Applied Science & Engineering Journal for Advanced Research *Peer Reviewed and Refereed Journal*
ISSN (Online): 2583-2468
Volume-3 Issue-3 || May 2024 || PP. 11-19 DOI: 10.5281/zenodo.11280078

Comprehensive Analysis of Recent developments of control strategies and Modular Multilevel Converter for HVDC

Patra Gowtami[1] and Dr. J. Ramakant[2]
[1]*Research Scholar, Department of Electrical and Electronics Engineering, Godvari Institute of Engineering and Technology (Autonomous), Affiliated to JNTUK, Kakinada, Rajahmundry, A.P, India*
[2]*Research Supervisor, Department of Electrical and Electronics Engineering, JNTUK, Kakinada, Rajahmundry, A.P, India*

[1]*Corresponding Author: patra12@giet.ac.in*

Received: 15-04-2024	Revised: 03-05-2024	Accepted: 21-05-2024

ABSTRACT
The growing need for Renewable Energy Sources (RESs) has made Wind Energy Conversion Systems (WECS)—that is, systems that use Modular Multilevel Converters (MMC) and Doubly Fed Induction Generators (DFIG)—essential components of modern power generation. Although these systems have advantages including enhanced grid integration and variable-speed operation, complex control techniques are required to realize their full potential. This requirement is acknowledged in the proposed study, which also presents proportional-integral (PI) and particle swarm optimization (PSO) controllers as essential components of an advanced control system. Optimizing WECS performance is the major goal, with a focus on achieving and sustaining a steady DC link voltage. In order to ensure overall system reliability and efficiency, DC link voltage stability is crucial, especially when using High-Voltage Direct Current (HVDC) technology to transmit electrical power across long distances. The MATLAB Simulink platform is employed to demonstrate the efficacy of the suggested work.

Keywords: *wind energy conversion system (wecs), high voltage direct current (hvdc), modular multilevel converter (mmc), particle swarm optimization (pso), doubly-fed induction generator (dfig)*

I. INTRODUCTION

Global energy consumption has increased as a result of rapid population growth and urbanization. Modernization in the agriculture and irrigation industries tends to boost energy demand dramatically. At the time, fossil fuels are the dominant energy source depletion of fossil resources, several countries are struggling to close the supply-demand gap. Furthermore, fossil fuels have significant negative effects on the environment, such as the greenhouse effect [1]. In order to meet load demand while limiting and minimizing the impact of conventional generators on global warming, integration of renewable energy is essential due to the exponential rise in electrical energy consumption induced by population and economic expansion. Renewable energy sources, often known as RES, are sustainable energy sources that use natural resources to produce power. Because RES emit no fossil fuels, using them helps to reduce CO2 emissions, which has a positive influence on global warming [2]. Moreover, the variable output power of RES is a feature that sets them apart from conventional synchronous generators. Conversely, the fuel burn rate of conventional generators can be adjusted. RES are location-constrained because, in contrast to conventional generators, their output varies geographically. Furthermore, one of the primary benefits of RES is that they essentially have no operational expenses [3]. One can include renewable energy sources into distribution or transmission networks. Larger power generators, whether they run on fossil fuels or renewable energy, are linked to transmission systems, whereas minor units are associated to distribution systems [4]. There are differences in the challenges associated with incorporating renewable energy into distribution and transmission networks. Transmission networks feature a greater voltage level since they are made to move loads across large distances. Distribution systems, on the other hand, are designed to feed adjacent loads and have lower voltage levels [5].

In this system, a generator is utilized to convert mechanical power into electrical power, In essence, an induction generator is an induction motor that is coupled to an electrical power system and is prime moved to a speed higher than its synchronous speed. They are unable to generate power on their own [6]. Synchronous generators, also referred to as alternators, are electrical devices that convert transforming mechanical energy from a prime mover into alternating current (AC) power at a particular frequency and voltage, outperforming induction generators in this regard. Despite some drawbacks, such as high costs, complexity, and maintenance [7]. Due to the generator's direct grid connection, the disadvantages of both current generators and Wind turbines with doubly-fed induction generator converters (DFIG) are reduced. The grid and rotor are powered via a back-to-back power converter are connected. Because their capacity to run at various speeds, DFIGs have a significant operational benefit [8].

