Particle Swarm Optimization Based Fuzzy Logic MPPT Inverter Controller for Grid Connected Wind Turbine

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Abstract- The wind energy source as an alternative to conventional sources to generate power has been increasingly popular due to abundant in nature and pollution free. The wind energy sources are undepletable, however, they are not able to generate as much electricity due to their intermittent nature. Therefore, a wind energy conversion system (WECS) with accurate maximum power point tracking (MPPT) inverter controller is essential in order to improve the wind energy capturing capability. This paper aims to develop an optimal Fuzzy logic MPPT inverter controller for grid connected wind turbine so that the energy capturing efficiency of the system can be maximized. In this research work, the MPPT inverter controller is designed on the basis of hill climb search method, fuzzy logic control and heuristic particle swarm optimization (PSO) algorithm. The performance of WECS is demonstrated with the generated output voltage, current and power waveforms, DC link voltage waveform, and the generator speed. According to the results obtained for both normal Fuzzy logic MPPT control and optimized Fuzzy logic MPPT control WECS, the performance of PSO optimized Fuzzy logic MPPT inverter controller has better maximum power point performance and efficiency in tracking wind energy in terms of much smooth, less distortion and fewer fluctuation outcomes at the various step wind speed conditions. The proposed optimal Fuzzy logic MPPT inverter controller have a good potentiality for WECS in sustainable grid application.

Keywords- Particle swarm optimization (PSO), Fuzzy logic control (FLC), hill climb search (HCS), maximum power point tracking (MPPT), inverter, grid connected, wind energy conversion.

1. Introduction

The demand of using renewable energy sources such as wind and solar as an alternative to conventional sources such as coal, fossil fuel and nuclear energy to generate power is gaining more popularity currently due the fact that they are abundant in nature and lesser pollution to the environment [1,2,3]. Although these energy sources are undepletable, they have several drawbacks despite the stated advantages. One of the main problems is intermittent of wind as it does not always provide strong enough or consistent wind speed to generate electricity. Therefore, wind energy cannot be fully extract to meet the electrical demands. Moreover, wind turbine is not able to generate power as much as conventional power sources such as coal, gas or nuclear plant [1]. It is essential to generate optimum power from the wind turbine by using a maximum power point tracking (MPPT) controller in the wind energy conversion system (WECS) to increase the energy capture efficiency from the wind and to improve the feasibility of wind energy as a renewable energy source to generate power [4]. The generator speed and power fluctuations are intensified mainly due to the high changing rate of the wind speed profile. A good MPPT controller is able to reduce the fluctuations considerably. The reduced power and speed fluctuations in the WECS might be able to enhance the lifespan and reduce maintenance cost of the system [5].

The conventional MPPT methods that are widely used in WECS are optimal torque control (OTC), optimal tip speed ratio (TSR), turbine power profile (TPP), power signal feedback (PSF), optimal relationship-based (ORB) control, hill climb search (HCS) control [6,7]. In OTC method, the generator torque is controlled continuously at the optimal operating point which corresponds to the maximum power conversion coefficient during wind speed changes. However, the OTC curve of the wind turbine requires field test to build the controller [6,8]. In the TSR control, the rotational speed of the generator requires to be controlled in order to keep TSR to an optimum value whereby the power extracted from the wind power generation system is maximum. However, the wind speed data, optimal TSR value and actual rotor speed for controller are requisites in TSR control method. The major drawback is the difficulty to obtain wind and turbine speed accurately in real time practice. Besides, the change of wind turbine specifications that changes with the optimal TSR value also contributes to the difficulty of implementation [9,10]. The PSF control which is also known as optimum relationship-based (ORB) control [6], requires the exact information of the turbine's maximum power curve and a lookup table to track the maximum power point. However, this method requires a lot of turbine and generator speed information from field test. These methods have several limitations and disadvantages such as low accuracy of wind turbine characteristic curve, prone to mechanical wear and tear of turbine blades and so on [10,11]. The HCS control method is widely utilized for MPPT control of WECS as it searches continuously the peak power point of wind turbine and also defines the shortcomings of the before mentioned methods. The HCS method does not require system specification, information of turbine's maximum power curve and field tests [6,12].

In recent years, Fuzzy Logic Controller (FLC) has been widely used for MPPT of WECS due to fact that it is able to take care of the nonlinearities and uncertainties [13]. These are independent of the process model, characterized by their abilities to understand nonlinearity problems and have robust performances compared to variations in atmospheric conditions and load [14]. To evaluate an inverter yield at an output waveform by using FLC is a new method applied to controllers to minimize the output distortion so as to keep it at an acceptable level [15]. Although FLC has robustness in controlling, the proper fixing of the membership parameter values of FLC is decisive for superior design and performance. The application of optimization in FLC development has been incorporated in various controllers and drives [16]. Particle swarm optimization (PSO) algorithm [17,18,19] is one of the most extensively used processes for solving optimization problems due to its robustness, ease of implementation, faster convergence, global exploration capability and capability to solve complex optimisation problems in different application domains as compared to genetic algorithm, backtracking searching algorithm etc. [20-23]. However, PSO has some limitations, it easily becomes trapped in local minima, and it improperly selects control parameters, which lead to poor solution [23]. PSO algorithm is used to improve the MPPT method to adjust the rotor side converter of a wind turbine fed induction generator [24]. Moreover, it is used to optimise the threshold parameters of the rule-based power management strategy for hybrid electric vehicles and to solve the optimal power flow problem of power systems, to determine optimal sizing of hybrid PV, wind, and battery system [20].

