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Optimizing Proportional Integral (PI) Controller Using Particle Swarm Optimization (PSO) Method in Active Rectifier

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Abstract – *In the era of Industry 4.0, power converters such as Active Rectifiers have become crucial for converting AC voltage to adjustable DC voltage. While implementing a DC Constant Power Load is beneficial, it introduces additional complexity in maintaining power system stability. This research optimizes PI control on Active Rectifiers using the PSO method to address this challenge. The results indicate that the PI controller optimized with PSO achieved a Kp of 0.4509 and a Ki of 2.7611 in tests with resistive loads, and a Kp of 3.1364 and a Ki of 6.8141 in tests with constant power loads. Using constant power loads showed a faster response with lower rise time but often resulted in higher overshoot compared to resistive loads. Nevertheless, both testing conditions demonstrated a stable system without undershoot, confirming the effectiveness of the PI-PSO controller in optimizing the performance of active rectifiers for more responsive and efficient power electronics applications.*

***Keywords**: Active Rectifier, PI Controller, PSO, Constant Power Load*

I. Introduction

In the era of Industry 4.0, marked by changes in production systems and technological devices, the interconnection between electronic devices has significantly increased. One key component in electrical systems is the power converter, which plays a crucial role in converting AC voltage to DC voltage[1]. In this context, the active rectifier represents an extraordinary evolution of power converters and has become a focus of cutting-edge research due to its ability to produce better-regulated DC voltage compared to conventional methods[2][3].

Active rectifiers face several challenges that need to be addressed to ensure their operational efficiency. One of the main obstacles is the use of DC Constant Power Load (CPL) as part of the power system, which introduces additional complexity. A DC CPL is a load that maintains constant power consumption regardless of input voltage fluctuations. Despite its many benefits, implementing a DC CPL can also present unique challenges, such as negative resistance, which increases current when voltage drops. Voltage fluctuations can lead to instability in the system[4].

To address these challenges, this study emphasizes the importance of optimizing the Proportional Integral (PI) controller in active rectifiers to maintain the stability of the DC output voltage. Employing the Particle Swarm Optimization (PSO) method can effectively overcome the challenges of determining the optimal PI parameters. Inspired by the collective behavior of groups in nature, PSO has proven successful in various optimization applications, including control settings. Through PSO, the search for optimal PI parameters (Kp and Ki) can be conducted both efficiently and accurately[5][6].

The use of the PSO optimization method on PI controllers has been conducted by previous researchers. In the study titled "Implementation of PV-Based Boost Converter Using PI Controller with PSO Algorithm," the PSO method and PI controller were applied to a photovoltaic (PV) system to achieve maximum power. MATLAB/SIMULINK simulations demonstrated improved tracking speed, oscillation elimination, and the ability to find the maximum power point[7]. Another study titled

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"Optimal Tuning of PI Controller for Speed Control of DC Motor Drive Using Particle Swarm Optimization" compared the PI controller parameter tuning methods using Ziegler-Nichols, Modified Ziegler-Nichols, and PSO optimization in a DC motor system. PSO showed superior performance in minimizing rise time, settling time, and overshoot for better speed response [19]. The study "PSO-Based PI Controller for Speed Sensorless Control of PMSM" tested various optimizations by comparing the speed of a permanent magnet synchronous motor (PMSM) without a sensor using PI controllers with Heuristics, MATLAB PID auto tuner, and PSO. Simulations showed that PSO produced better performance in parameters such as rise time, settling time, overshoot, undershoot, and root mean square error (RMSE)[8]. In the research titled "Design of PI Controller in Pitch Control of Wind Turbine: A Comparison of PSO and PS Algorithm," the PI controller with PSO optimization method was used in a wind energy conversion system (WECS). PSO demonstrated advantages in designing controllers with shorter times and better accuracy compared to other algorithms[9].

II. Research Method

The primary objective of this research is to analyze the stability of an active rectifier with a PI controller optimized using PSO under constant power load and resistive load conditions. The research process includes various essential stages: beginning with the initial stage, marking the start of the research; problem identification and formulation to analyze the characteristics of constant power loads and compare them with resistive loads; a literature review and analysis of relevant studies on active rectifiers, PI controllers, and PSO optimization, along with data collection on parameters. Following this is the determination of main parameters for simulation, including system parameters, PI controller criteria, performance metrics, and PSO parameters. The system design phase involves designing the active rectifier system with the PI controller and PSO optimization. Simulations are then conducted in MATLAB with constant power and resistive loads. Performance evaluation and analysis follow, assessing the system's performance before and after optimization, evaluating the effectiveness of the PSO-optimized PI controller, and validating simulation results against literature to ensure accuracy and reliability. The final stage concludes by summarizing the key findings and drawing conclusions based on the research results.