In addition to being able to connect a VSC-HVDC system is accomplished of controlling real and reactive power, producing no sub-synchronous resonances, supporting reactive power, preventing the propagation of AC side faults, and providing independent control over frequency, black start support and supply voltage. These advantages make the VSC-HVDC transmission technology competitive in terms of distant renewable energy sources grid integration [9]. Because of its modular features related to a two-level converter, the Modular Multilevel Converter dominates VSC-HVDC transmission. MMC-HVDC is "modular" in the sense that it can be readily scaled up or down by adding or deleting converter modules. It is a versatile solution for changing power ratings and can be tailored to the individual needs of a wind farm due to its versatility. Converter's modular creation allows it to continue functioning even if one or more modules fail, ensuring system resilience and minimizing downtime. This results in a more steady and reliable power supply to the grid [10].

In order to govern nonlinear components in power systems, a number of many contemporary control strategies have been thoroughly examined, such as adaptive control, variable structure control, and intelligent control. The way DFIG-equipped wind turbines are managed demonstrates why standard PI controllers—with their simple designs—remain the most popular techniques for power system regulation. However, due to the system's great complexity and nonlinearity, it is hard to appropriately alter PI gains and controllers. As a result, these control approaches have limited real-world applicability [11].

The objective function does not have to be continuous and differentiable in order for the methods to work. One of the new heuristic methods, PSO, is used for nonlinear optimization problems with continuous variables. Through the modeling of streamlined social models, it was produced [12]. PSO has the memorial ability to allow all particles to keep their knowledge of good solutions, unlike GA, which does not require considering prior knowledge after each evolution. PSO is also a popular option for a variety of applications due to its quick convergence, ease of implementation, and cheap processing cost. Some research has also been conducted to reinforce the PSO [13].

This paper examines the effectiveness of PSO – PI controller for DFIG's active and reactive power control.

- Implementation of MMC for power conversion process within the DFIG-based MMC system.
- Incorporation of PSO-PI controller to ensure optimal performance of MMC.
- To maintain a stabilized DC link voltage for utilization of HVDC technology.

II. PROPOSED SYSTEM DESCRIPTION

The dynamic energy generated from wind turbine is transformed into electrical energy utilizing a DFIG. DFIG-WECS is connected to a MMC. Figure 1 demonstrates the architecture of proposed DFIG based MMC system. The DFIG generates variable-frequency AC power, which is converted by the MMC in the WECS into stable and controllable DC power. For optimal performance of MMC, PSO-PI controller is implemented in this research. The PSO algorithm, a heuristic optimization technique inspired by social behavior, is used to progressively improve the PI controller's parameters. This dynamic optimization process ensures that MMC is optimized for the prevailing operating conditions. This adjustment contributes to the overall stability of the WECS, preventing voltage fluctuations and ensuring a consistent and reliable DC link voltage. Achieved DC link voltage is utilized by HVDC technology, where stable DC voltages are essential for minimizing losses and ensuring the effective long-distance transmission of electrical power.