This paper mainly aims to develop an optimal Fuzzy logic MPPT inverter controller for gird connected wind turbine. The HCS method is used to implement the MPPT control of WECS for searching the exact maximum power point. An optimal FLC is used to control the duty of converter switching for producing the maximum and stable power output to grid. The PSO algorithm is employed to optimize the input and output membership parameters of Fuzzy system for obtaining the accurate duty value of PWM signal to inverter switches that in turn produces maximum power output in WECS. It is anticipated that the proposed optimized Fuzzy system might be able to create a smooth and undistorted output to grid at different wind speed variation conditions. The proposed optimal Fuzzy logic MPPT inverter controller of WECS is implemented in Matlab/Simulink and the results are compared with the normal Fuzzy logic MPPT control.

The rest of the paper is organized as follows. Section 2 describes overview of MPPT inverter controller. Section 3 explains proposed system design and implementation. Section 4 presents results and discussions of the performance of the proposed system with a comparison. Finally section 5 concludes and highlights the main contributions of the paper.

2. Overview of MPPT Inverter Controller

Wind energy conversion system has been enormously interested as renewable energy conversion as the alternate of fossil fuel and nuclear energy conversions, currently due to ecological concerns. Although wind energy is plentiful, its output changes frequently with the change of its speed all the time. The output power depends on how accurately the peak power points are tracked by the MPPT controller in WECS. This section explains about overview of the maximum power point tracking inverter controller including MPPT configuration, MPPT control method, and power conversion and control.

2.1. MPPT configuration

The configuration of the system is shown in Fig.1, and it is connected to the transformer *T* to grid. The wind speed is represented by v_{wind}, the generator axis rotor speed is ω, and the grid converter controller uses the grid voltage V_g, the AC current *i* and the voltage references *e*, for power conditioning on the grid side. The power P_{wt} is the electric power that is injected into the grid. The corresponding configuration model also consists of the wind turbine, the permanent magnet synchronous generator (PMSG), converters, the MPPT and inverter controller [6,10,25,26]. The converters consists of AC-DC rectifier, controlled DC-DC converter and feedback controlled DC-AC inverter[27].

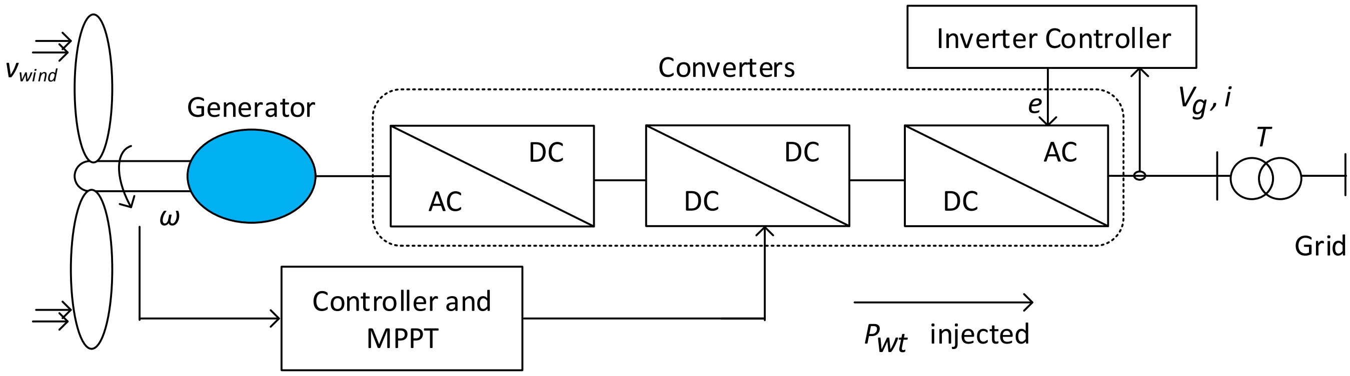

Fig. 1. Wind turbine MPPT configuration

2.2. MPPT control method

Variable speed WECSs are high in demand nowadays, due to their advantages of having better wind energy capturing capability compared to fixed system, and they are more flexible due to their wide speed range operation. Thus, effective control method is very important in variable speed WECS in order to achieve higher efficiency in capturing wind energy to generate electricity [5,8]. MPPT is accomplished by tracking the highest power coefficient locus of wind turbine characteristic curve.

Hill Climb Search (HCS) control method that is commonly known as Perturb and Observe (P&O) control method, is used in this proposed MPPT control of WECS. As presented in Fig.2a, the HCS method tracks the maximum power of the wind turbine by calculating the desired signal to drive the system to maximum power point based on the locality of the operating point and relationship between the changes in power and speed. Besides, the changes in output power due to changes in speed are estimated in HCS method as shown in Fig.2b. The search continues in the same direction if the change in power is positive with last positive change in speed. However, the direction is reversed if the increase in speed causes the decrease in the obtained power [6,10,12]. In this MPPT inverter controller design the HCS control method is implemented for obtaining the possible maximum output of WECS.

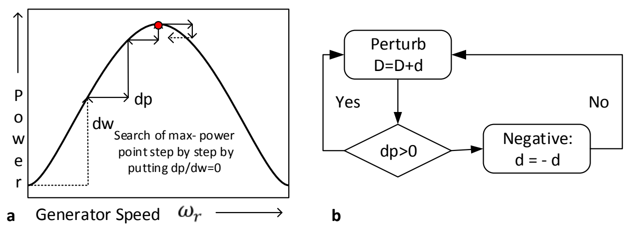

Fig. 2. HCS control method, **a)** MPPT Graph, **b)** MPPT Flowchart

2.3. Power Conversion and Control

The power conversion of WECS usually involves two stages which is known as rectification and inversion. Rectification is the first stage in the power conversion as the AC/DC stage. The rectification system is configured by using diode bridge network [28]. Inverters are being used in the second stage to convert the DC output from the DC link to AC (AC load or the grid system) [5,29]. In the DC link inverter system, the DC power might be boosted up by means of power DC chopper network with an intelligent or optimized control system [1,5]. The most common inverters use bridge inverter network using MOSFETs and IGBTs. The electronic switches require switching signals which are generated by pulse width modulated (PWM) technique. The electronic switches are more efficient as compared to passive diodes bridge and have higher switching speeds, however, they have more complex configuration [16]. A control system regulates the output parameters' values as desired in the inverter system using PI/PID controller, FLC controller and optimization algorithm [14]. It is important that the duty of switching signals to MOSFET or IGBT switches need to be precisely generated to obtain stable, undistorted outputs of the converters of WECS [20].

