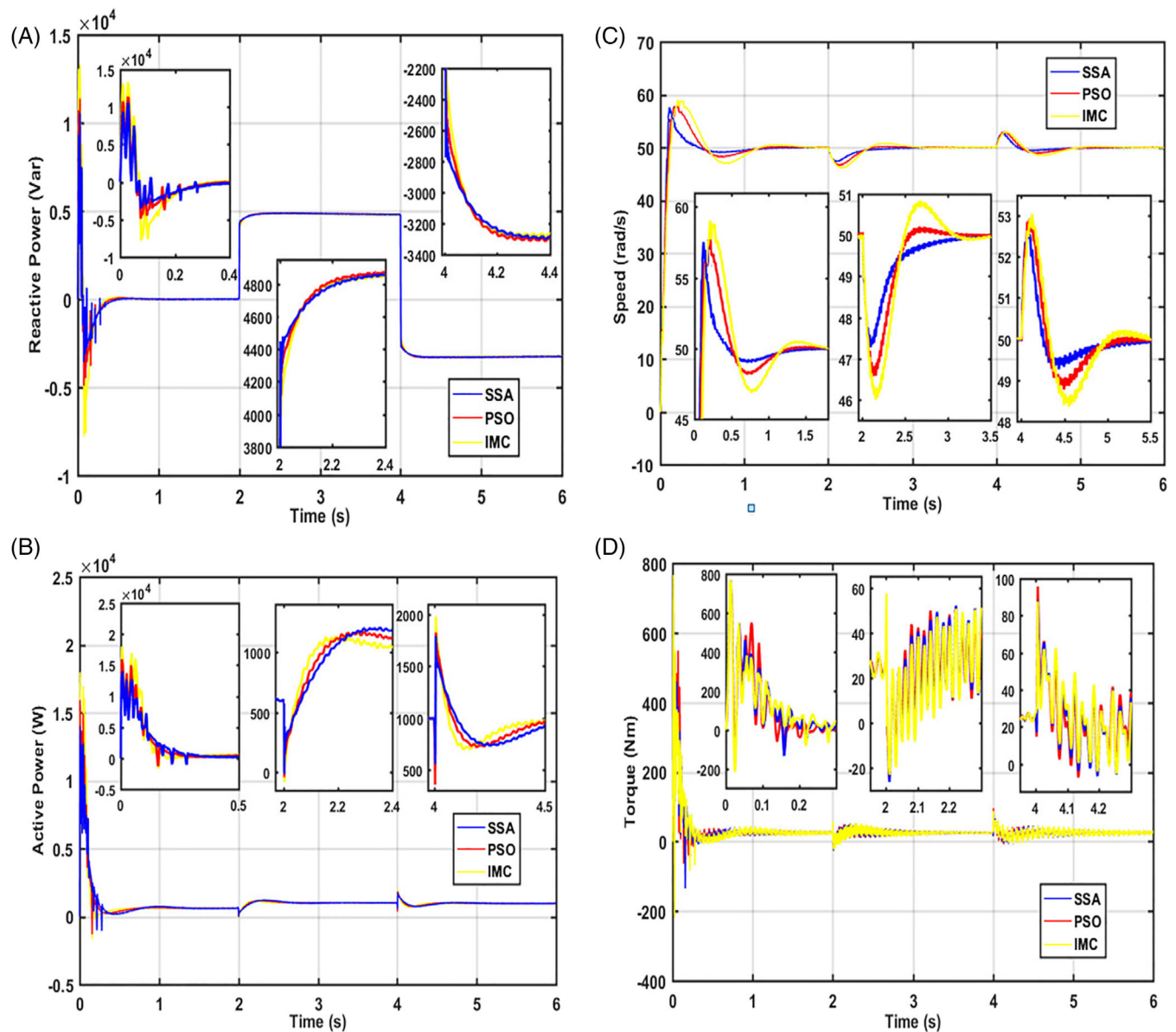


FIGURE 9 (A) Reactive power, (B) active power, (C) speed regulator, and (D) torque during a reactive power change

TABLE 7 Dynamic response evaluation for Torque

	Torque		
	SSA	PSO	IMC
Rise time (ms)	1.541	3.106	2.857
Overshoot (%)	68.626	81.325	149.704
Settling time (s)	0.7370	1.2497	1.5431
Peak (Nm)	713.9	804.2	879.0

As shown in Figure 8 that, despite the sharp changes in the applied torque, the machine is able to maintain its rated active power, reactive power, and synchronous speed with an appropriate dynamic response under all the studied control schemes. Nevertheless, the SSA-based controller provides the most optimal dynamic response as compared to PSO- and IMC-based controllers, thus validates the efficacy of the proposed control scheme. To extract