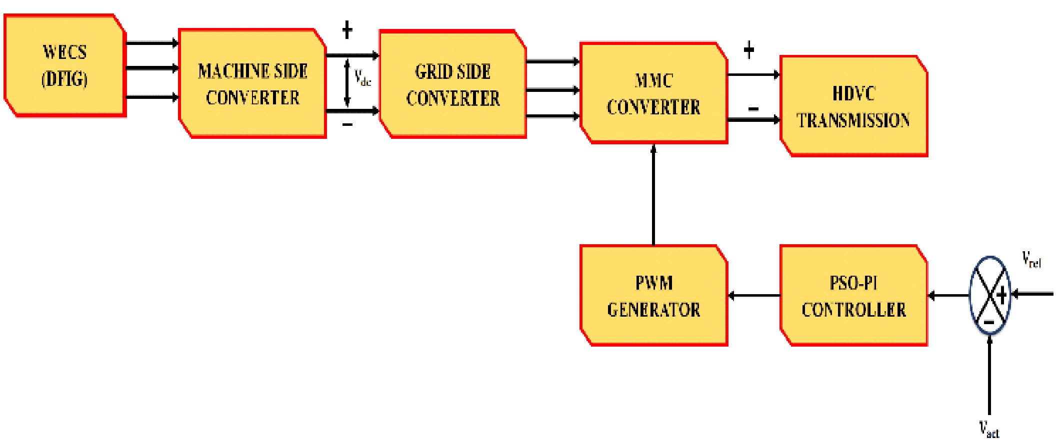

Figure 1: Architecture of the Proposed DFIG based MMC system

ISSN (Online): 2583-2468
Volume-3 Issue-3 || May 2024 || PP. 11-19 DOI: 10.5281/zenodo.11280078

III. PROPOSED SYSTEM MODELLING

Design of WECS Based on DFIG

DFIG-based transmission of wind energy is a technology commonly employed in wind power generation systems. In the setup illustrated in Figure 2, the DFIG serves as the generator in a wind turbine, capable of converting kinetic energy from the wind into electrical power.

Design of Turbine

Wind speed directly affects the kinetic power, which is represented as where the V signifies wind speed, denotes air density, the range scattered by turbine blades, and indicates power change efficacy.

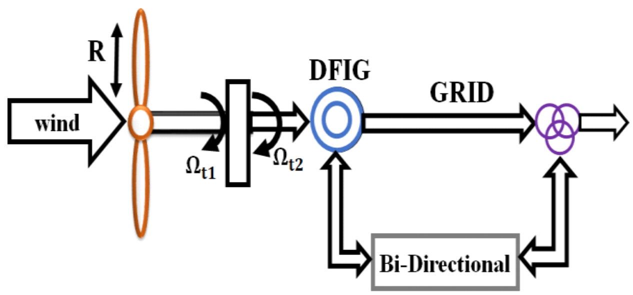

Figure 2: DFIG-based transmission of wind energy

The aerodynamic torque is denoted by:
Is speed of turbine

DFIG Model

The equation of voltage for the stator and rotor are given by:

Where catalogs of stator and rotor, individually, and synchronous orientation setting modules. Voltage, current, flux, and electrical frequency are represented by respectively denotes resistance.

The rotor and stator flux equations are provided by:
Where L denotes inductance and M denotes reciprocal induction.
The source of the WECS mechanical equation based on DFIG is

Where, denotes total inertia of the turbine, is speed of DFIG, is electromagnetic torque produced by generator, and is the coefficient of damping.

The DFIG's electromagnetic torque:
zsWhere p denotes the pole pairs quantity of DFIG.
The stator side's active and reactive powers are as follows:

MMC-HVDC Transfer System Among the Wind Energy Based DFIG

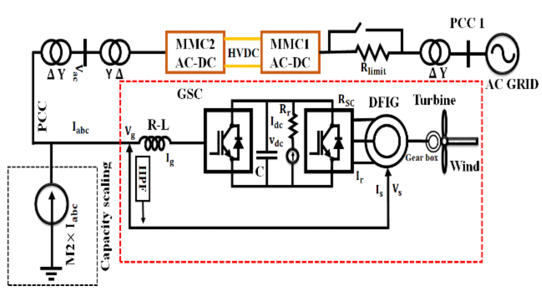

Figure 3: DFIG based MMC-HVDC system

Figure 3 depicts DFIG-powered wind power, encompassing the MMC-HVDC grid. MMC1 controls the voltage needed for the HVDC connection, while MMC2 produces the AC voltage needed for wind farm integration. Two thirds of the wind energy is transferred by the DFIG stator terminal, and depending on the rotor's speed, the rotor side converter can either provide or receive energy. Wind speed affects the optimal turbine mechanical energy point, based on wind turbine power vs generator speed curve. When determining the ideal electromagnetic torque based on the rotor side converter (RSC) employing field-oriented control to capture wind energy at its peak. The rotor side converter organizes the DFIG, so the slip angle—the difference between the rotor angle difference and the stator flux angle—is active to produce the modulating signal and convert the stationary rotor current to rotary dq current. In the frame, the stator flux.

Qs = In the DFIG stator-rotor side reactive power's magnetizing reactive power, reactive power (Qs) is the outcome of switching between the AC system and the stator changes the reactive current of RSC, However, stator voltage's magnetizing reactive power doesn't change. Therefore, the function of DFIG results in either leading, lagging, or unity power factor generator, depending on the value of. The following is the definition of electromagnetic torque:

A PI controller processes any current deviation and multiplies the result by the phrase for decoupling to produce the voltage on the dq axis of the rotor side converter. Ultimately, dq axis voltage is used to produce the modulating signal (abc signal) by using slip angle. Conversely, the GSC retains the DC link voltage at predetermined level. Because it receives electricity when the synchronous speed is higher than the grid side converter, rotor speed and vice versa, has bidirectional power flow.

PSO Used in the Design of a PI Controller

The PSO uses a population-based search method as an optimization tool, wherein individuals, referred to as particles, alter state of position over time. Within a PSO system, particles go across a multi-dimensional search space. Using the best location found by both itself and its neighbor, each particle modifies its position during flight depending on its own experience and the experience of a nearby particle.

To demonstrate this shift, consider the idea of velocity. One can alter each agent's velocity by utilizing the following equation:

Using the aforementioned equation, a specific velocity that approaches and can be figured. To modify the present position (searching point) in the solution space, utilize the following equation:

In this case, stands for current velocity, for updated searching point, for modified velocity, and for current searching point. With representing weight of inertia, and being two constants positive, and a random number with an array of [0, 1], the best solution observed by particle is, and finest result observed by all particles is.

Where k and represent the maximum and current iterations, respectively. The minimum and maximum weights are denoted and, respectively. Although 2 is frequently the most suitable, the recommended ranges for and are 1-2. The suitable standards for and are 0.4 and 0.9, respectively.

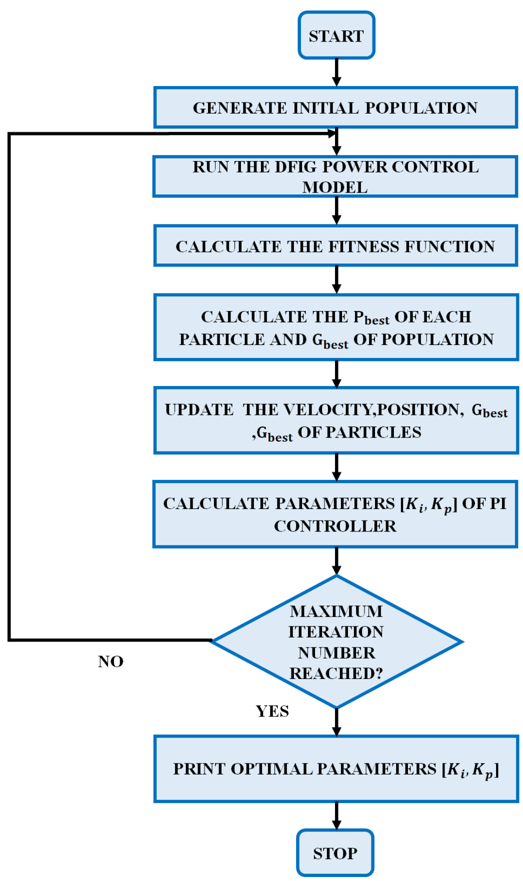

Figure 4: PSO-based technique for figuring out an objective function's global maximum value