II.1. *Active Rectifier System*

Figure 1 illustrates the block diagram scheme of an Active Rectifier system. The grid eabc is known as a 3-phase voltage source that feeds back to the DC Bus Controller. Together with Vdc from the capacitor, these voltages are used to regulate and control the output voltage of the active rectifier[10]. The DC Bus Controller comprises several key components: the Clark Transform, which converts 3-phase voltage (abc) into 2-phase voltage (αβ); the Park Transform, which converts 2-phase voltage (αβ) into voltage in dq reference; the Phase Locked Loop (PLL), which synchronizes the frequency and phase of the grid voltage with the control system; and the Proportional Integral (PI) controller[11][12][2]. In this study, the PI controller is optimized using Particle Swarm Optimization (PSO) to find optimal values of Kp and Ki that maximize the performance of the active rectifier system.

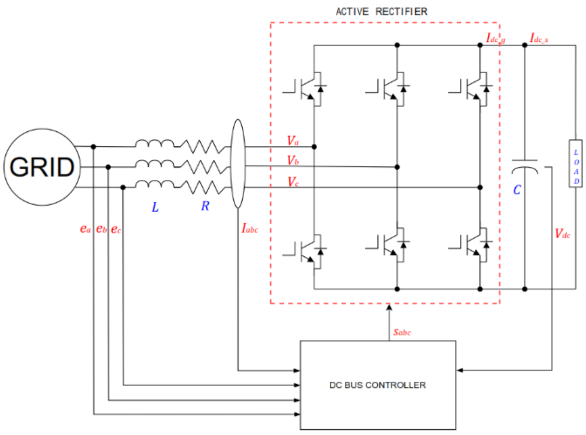

Fig. I. Block Diagram of Active Rectifier System

II.2. *Proportional Integral Controller*

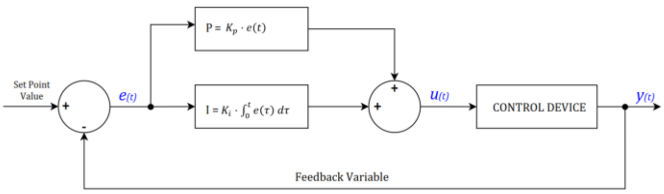

Fig. II. Block Diagram of Control System with PI Controller

A PI controller is a feedback controller consisting of Proportional (P) and Integral (I) components. The Proportional component generates a control signal based on the error between the set point and the actual output, while the Integral component accumulates error over time to reduce steady-state error, thus providing a quick response to changes [13]. The basic equation for a PI controller is as follows:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(\tau)\, d\tau \qquad (2.1)$$

Where u(t) is the generated control signal, e(t) represents the error between the set point and the actual output, Kp denotes the proportional gain, and Ki represents the integral gain. To evaluate controllers such as the PI controller, several indicators are used, including

IAE (integral absolute error)

$$IAE = \int_0^T |e(t)| dt \qquad (2.2)$$

ISE (integral of square error)

$$ISE = \int_0^T e^2(t)\, dt \qquad (2.3)$$

ITAE (integral of absolute error)

$$ITAE = \int_0^T t|e(t)| dt \qquad (2.4)$$

ITSE (integral of square error)

$$ITSE = \int_0^T t\, e^2(t)\, dt \qquad (2.5)$$

In this study, the objective function used is the ITAE indicator. This performance metric combines time and error magnitude, giving greater weight to errors occurring at the beginning of the control process. ITAE provides a better depiction of system performance in reducing overall error and the time required to reach the set point [14][15]. A smaller ITAE value indicates better controller performance in reducing error and achieving the set point in less time [16].

II.3. *PI Controller with PSO*

The PI controller system using the Particle Swarm Optimization (PSO) method is implemented by searching for PI parameters (Kp and Ki) through simulations in MATLAB software. The process flow of tuning PI parameters using the PSO method is illustrated in Figure 4.