3. System Design and Implementation

The MPPT inverter controller for grid connected wind turbine is developed using the optimized Fuzzy P&O algorithm to obtain the accurate duty of converter switching. This best duty value might produce the optimum output of WECS. In this section the P&O algorithm, Fuzzy logic control and PSO algorithm are described with detail implementation.

3.1. P&O Algorithm

In P&O algorithm method as mentioned in Fig.3 [12], the operating point is perturbed in a particular moving direction with fixed step size to see how the output power varies. When output power increases with voltage, the system operating point moves in the same direction. If this is not the case, the operating direction should be reversed. The inputs of this P&O Fuzzy logic controller in this system are current, *I* and voltage, *V* respectively.

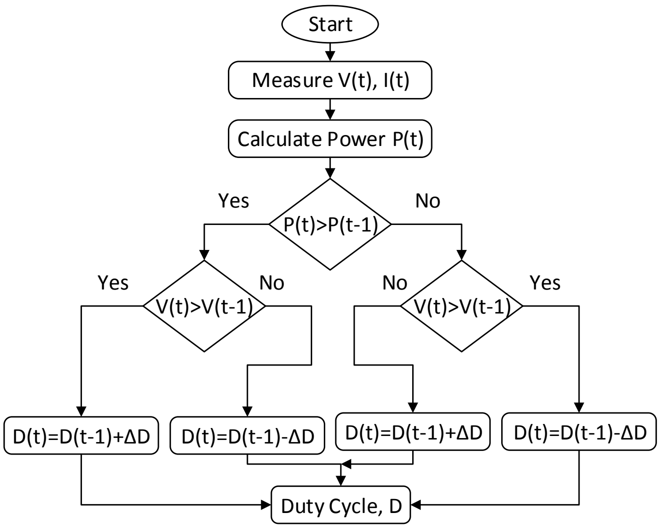

Fig. 3. Flowchart of P&O algorithm

After the input current and voltage pass through the fuzzy logic controller, a series of numerical calculations might occur inside the fuzzy controller to process the input data. After the process of selection and calculation is done, the fuzzy controller might output the required optimum value for the system. In this system, the output of the fuzzy controller is duty cycle of the boost converter. Different duty cycle values might have different output voltage values. Therefore, by manipulating the duty cycle, we can adjust the voltage value of the boost converter and also the inverter indirectly.

3.2. Fuzzy Logic Controller (FLC)

This MPPT controller method measures the current and voltage values of rectifier first followed by searching the maximum power point. Then the controller DC power is fed to the FLC controlled inverter system. Figure 4 below shows the basic block diagram of a FLC [15]. There are two inputs in this Fuzzy algorithm. The Fuzzy controller has three main parts namely fuzzification, Fuzzy inference and defuzzification described below.

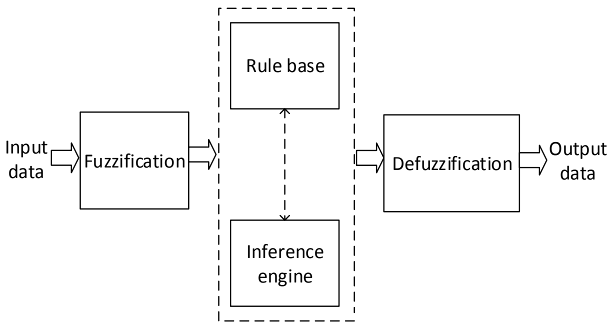

Fig. 4. FLC basic block diagram

The process of converting physical set known as crisp set as input data of Fuzzy controller to Fuzzy set starts first in fuzzification [16]. The Fuzzy inference engine processes rules to produce Fuzzy output sets according to the IF-THEN rule logic. The Fuzzy system combines all Fuzzy output sets into a single output Fuzzy thus producing a single crisp solution for the output variable [16]. Then, the defuzzification process is executed to convert Fuzzy set into classical set or crisp value. Figure 5 presents the membership function editor of Fuzzy logic controller in Matlab/Simulink.

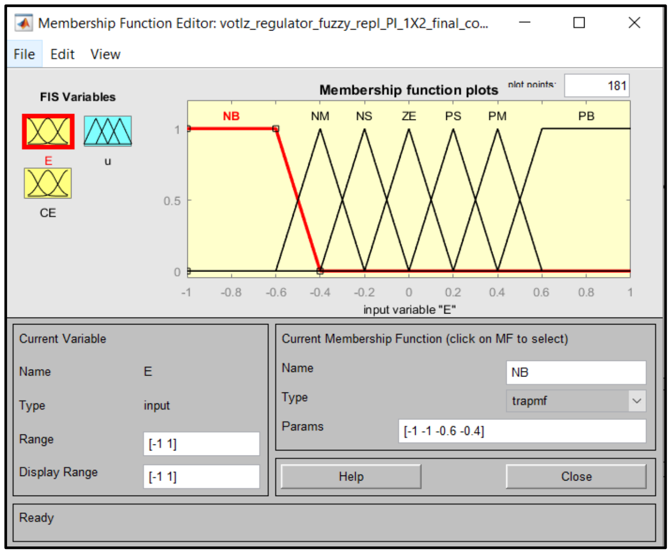

Fig. 5. Membership function editor of fuzzy logic controller

For each input variable, there is a total of seven membership functions. Since there are two inputs in this case, therefore there are forty nine fuzzy rules in total. The range of the membership functions has to be set so that each membership function might have its own range value. Based on these rules, a fuzzy rule table is constructed to simplify it so that it can be seen clearly.