ISSN (Online): 2583-2468
Volume-3 Issue-3 || May 2024 || PP. 11-19 DOI: 10.5281/zenodo.11280078

To utilize the plant, one must comprehend its mathematical model the PI controller, which is a great machine control controller. Various methods have been developed for adjusting the PI controller in order to address issues with the system as a whole. By utilizing the PSO, the recommended method maximizes the power PI controller, both active and reactive settings. DFIG's performance varies with PI controller advances measured according to the integral time absolute error (ITAE) value. As objective function, the total performance index (ITAE) taken. Stochastic algorithms are designed to minimize the objective function. For and, all particles in the population have been deciphered.

When evaluating a control system's dynamic performance, the integral time absolute error criterion is frequently employed.

This study uses a time domain criterion to appraise presentation of PI controller. Presentation parameters are used to contrast manually tuning a PI controller with using a PSO-tuned controller. The PI controller consists of integrated squared error (ISE) and integration absolute error (IAE).

IV. RESULTS AND DISCUSSION

In this work, an MMC system based on DFIG is used to convert the variable frequency AC power provided by the DFIG in the WECS into stable and controllable DC power. The PI controller's parameters are iteratively improved using the PSO approach. The resultant DC connection voltage is used in the HVDC approach. This section demonstrates the outcomes of proposed system validated using MATLAB Simulation-based deployment of renewable energy sources. Table 1 gives specifics on the projected system's design specification.

Table 1: Details of the parameters

Components	Ratings
MMC	
Power	
Voltage	
IGBT used	
Switching frequency	

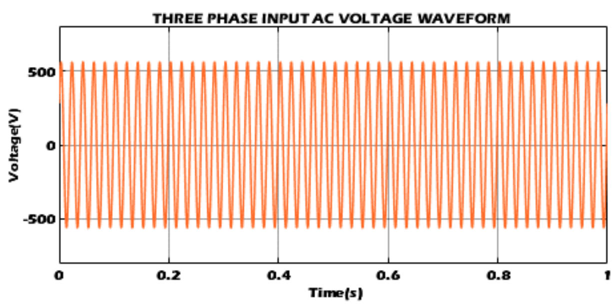

Figure 5: Three Phase Input AC Voltage Waveform

Figure 5 shows the input three-phase AC voltage representation. It is noticed that a stabilized supply of 550V is accomplished.

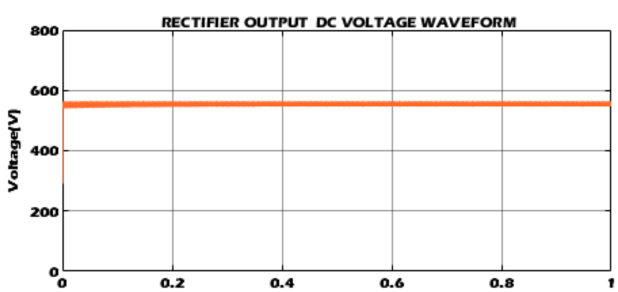

Figure 6: Rectifier Output DC Voltage Waveform

The rectified AC voltage waveform is illustrated in Figure 6. It is noticed that, a stabilized DC link voltage of 550V is maintained constant throughout the system.