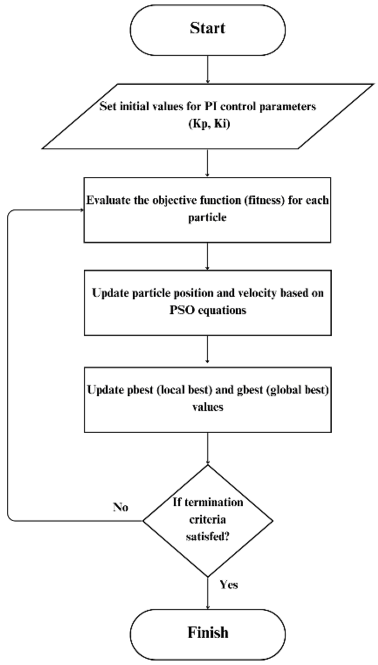

Fig. III. Flowchart of PI Controller Design with PSO Optimization Method

In this study, the objective function applied is the integral of absolute error (ITAE). The boundary function in this research is set as the minimum ITAE value, meaning the optimization goal is to minimize ITAE to achieve optimal controller system performance. The parameters used in this study include various variables relevant to PI controller tuning, such as the proportional constant (Kp) and integral constant (Ki) [17][18]. These parameters will be optimized using the Particle Swarm Optimization (PSO) method to find combinations of values that yield the best performance according to the predefined ITAE criteria [19][20]. During this optimization process, simulations are conducted using MATLAB to ensure accuracy and efficiency in tuning control parameters.

TABLE. 1
PSO PARAMETER FOR PI CONTROLLER

No	Parameter	Unit
1	Number Variabel (nVar)	2
2	Number of Particel (noP)	5
3	Maksimal Iteration (maxIter)	50
4	Upper Bound Kp, Ki	10, 10
5	Lower Bound Kp, Ki	0, 0

No	Parameter	Unit
6	Acceleration Constant (C1)	2
7	Acceleration Constant (C2)	2
8	Weight Factor	$w = wMax - t\left(\frac{wMax - wMin}{maxIter}\right)$

TABLE. 2
GBEST VALUES (KP AND KI) AND OBJECTIVE FUNCTION FOR EACH ITERATION IN RESISTIVE LOAD

Iteration	Gbest		Objective Function
	Kp	Ki	
1	1.8410	7.2578	5.7092
5	0.5661	6.2074	1.5234
10	0.5661	6.2074	1.5234
15	0.6030	3.2489	1.3357
20	0.4843	3.0666	1.3139
25	0.3930	2.6823	1.2939
30	0.4728	2.8152	1.2886
35	0.4534	2.8267	1.2800
40	0.4513	2.7332	1.2758
45	0.4513	2.7332	1.2758
50	0.4509	2.7611	1.2742

III. Results And Discussion

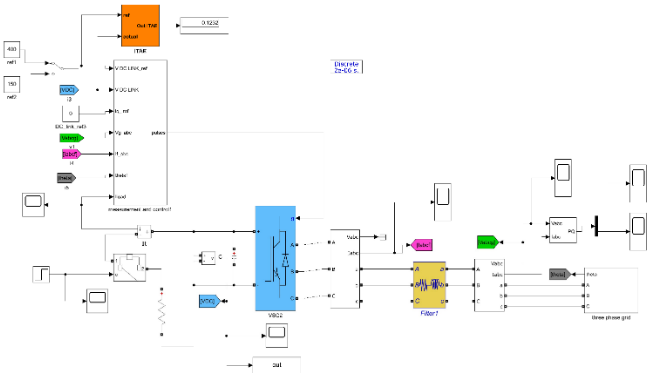

Fig. IV. Simulation of Active Rectifier System with PI-PSO Controller

At this stage, several tests are conducted. Firstly, tuning of the PI controller using the PSO method on the active rectifier with resistive load. Secondly, tuning of the PI controller using the PSO method on the constant power load. The PI controller needs to be optimized with PSO because this method can efficiently and effectively find optimal parameters, thereby enhancing controller performance in maintaining system stability and response. Thirdly, testing of the PI controller optimized with the PSO method on the active rectifier, both with resistive and constant power loads. These tests aim to measure reference voltage and actual voltage to observe the effect of load variations. Figure 4 depicts the testing of the active rectifier with the PI-PSO controller using MATLAB software.