Table 1. P&O Fuzzy rules table

V / I	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NM	NM	NS	NS	ZE	PS
NS	NM	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PS	PM	PM	PB
PB	ZE	PS	PS	PM	PM	PB	PB

NB: Negative Big; NM: Negative Medium; NS: Negative Small; ZE: Zero; PS: Positive Big; PM: Positive Medium; PB: Positive Big

Based on Table 1, the rules created are responsible for the controller's decision to execute task. For example:

Rule 1: IF voltage is NB AND current is NB THEN the output duty cycle is NB

Rule 2: IF voltage is NB AND current is NM THEN the output duty cycle is NB

A clear understanding of P&O Fuzzy rules setup might be obtained from the FLC rules editor in Fig.6a and FLC rules viewer in Fig.6b. The figures of FLC rules editor and viewer are made in Matlab/Simulink.

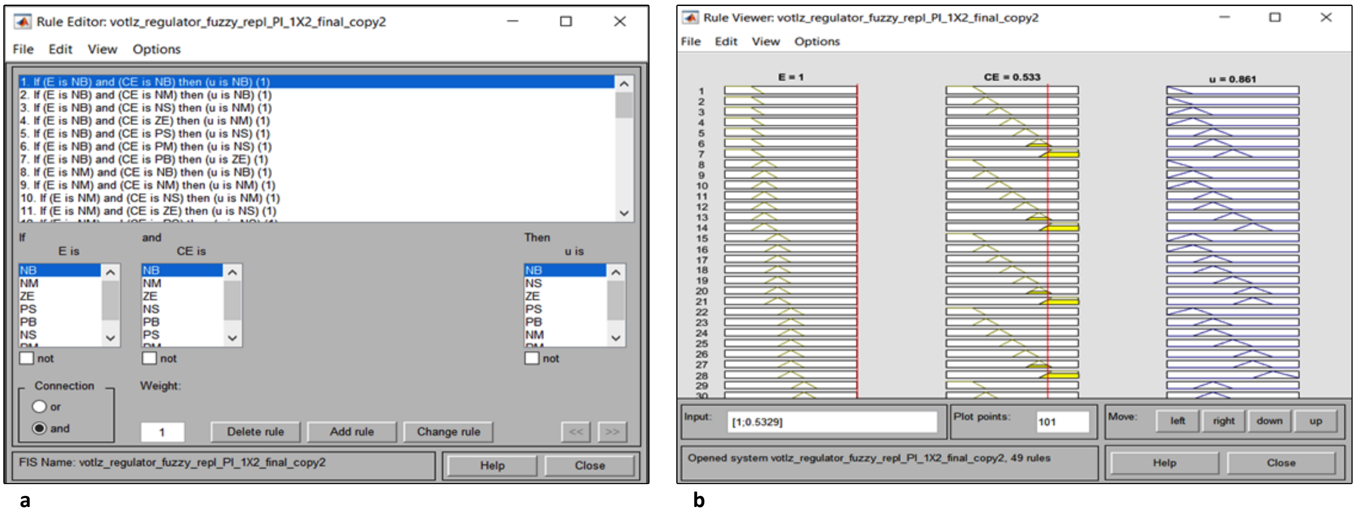

Fig. 6. a) FLC Rules Editor, **b)** FLC Rules Viewer

3.3. Particle Swarm Optimization (PSO) Algorithm

PSO is an evolutionary computation technique which is widely applied because of its verified robustness, ease of implementation, and global exploration capability in various applications to iteratively optimize a candidate solution as a particle of a given problem [21]. It finds a minimum value of the objective function through an iteration process by searching the optimized particle's position and velocity to obtain the optimal solution. The algorithm uses parameters such as swarm size (N), iteration number (T), and searchspace dimension (D) along with few learning and weight factors. The proposed optimal Fuzzy based MPPT inverter controller is developed using PSO algorithm where FLC is designed by searching the best values of input and output membership parameters via PSO algorithm to obtain the optimum output power of WECS.

The flowchart of PSO algorithm is given in Fig.7 for tuning the FLC parameters that is executed in five steps. PSO process starts by setting N, T, D, constants and initial values in first step. Then, the fitness values are computed corresponding each particles by means of the best fit objective function that is Mean Square Error (MSE) (see Equation (1)) in second step. The iteration commences to compute the best fitness value, the best local "pbest" value in each iteration in third step and the global best "gbest" value after the maximum iteration in fourth step. In the meanwhile, the particles' velocities are obtained and swarms' positions are updated using Equations (2) and (3) [17]. The positions are checked whether they are in the searchspace. Then, the fitness values are recomputed and matched with preceding values, and finally, the PSO process obtains the values of optimal FLC parameters corresponding to the minimal objective function fitness value in last step. The proposed PSO based Fuzzy logic MPPT inverter controller uses 30 iterations to obtain minimum mean square error as shown in Fig.8.