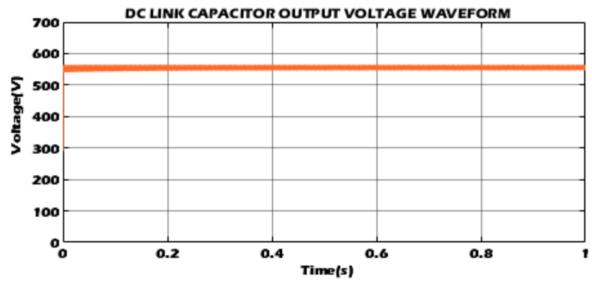

Figure 7: DC Link Capacitor Output Voltage Waveform

The DC link capacitor voltage waveform representing a consistent voltage is demonstrated in Figure 7. It is noticed that a stabilized DC voltage of 550V is accomplished by the system.

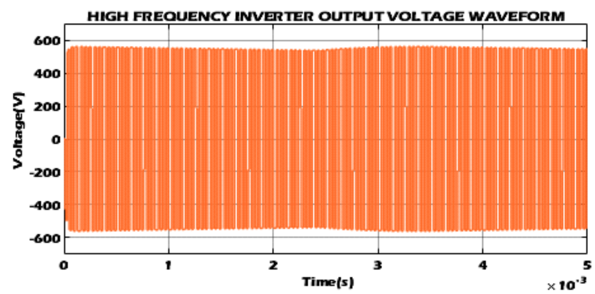

Figure 8: High Frequency Voltage Waveform of an Inverter Output

The high frequency inverter's output voltage of 550V is consistently defined by the waveform shown in Figure 8.

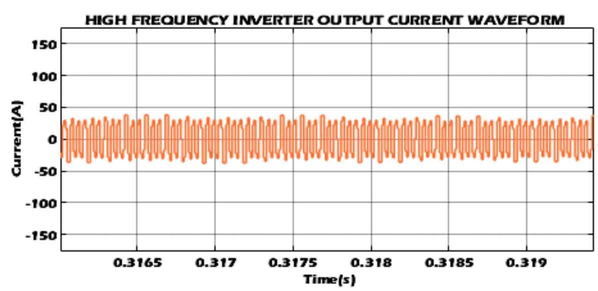

Figure 9: High Frequency Inverter Output Current Waveform

In Figure 9, current waveform of high frequency inverter resulting in a consistent current of 45A without any disruptions is observed.

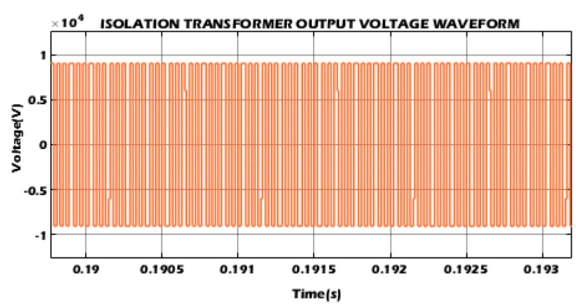

Figure 10: Isolation Transform Output Voltage Waveform

In this figure 10, the isolation transformer output voltage waveform exhibits the voltage as an input source to the HVDC system with 0.9V resulting with no further disruptions.

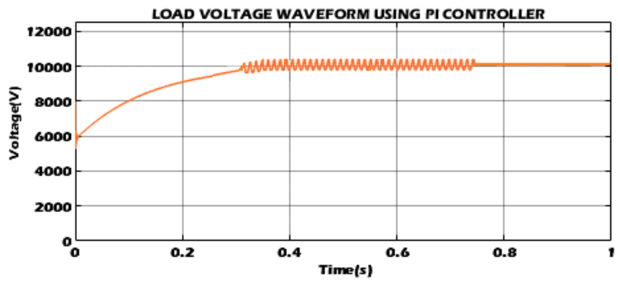

Figure 11: Waveform of Load Voltage Employing a PI controller

Figure 11 provides the explanation of. voltage waveform using a PI controller. The voltage steadily rise from 6000V and, after 0.77 seconds, stabilized at 10000V.