Based on Table 2, the analysis of the first test, which involves tuning the PI controller using the PSO method on the active rectifier with resistive load at time 0 seconds, shows successful optimization in reducing the objective function values through adjustments in Kp and Ki parameters. From the first iteration to the 5th iteration, there is a significant decrease in Kp, Ki values, and the objective function. However, from the 5th iteration to the 10th iteration, both Kp, Ki values, and the objective function remain constant, indicating temporary stability in the optimization process. The significant drop in Kp and Ki values in the first iteration, followed by a slower decrease from the 10th to the 50th iteration, demonstrates that the PSO optimization method swiftly identifies a better parameter range and then makes minor adjustments to Kp and Ki values. This process continues until the 50th iteration to achieve optimal results. It is noted that the optimal objective function value reached at the 50th iteration is 1.2742, with Kp = 0.4509 and Ki = 2.7611. The PI controller resulting from PSO tuning is henceforth referred to as the PI-PSO controller.

In the second test, an evaluation was conducted on the PI-PSO controller applied to the active rectifier with resistive load at time 0 seconds. In this test, the parameters Kp and Ki obtained from the PI-PSO tuning process are 0.4509 and 2.7611, respectively. The evaluation involved measuring the voltage at the active rectifier, where the reference voltage was set to 400 VDC, and a resistive load of 100 ohms was used. The results of the actual voltage measurements at the active rectifier with a 100-ohm load are presented in Figure 5.

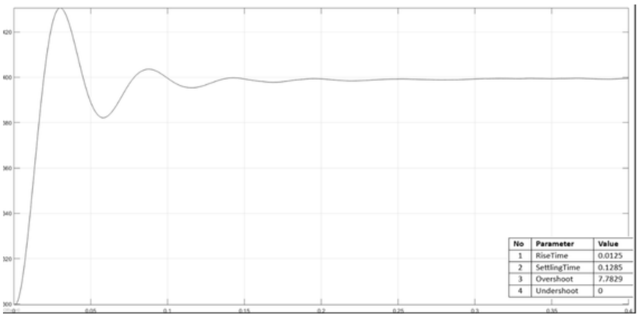

Fig. V. Actual Voltage with 100-ohm Resistive Load at Time 0 Seconds

From the test results, it can be observed that the system exhibits a very fast rise time of 0.0125 seconds, indicating a swift response to changes. The settling time of 0.1285 seconds demonstrates that the system quickly reaches a stable condition after the addition of the resistive load. An overshoot of 7.7829% indicates a slight surge above the desired reference voltage before achieving stability, which is a common characteristic of systems with a fast response. The undershoot value of 0% indicates that the system does not experience a drop below the reference voltage during the transient period.

In the third test, an evaluation was conducted on the PI-PSO controller applied to the active rectifier with a resistive load at time 0.25 seconds. In this test, the parameters Kp and Ki obtained from the PI-PSO tuning process were 0.4509 and 2.7611, respectively. The evaluation involved measuring the voltage on the active rectifier, with the reference voltage set to 400 VDC and a resistive load of 100 ohms applied at time 0.25 seconds. The results of the actual voltage measurements on the active rectifier with the 100-ohm load are presented in Figure 6.

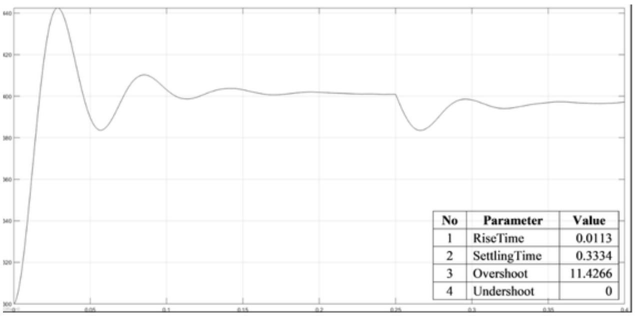

Fig. VI. Actual Voltage with 100-ohm Resistive Load at Time 0.25 Seconds

From the test results, it was found that the system has a very fast rise time of 0.0113 seconds, which is even slightly faster than the rise time of 0.0125 seconds observed in the second test. This indicates that the addition of a 100-ohm resistive load does not significantly slow down the initial system response, as the resistive load becomes active at 0.25 seconds. However, the settling time increased to 0.3334 seconds compared to 0.1285 seconds in the second test. This shows that after adding the resistive load, the system takes longer to reach a stable condition. A resistive load can slow down the settling time because it adds extra load that the system must stabilize, increasing complexity and requiring more time for the system to adjust and achieve stability.