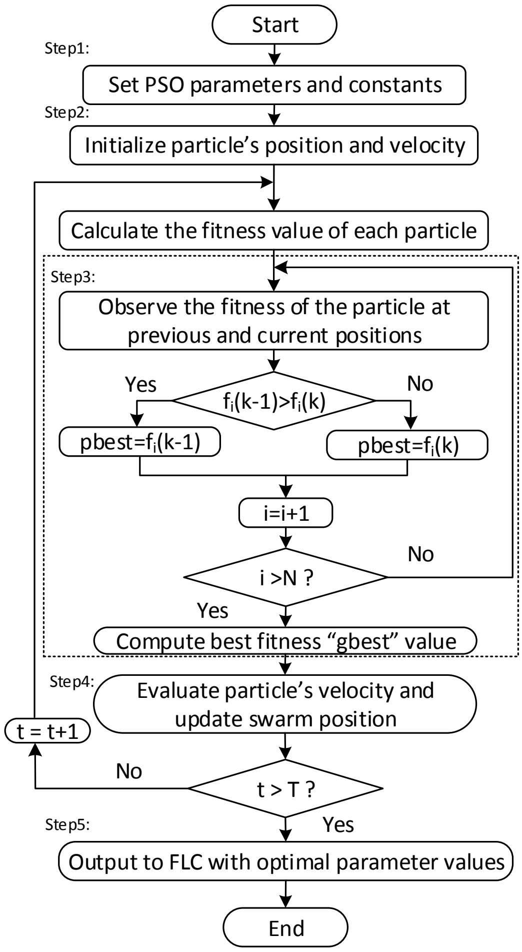

Fig. 7. Flowchart of PSO algorithm

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}|Y_r - Y_a|^2 \qquad (1)$$

$$V_i^d(t+1) = wV_i^d(t) + c_1 r_1\left(P_i^d(t) - X_i^d(t)\right) + +c_2 r_2\left(P_t^d(t) - X_i^d(t)\right) \qquad (2)$$

$$X_i^d(t+1) = X_i^d(t) + V_i^d(t+1) \quad (3)$$

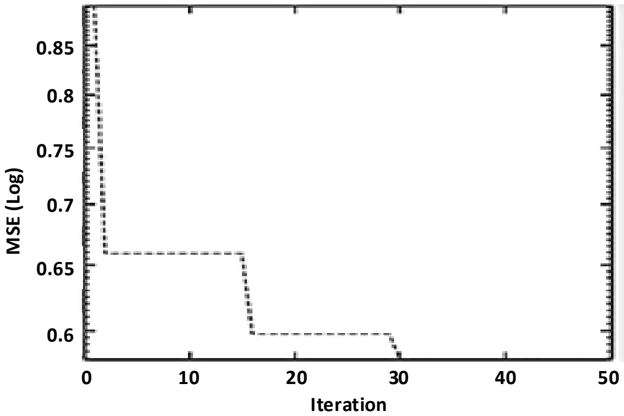

Fig. 8. Optimization response curve for Fuzzy logic MPPT controller

where Y_r is the reference value, Y_a is the actual value, n is the number of samples, c_1 is the social rate, and c_2 is the cognitive rate, r_1 and r_2 are the random in the interval (0,1), V is the velocity factor of agent i at iteration d, t is the present iteration, w is the inertia factor, and X is the position factor.

4. Results and Discussions

Optimal Fuzzy logic controller based MPPT inverter controller is implemented in Matlab/Simulink for gird connected wind turbine. In this paper, the input and output membership parameters of Fuzzy logic controller are optimized via PSO algorithm. In this section, results of WECS such as the instantaneous output voltage and current waveforms of PMSG, the root mean square (RMS) output voltage and current waveforms of PMSG, the output power waveform of PMSG, DC link voltage waveform, and generator speed of WECS. The results are presented in both normal MPPT control and optimized MPPT control to evaluate the performance of PSO optimized Fuzzy logic MPPT inverter controller for grid connected wind turbine. The wind speed data used in this development is 5, 7, 9 and 11m/s respectively to test the tracking performance of the optimized fuzzy logic MPPT controller as shown in Fig.9.

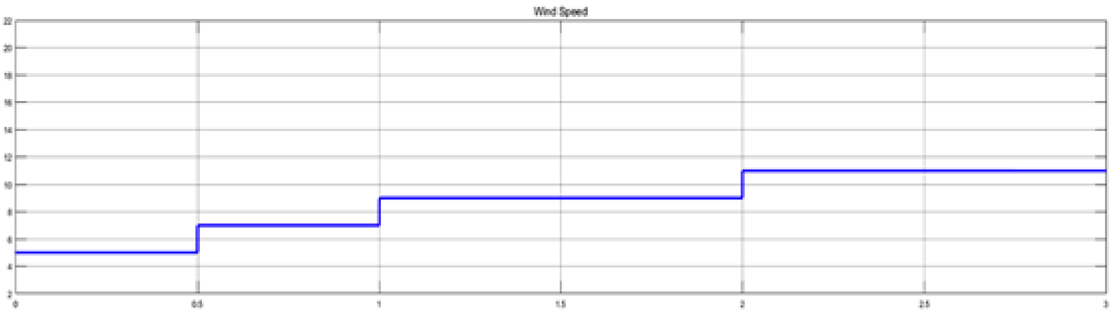

Fig. 9. Wind speed data for the proposed WECS

The PMSG instantaneous output voltage waveform of WECS is shown in Fig.10 at different wind speed variation. The instantaneous output voltage produced in PMSG with optimized MPPT control as in Fig.10b is better than that with normal MPPT control as in Fig.10a. The output voltage in normal MPPT control (see Fig.10a) has more distortion as compared to that in optimized MPPT control (see Fig.10b).