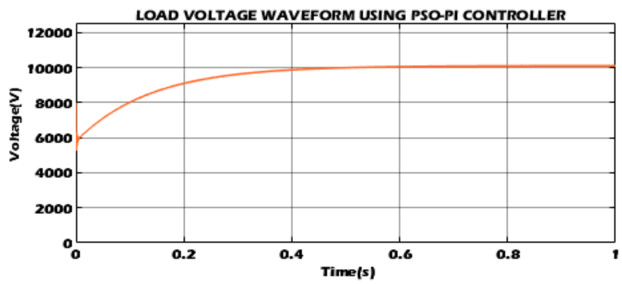

Figure 12: The PSO-PI Controller's load voltage waveform

The voltage accomplished by PSO- PI controller is illustrated in Figure 12. It noticed that the load voltage waveform increases from 6000V and then stabilize at 0.42s with 10000V, having no further disruptions in figure 12.

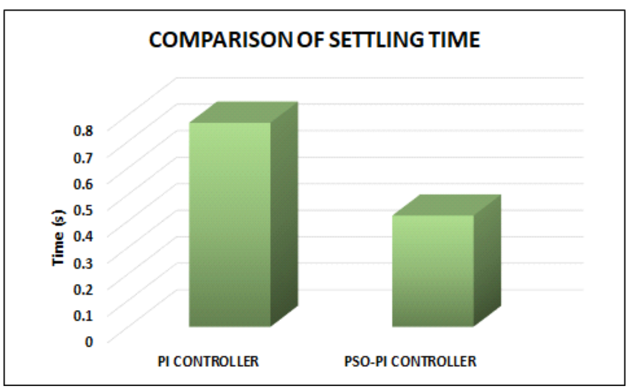

Figure 13: Comparison of Controller Performance

The comparison of settling time for control approaches including PI and PSO-PI is displayed in Figure 2. It is observed that proposed PSO-PI shows faster convergence at 0.42s with stable voltage of 10000V while conventional PI shows settlement at 0.77s.

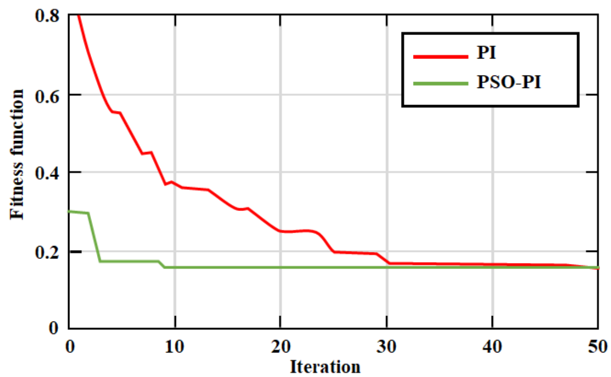

Figure 14: Analysis of Convergence Speed

The performance analysis of PI and proposed PSO-PI is illustrated in Figure 14, in terms of convergence speed. It is observed that, the proposed PSO-PI controller shows faster convergence in contrast to conventional PI controller.

V. CONCLUSION

The suggested work describes how to use an MMC system based on DFIG to transform the variable frequency AC power that the DFIG in the WECS supplies into steady and regulated DC power. The PSO method is used to iteratively improve the PI controller's parameters. It is an optimization technique inspired by social behavior and heuristics. Through the reduction of voltage swings and maintenance of a steady and dependable DC link voltage, this adjustment helps to preserve the overall stability of the WECS. In the HVDC technique, the DC connection voltage that results is used. Stable DC voltages are necessary to reduce losses and enable efficient long-distance electrical power transmission. However, the comprehensive MATLAB simulation-based application of renewable energy sources requires a reliable and effective mechanism for WECS integration with the HVDC infrastructure, which is provided by the suggested method. When compared to other current approaches, the optimized PSO-PI shows a faster time of 0.42s.