Additionally, there was an increase in overshoot to 11.4266% of the reference voltage. This value indicates that the overshoot becomes larger after the resistive load is added at 0.25 seconds, up from 7.7839% in the second test. The undershoot value remains at 0%, indicating that despite the increase in overshoot, the system does not experience a drop below the final value during the transient period.

TABLE. 3
GBEST VALUES (KP AND KI) AND OBJECTIVE FUNCTION FOR EACH ITERATION IN CPL LOAD

Iteration	Gbest		Objective Function
	Kp	Ki	
1	1.2699	9.1338	2.9286
5	0.7582	6.9244	1.8025
10	0.7582	6.9244	1.8025
15	3.1268	8.1334	1.6835
20	3.1268	8.1334	1.6835
25	3.1268	8.1334	1.6835
30	3.1268	8.1334	1.6835
35	3.1213	7.2025	1.6497

Iteration	Gbest		Objective Function
	Kp	Ki	
40	3.1392	6.7944	1.6307
45	3.1364	6.8160	1.6273
50	3.1364	6.8141	1.6273

In the fourth test, the tuning of the PI controller using the PSO method was evaluated on the active rectifier with a constant power load at time 0 seconds. Based on Table 3, the analysis results show the success of the optimization process in reducing the objective function value through the adjustment of the Kp and Ki parameters. From iteration 1 to iteration 5, there was a significant decrease in the values of Kp, Ki, and the objective function. However, after iteration 10, Kp increased while Ki remained consistent at a high value before eventually decreasing again from iteration 35 to iteration 50.

There were small fluctuations in the Kp and Ki values from iteration 40 to iteration 50, indicating that the parameters were still being optimized to achieve the minimum objective function value. The objective function showed a significant decrease from iteration 1 to iteration 10, indicating rapid improvement in the optimization. The stability of the objective function values from iteration 15 to iteration 30 suggests that the optimization process found an optimal parameter area. A small decrease from iteration 35 to iteration 50 indicates that optimization was still ongoing, with room for minor improvements. The PI controller resulting from the PSO tuning is hereafter referred to as the PI-PSO controller.

In the fifth test, an evaluation was conducted on the PI-PSO controller applied to the active rectifier with a constant power load implemented at time 0 seconds. In this test, the Kp and Ki parameters obtained from the PI-PSO tuning process were 3.1364 and 6.8141, respectively. The evaluation involved measuring the actual voltage on the active rectifier, with the reference voltage set to 400 VDC and the constant power load set to 100 watts. The results of the actual voltage measurements on the active rectifier with a 100-watt constant power load are presented in Figure 7.

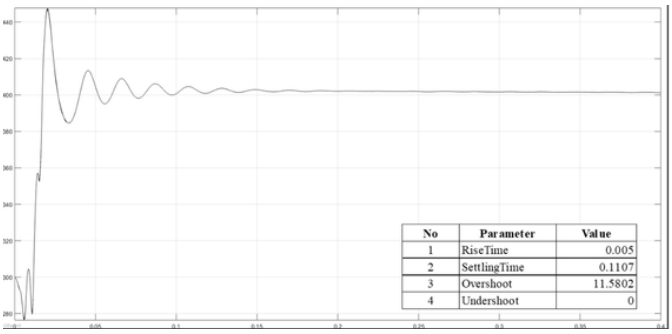

Fig. VII. Actual Voltage on a 100 Watt Constant Power Load at Time 0 Seconds

From the test results, the system has a very fast rise time of 0.0050 seconds, indicating a rapid response to changes. This is the fastest rise time compared to the second and third tests. The settling time of 0.1107 seconds shows that the system reaches a stable state quickly with the addition of a constant power load, faster than some previous conditions (resistive load). An overshoot of 11.5802% indicates that the system experiences a significant spike above its reference voltage value, suggesting that a faster/aggressive rise time results in a higher overshoot. The undershoot value of 0% indicates that the system does not dip below the reference voltage value during the transient period.

In the final test, an evaluation was conducted on the PI-PSO controller applied to the active rectifier with a constant power load implemented at 0.25 seconds. In this test, the Kp and Ki parameters obtained from the PI-PSO tuning process were 3.1364 and 6.8141, respectively. The evaluation involved measuring the actual voltage on the active rectifier, with the reference voltage set to 400 VDC and the constant power load set to 100 watts, applied at 0.25 seconds. The results of the actual voltage measurements on the active rectifier with a 100-watt constant power load are presented in Figure 8.