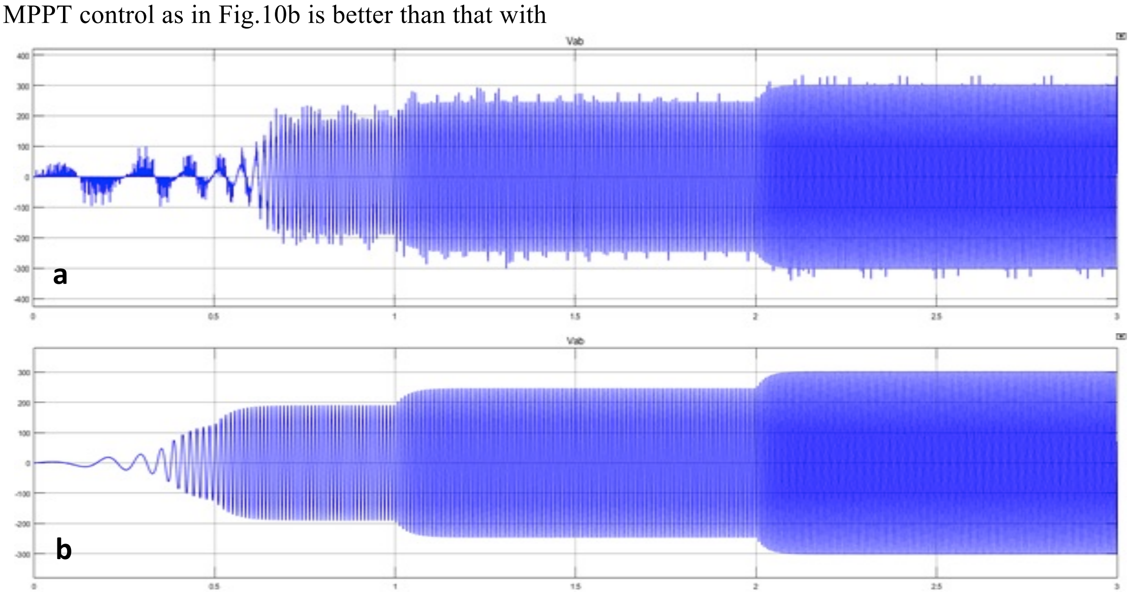

Fig. 10. PMSG voltage of WECS with, **a)** normal MPPT control, **b)** optimized MPPT control

Similarly, Fuzzy logic MPPT controllers are analytically compared with regard to the impact of harmonic distortion on current of WECS with optimized MPPT control and current of WECS with normal MPPT control. The PMSG instantaneous output current waveforms are illustrated in Fig.11 for both normal MPPT control and optimized control at various wind speed conditions. Figure 11a for the current in normal MPPT control has more harmonic distortion compared to Fig.11b for that in optimized MPPT control.

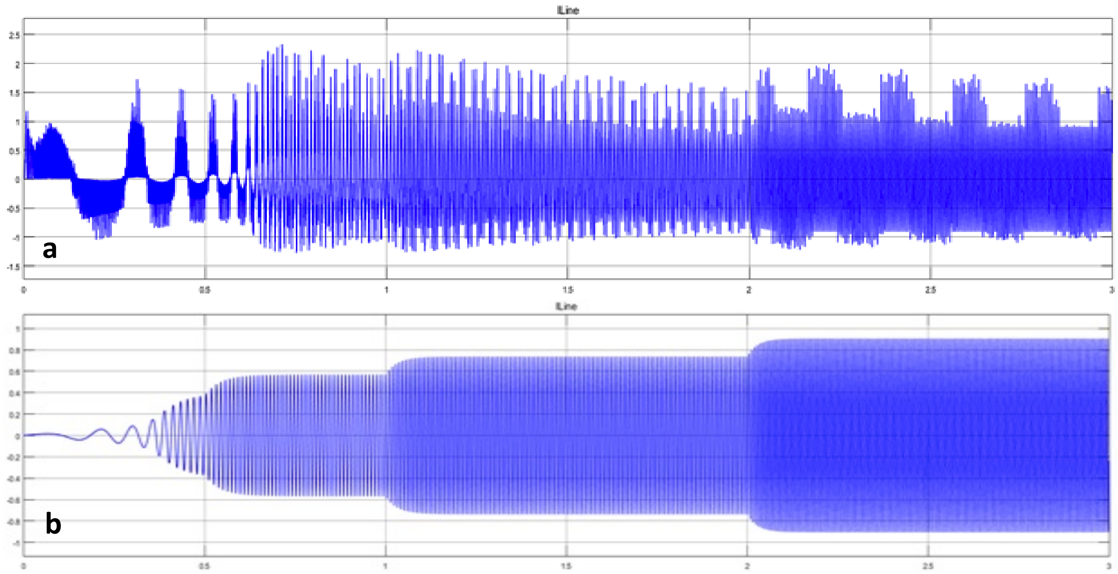

Fig. 11. PMSG current of WECS with, **a)** normal MPPT control, **b)** optimized MPPT control

The RMS output voltage, RMS output current and output power waveforms in PMSG of WECS are shown in Fig.12, Fig.13 and Fig.14, respectively. By comparing result waveforms between Fig.12a and Fig.12b, between Fig.13a and Fig.13b, and between Fig.14a and Fig.14b for a step changing wind speed, it can be clearly observed that WECS with optimized MPPT control has better wind energy tracking capability with fast response time. The output power is much smoother in optimized MPPT control (see Fig.14b) than normal MPPT control (see Fig.14a).