TABLE 8 Dynamic response evaluation for reactive power

	Active Power		
	SSA	PSO	IMC
Rise time (ms)	1.221	1.874	2.235
Overshoot (%)	23.123	60.192	66.827
Settling time (s)	0.8136	1.1248	1.3152
Peak value (W)	1.401e ⁴	1.623e ⁴	2.17e ⁴
	Reactive power		
	SSA	PSO	IMC
Rise time (s)	2.253	2.890	2.717
Overshoot (%)	19.767	26.974	41.437
Settling time (s)	1.2166	1.3264	1.3952
Peak (var)	1.243e ⁴	1.398e ⁴	1.611e ⁴

TABLE 9 Dynamic response evaluation for shaft speed

	Speed		
	SSA	PSO	IMC
Rise time (ms)	30.248	47.612	63.863
Overshoot (%)	10.75	13.615	19.401
Settling time (s)	1.2143	1.3521	1.4256
Peak (rad/s)	62.61	63.88	63.91

TABLE 10 Values for reactive power

	Reactive Power		
	SSA	PSO	IMC
Rise time (s)	1.826	2.562	3.403
Overshoot (%)	39.023	52.039	61.455
Settling time (s)	0.6124	0.8476	0.9251
Peak (Var)	1.056e ⁴	1.137e ⁴	1.327e ⁴

TABLE 11 Values for active power and torque

	Active power		
	SSA	PSO	IMC
Rise time (ms)	0.854171	0.970235	1.494
Overshoot (%)	60.208	109.306	112.933
Settling time (s)	0.8146	1.0241	1.1451
Peak value (W)	1.399e ⁴	1.591e ⁴	1.797e ⁴
	Torque		
	SSA	PSO	IMC
Rise time (ms)	2.045	2.384	3.254
Overshoot (s)	49.533	104.899	114.842
Settling time (s)	0.8146	1.0945	1.1854
Peak (Nm)	739.2	754.7	764.6

TABLE 12 Values for speed

	Speed		
	SSA	PSO	IMC
Rise time (ms)	61.789	76.836	86.854
Overshoot (%)	1.698	8.452	9.880
Settling time (s)	1.1761	1.2668	1.5263
Peak (rad/s)	57.21	57.78	59.03

the insight information regarding the dynamic response of the active and reactive power and shaft speed during sharp changes in torque, the assessment of the dynamic response is made and provided in tabular form in Tables 7 to 9, respectively.

The proposed SSA-based BDFIG controller provides the most optimal dynamic response as compared to the IMC- and PSO-based controllers during sharp changes in shaft speed. The proposed controller provides a rise time of 1.541 seconds, percentage overshoot of 78.626 and settling time of 1.7370 seconds, which are better than their corresponding values with IMC- and PSO-based tuning methods.

4.3 | Case C: Reactive power control

Regulation of the reactive power is very essential in wind turbines as it helps to fulfill the grid code requirements during normal and grid fault conditions. Therefore, it is very important to assess the performance of the designed control scheme in efficiently tracking the preset value of reactive power with a suitable dynamic response. To accomplish this task, sharp changes in the reference reactive power are injected at 2.0 and 4.0 seconds of the simulation run. The corresponding response of the mentioned changes in reactive power is shown in Figure 9A, while its impact on active power, shaft speed, and torque for all the studied control schemes is depicted in Figure 9B-D, respectively.

Once again, the proposed control scheme outperforms all the studied control schemes in achieving the most optimal dynamic response during the considered changes in reactive power. The quantification of the dynamic response for all the studied PI tuning methods provided in Figure 9A-D is made in Tables 10 to 12, respectively.

The proposed control scheme provides the least parentage overshoot and settling time among the considered parameter selection methods, thus, proves its efficacy and essence in designing an optimal VC scheme-based BDFIG-WECS.

5 | CONCLUSION

In this article, the SSA-based VC scheme is presented for enhancing the dynamic response of a WECS utilizing a BDFIG machine as the electric power generator. To avoid the demerits of conventional time-consuming and inefficient manual PI tuning methods used in conventional VC schemes, the intelligence of SSA is utilized to select the most optimal set of PI gains automatically through an iterative process. This is achieved through minimization of an error integrating FF, which consequently led to the least percentage overshoot and settling time in speed, torque, and reactive power curves at the end of the iterative process. The outcomes obtained from the SSA-based VC scheme are compared with that of the PSO and conventional IMC method-based controllers under identical operating conditions and system configuration. The SSA provides better solution quality and a higher convergence rate than PSO and achieves a better transient response in terms of rise time, settling time, overshoot, and peak value, thus validates the essence and efficacy of the proposed control scheme.

PEER REVIEW

The peer review history for this article is available at <https://publons.com/publon/10.1002/2050-7038.13157>.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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