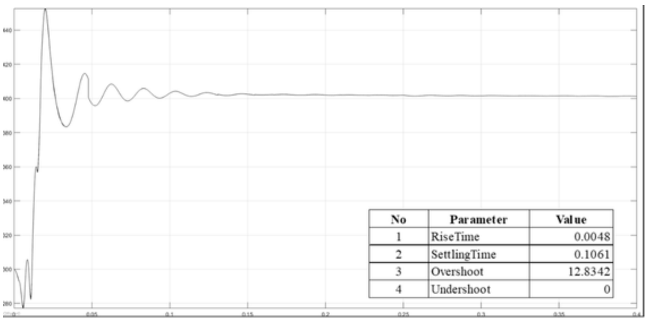

Fig. VIII. Voltage on a 100 Watt Constant Power Load at Time 0.25 Seconds

From the test results, it can be observed that the system has an extremely fast rise time of 0.0048 seconds, compared to the previous test (0.0050 seconds), due to the load not operating during the rise time. The settling time of 0.1061 seconds indicates that the system reaches stability very quickly, even with the addition of a constant power load at 0.25 seconds. This contrasts with resistive loads, which tend to slow down the settling time. The overshoot of 12.8342% shows that the system experiences a significant spike above the reference voltage, suggesting that a faster/aggressive rise time leads to a higher overshoot. The undershoot remains at 0%, indicating that the system does not dip below the reference voltage during the transient period. The system demonstrates good stability without undershoot, but the increased overshoot may require further attention due to the characteristics of the constant power load. The constant power load forces the system to quickly adjust voltage and current to maintain stable power, resulting in a more aggressive response and higher overshoot.

IV. Conclusion

Based on this study, the PI controller optimized with PSO for the active rectifier shows distinct performance characteristics under different load conditions. When using a resistive load, the optimized parameters were Kp = 0.4509 and Ki = 2.7611 achieved at iteration 50, minimizing the objective function to 1.2742. Meanwhile, with a constant power load, the parameters were tuned to Kp = 3.1364 and Ki = 6.8141, minimizing the objective function to 1.6273.

Introducing a resistive load at t = 0 seconds resulted in a rapid system response with a rise time of 0.0125 seconds and settling time of 0.1285 seconds. The system exhibited a moderate overshoot of 7.7829% without undershoot, indicating effective overshoot control and adherence to the reference voltage. Introducing the resistive load at t = 0.25 seconds reduced the rise time to 0.0113 seconds but extended the settling time to 0.3334 seconds. The overshoot increased to 11.4266%, still without undershoot, demonstrating stable performance despite the higher peak.

In contrast, introducing a constant power load at t = 0 seconds resulted in an exceptionally fast rise time of 0.0050 seconds and a relatively quick settling time of 0.1107 seconds. The system exhibited a high overshoot of 11.5802%, indicating an aggressive initial response, yet remained stable without undershoot. Introducing the constant power load at t = 0.25 seconds further reduced the rise time to 0.0048 seconds and settling time to 0.1061 seconds. However, the overshoot reached its highest value at 12.8342%, suggesting a very aggressive response without undershoot.

In summary, the constant power load induces faster responses compared to resistive loads but with higher overshoot, especially when introduced at t = 0.25 seconds. All conditions demonstrate stability without undershoot, but the higher overshoot requires further tuning for optimal performance.

References

[1] C. Bai, P. Dallasega, G. Orzes, and J. Sarkis, “Industry 4.0 technologies assessment: A sustainability perspective,” *Int. J. Prod. Econ.*, vol. 229, p. 107776, 2020, doi: 10.1016/j.ijpe.2020.107776.

[2] I. Setiawan *et al.*, “Investigation of Symmetrical Optimum PI Controller based on Plant and Feedback Linearization in Grid-Tie Inverter Systems,” 2017.

[3] G. Gruosso, Q. Zhou, and F. Bizzozero, “Comparison among passive and active rectifier for seawave energy production,” *5th Int. Conf. Clean Electr. Power Renew. Energy Resour. Impact, ICCEP 2015*, pp. 493–498, 2015, doi: 10.1109/ICCEP.2015.7177562.

[4] J. Liu, W. Zhang, and G. Rizzoni, “Robust Stability Analysis of DC Microgrids With Constant Power Loads,” *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 851–860, 2018, doi: 10.1109/TPWRS.2017.2697765.