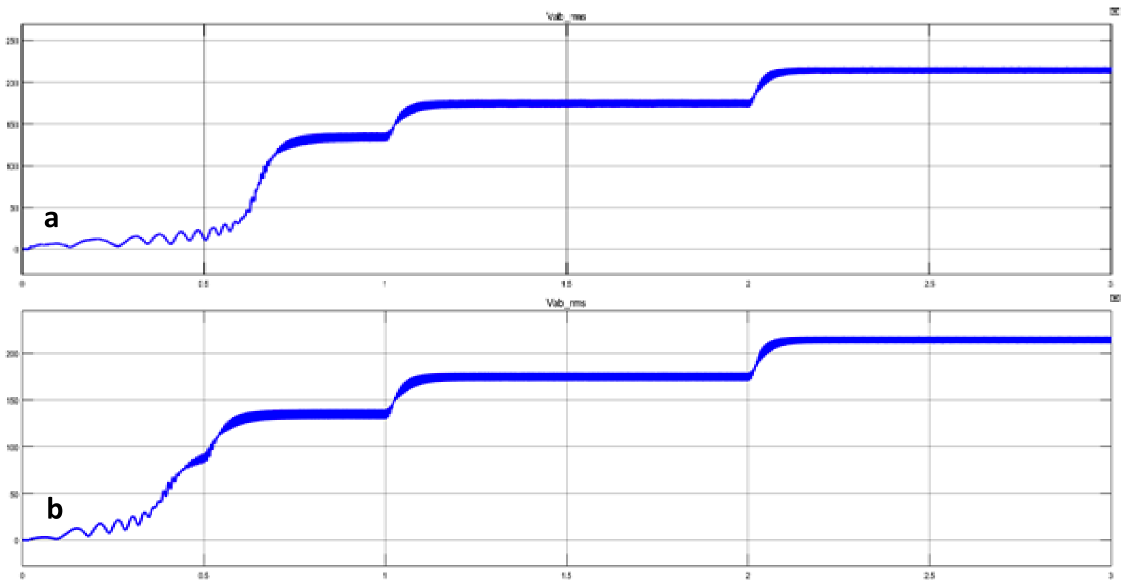

Fig. 12. PMSG RMS voltage of WECS with, **a)** normal MPPT control, **b)** optimized MPPT control

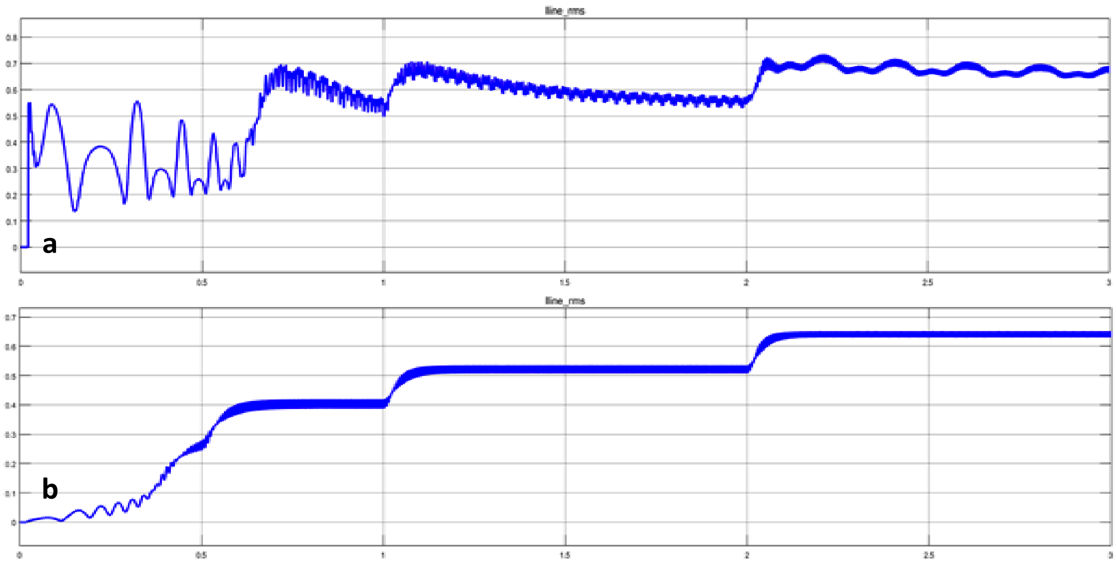

Fig. 13. PMSG RMS current of WECS with, **a)** normal MPPT control, **b)** optimized MPPT control

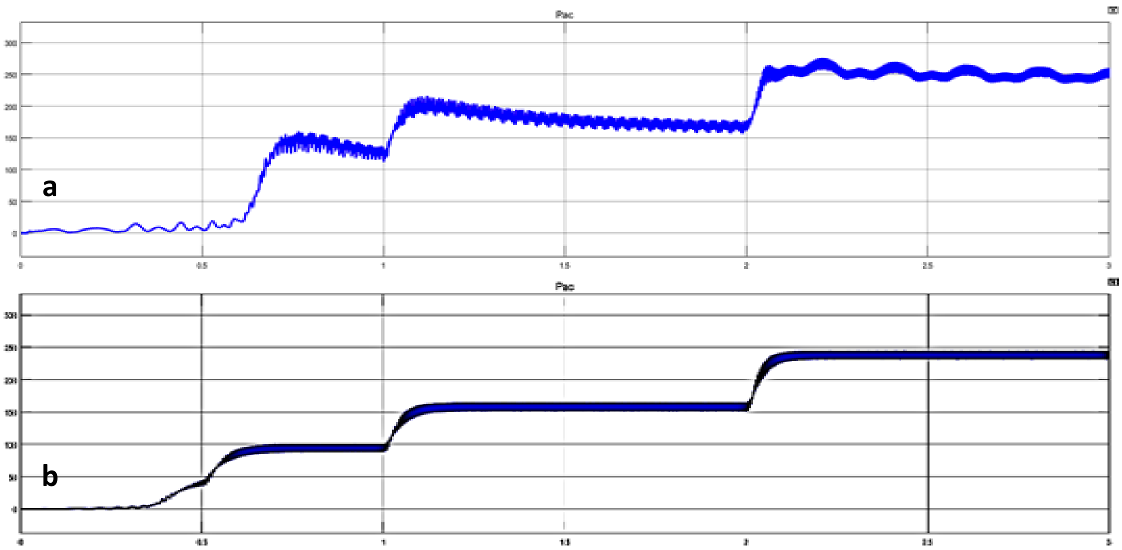

Fig. 14. Output power of WECS with, **a)** normal MPPT control, **b)** optimized MPPT control

The DC link output voltage waveforms are depicted in Fig.15. Comparing waveforms between Fig.15a and Fig.15b for a step variation of wind speed, it is clearly realized that, even though startup succeeded, Fig.15a in normal MPPT control have periedically more fluctuates and oscillates.