REFERENCES

1. Tiwari, R., & Babu, N. R. (2016). Recent developments of control strategies for wind energy conversion system. *Renewable and Sustainable Energy Reviews, 66*, 268-285.
2. Al Talaq, M., & Al-Muhaini, M. (2024). Optimal coordination of time delay overcurrent relays for power systems with integrated renewable energy sources. in *Power System Protection in Future Smart Grids*, pp. 81-107. Academic Press.
3. Abid, M. S., Ahshan, R., Al Abri, R., Al-Badi, A., & Albadi, M. (2023). Multi-objective optimal planning of virtual synchronous generators in microgrids with integrated renewable energy sources. *IEEE Access*.
4. Hamid, B., Hussain, I., Iqbal, S. J., Singh, B., Das, S., & Kumar, N. (2022). Optimal MPPT and BES control for grid-tied DFIG-based wind energy conversion system. *IEEE Transactions on Industry Applications, 58*(6), 7966-7977.
5. Ma, Y., Tao, L., Zhou, X., & Shi, X. (2020). Analysis and control of fault ride-through capability improvement for wind energy conversion system using linear active disturbance rejection control with correction link. *IEEE Access, 8*, 73816-73827.
6. Jabbour, N., Tsioumas, E., Mademlis, C., & Solomin, E. (2020). A highly effective fault-ride-through strategy for a wind energy conversion system with a doubly fed induction generator. *IEEE Transactions on Power Electronics, 35*(8), 8154-8164.
7. Rao, Y. T., Chakraborty, C., & Sengupta, S. (2020). Performance and stability of brushless induction excited synchronous generator operating in self-excited mode for wind energy conversion system. *IEEE Transactions on Energy Conversion, 36*(2), 919-929.
8. Puchalapalli, S., Singh, B., Tiwari, S. K., & Goel, P. K. (2020). Design and analysis of grid-interactive DFIG based WECS for regulated power flow. *IEEE Transactions on Industry Applications, 56*(5), 5396-5407.
9. Lin, C. H., & Wu, Y. K. (2021). Overview of frequency-control technologies for a VSC-HVDC-integrated wind farm. *IEEE Access, 9*, 112893-112921.

10. Zhang, J., Li, K. J., Sun, K., Liu, W., & Liu, Z. (2020, October). Dynamic reactive droop control strategy for the MMC-HVDC system integrating the suburban wind farms into the urban power grid. in *IEEE Industry Applications Society Annual Meeting*, pp. 1-7. IEEE.
11. Mosaad, M. I., Ramadan, H. S. M., Aljohani, M., El-Naggar, M. F., & Ghoneim, S. S. (2021). Near-optimal PI controllers of STATCOM for efficient hybrid renewable power system. *IEEE Access*, *9*, 34119-34130.
12. Sharma, S., & Tayal, V. K. (2022). Optimised controller design for frequency control of a wind turbine driven doubly fed induction generator. *International Journal of Ambient Energy*, *43*(1), 7197-7206.
13. Hamdan, I., MM Youssef, M., & Noureldeen, O. (2023). A review of intelligent control systems for grid tie doubly fed induction generator based wind farm. *SVU-International Journal of Engineering Sciences and Applications*, *4*(2), 269-278.
14. Chhipą, A. A., Chakrabarti, P., Bolshev, V., Chakrabarti, T., Samarin, G., Vasilyev, A. N., ... & Kudryavtsev, A. (2022). Modeling and control strategy of wind energy conversion system with grid-connected doubly-fed induction generator. *Energies*, *15*(18), 6694.
15. Hossain, M. I., Shafiullah, M., Al-Sulaiman, F. A., & Abido, M. A. (2022). Comprehensive analysis of PV and wind energy integration into MMC-HVDC transmission network. *Sustainability*, *15*(1), 253.
16. Bekakra, Y., & Attous, D. B. (2014). Optimal tuning of PI controller using PSO optimization for indirect power control for DFIG based wind turbine with MPPT. *International Journal of System Assurance Engineering and Management*, *5*, 219-229.