[5] R. R. Nasyrov and R. I. Aljendy, “Comprehensive comparison between hybrid fuzzy-PI and PSO-PI controllers based active power filter for compensation of harmonics and reactive power under different load conditions,” *Proc. 2018 IEEE Conf. Russ. Young Res. Electr. Electron. Eng. ElConRus 2018*, vol. 2018-Janua, pp. 725–730, 2018, doi: 10.1109/EIConRus.2018.8317195.

[6] Y. Romasevych, V. Loveikin, and V. Makarets, “Optimal constrained tuning of PI-controllers via a new PSO-based technique,” *Int. J. Swarm Intell. Res.*, vol. 11, no. 4, pp. 87–105, 2020.

[7] R. Nagarajan, R. Yuvaraj, V. Hemalatha, S. Logapriya, A. Mekala, and S. Priyanga, “Implementation of PV - Based Boost Converter Using PI Controller with PSO Algorithm,” *Int. J. Eng. Comput. Sci.*, vol. 2, no. 10, pp. 17–24, 2017, doi: 10.18535/ijecs/v6i3.14.

[8] A. M. Nazelan, M. K. Osman, A. A. A. Samat,

and N. A. Salim, "PSO-Based PI Controller for Speed Sensorless Control of PMSM," *J. Phys. Conf. Ser.*, vol. 1019, no. 1, 2018, doi: 10.1088/1742-6596/1019/1/012027.

[9] S. Behera, B. Subudhi, and B. B. Pati, "Design of PI controller in pitch control of wind turbine: A comparison of PSO and PS algorithm," *Int. J. Renew. Energy Res.*, vol. 6, no. 1, pp. 271–281, 2016, doi: 10.20508/ijrer.v6i1.3137.g6783.

[10] P. Davari, F. Zare, and A. Abdelhakim, "Active rectifiers and their control," in *Control of Power Electronic Converters and Systems*, Elsevier, 2018, pp. 3–52.

[11] J. Benzaquen, F. Fateh, M. B. Shadmand, and B. Mirafzal, "Performance comparison of active rectifier control schemes in more electric aircraft applications," *IEEE Trans. Transp. Electrif.*, vol. 5, no. 4, pp. 1470–1479, 2019.

[12] A. Faidlon, I. Setiawan, and Hermawan, "Basis Active Rectifier Tiga Fase pada Kontroler PI."

[13] M. Hartmann, H. Ertl, and J. W. Kolar, "Current control of three-phase rectifier systems using three independent current controllers," *IEEE Trans. Power Electron.*, vol. 28, no. 8, pp. 3988–4000, 2013, doi: 10.1109/TPEL.2012.2231946.

[14] K. J. (Karl J. Åström, T. Hägglund, and K. J. (Karl J. Åström, *PID controllers*. International Society for Measurement and Control, 1995.

[15] M. S. Alam, F. S. Al-Ismail, and M. A. Abido, "PV/wind-integrated low-inertia system frequency control: PSO-optimized fractional-order PI-based SMES approach," *Sustainability*, vol. 13, no. 14, p. 7622, 2021.

[16] H. Garg, "A hybrid PSO-GA algorithm for constrained optimization problems," *Appl. Math. Comput.*, vol. 274, pp. 292–305, 2016, doi: 10.1016/j.amc.2015.11.001.

[17] V. Veerasamy *et al.*, "A Hankel matrix based reduced order model for stability analysis of hybrid power system using PSO-GSA optimized cascade PI-PD controller for automatic load frequency control," *IEEE Access*, vol. 8, pp. 71422–71446, 2020.

[18] P. Saini, R. Kumar, and P. K. Juneja, "Design of PI Controller for Consistency of Stock in Paper Machine Headbox using Particle Swarm Optimisation (PSO)," in *2019 International Conference on Innovative Sustainable Computational Technologies (CISCT)*, 2019, pp. 1–6.

[19] M. E. B. Aguilar, D. V. Coury, R. Reginatto, and R. M. Monaro, "Multi-objective PSO applied to PI control of DFIG wind turbine under electrical fault conditions," *Electr. Power Syst. Res.*, vol. 180, p. 106081, 2020.

[20] U. Sultana, S. H. Qazi, N. Rasheed, and M. W. Mustafa, "Performance analysis of real-time PSO tuned PI controller for regulating voltage and frequency in an AC microgrid," *Int. J. Electr. Comput. Eng.*, vol. 11, no. 2, p. 1068, 2021.

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