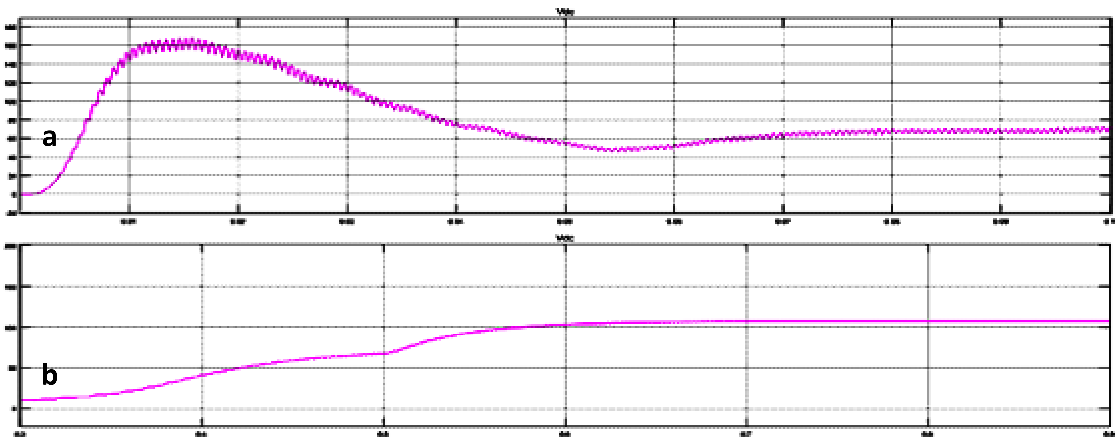

Fig. 15. DC link voltage of WECS with, **a)** normal MPPT control, **b)** optimized MPPT control

Figure 16 presents the generator speed of WECS with both normal MPPT control and optimized MPPT control. The output power in Fig.16b is much smoother and has lesser speed fluctuations compared to Fig.16a. The generator speed and power fluctuations are intensified mainly due to the high changing rate of the wind speed profile. With a reasonable reduction of speed and power fluctuations the optimized MPPT control in WECS proves as a good MPPT controller for grid connected wind turbine. Hence, the proposed controller might be able to enhance the lifespan and reduce maintenance cost of the system.

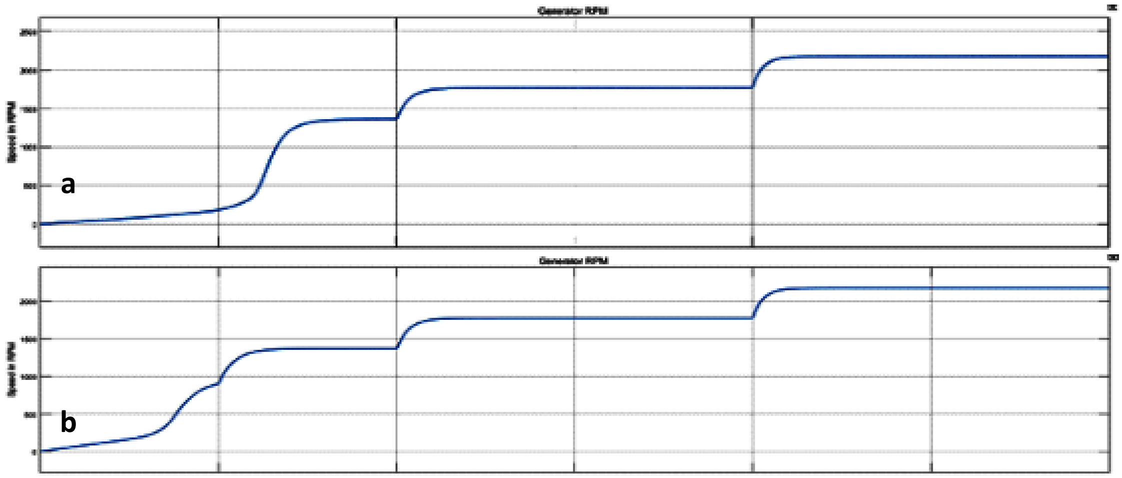

Fig. 16. Generator speed of WECS with, **a)** MPPT control, **b)** optimized MPPT control

Form the overall results and discussions above, the proposed PSO based Fuzzy logic MPPT inverter controller produces the outputs with much even, less distortion and fewer fluctuation at the various step wind speed conditions. So, it might have a good impact to be applied in WECS that might produce reliable and stable output, and enhance the system performance and overall lifecycle.

5. Conclusion

This paper proposes a PSO algorithm approached Fuzzy logic MPPT inverter controller for gird connected wind turbine. The MPPT control of WECS is implemented using HCS (P&O) method with minimum and accurate system conditions. With precisely tracked the maximum power point to produce maximum power output in WECS the PSO algorithm is employed to optimize the input and output membership parameters of Fuzzy system. The optimized Fuzzy system might be able to create an absolute duty value for the converter switching to inverter and hence for maximum power output at different wind speed variation conditions. The proposed controller is implemented in Matlab/Simulink to get output response of the developed system as results are explained based on its performance. The optimization of the Fuzzy system parameters for precise switching duty control is exposed to get the best fitness value with minimal MSE in 30 iterations. The performance results of WECS are shown with the PMSG instantaneous output voltage and current waveforms, the RMS output voltage and current waveforms, and the output power waveform, DC link voltage waveform, and generator speed. Based on the results obtained of both optimized and non-optimized Fuzzy logic MPPT control WECS, the system with optimized Fuzzy logic MPPT control is found to have better maximum power point performance and efficiency in tracking wind energy in terms of much uniform, less distortion and fewer fluctuation outcomes at the various step wind speed conditions. Thus, the developed system might have a good potentiality for WECS in grid application. This proposed MPPT controller model will experience an experimental test to assess the performance of the controller in optimal power generation from natural wind energy resources and later be developed in prototype for testing and validation to apply in real grid connected wind turbine.

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