Closed Loop Control of PV System Using Grey Wolf Optimization Algorithm under Partial Shading Condition

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Abstract. Globally there is an increased awareness of the havoc that climate change and rising pollution are due to the over consumption of carbon riddled fossil fuels making the environment unfit for living. Thus, it is important to make discerning choices to incorporate more clean energy to produce power. Therefore, Renewable energy emerges as an obvious alternative. Renewable resources like solar and wind are now being utilized for power generation. The power output of a solar panel depends on the amount of irradiance of sunlight which is also called insolation. The main drawback in solar is the power output of a PV panel for a particular irradiance is not a linear function of voltage and the power is maximum only at a particular voltage called optimum voltage. When the solar panel is subjected to non-uniform irradiance which is referred to as partial shaded condition, then there will be multiple power peaks in the P-V characteristics and it becomes unable to meet the load requirements. The proposed system will help to overcome this drawback as it consists of two cascaded boost converters. A battery is connected in parallel to output of MPPT boost converter so that load power demand is met by parallel combination of PV panel and battery. The system is optimized for best performance using multi objective GWO optimization technique. Thus, maximum power is extracted even under partial shading condition and constant power is supplied.

Keywords: Photo Voltaic (PV), Proportional Integral (PI), Partial Shading Conditions (PSC), Grey Wolf Optimization (GWO), Integral Square Error (ISE).

1. Introduction

As a fastest growing large economy, the demand for electricity is instantly rising. Hence it is essential to increase our energy output in order to sustain this pace of growth. Renewable resources like solar and wind are now being utilized for power generation. The power output of a solar panel depends on the amount of irradiance of sunlight which is also called insolation. The main drawback in solar is the power output of a PV panel for a particular irradiance is not a linear function of voltage and the power is maximum only at a particular voltage called optimum voltage [1], [4], [5]. When the solar panel is subjected to non-uniform irradiance which is referred as partial shaded condition, then there will be multiple power peaks in the P-V characteristics and it becomes unable to meet the load requirements.
Using MATLAB simulation P-V characteristics is plotted for various irradiance patterns using the specifications given in the table 1.

**Table 1. Specification of PV panel**

| Parameters                  | Rating     |
|-----------------------------|------------|
| Maximum power               | 360 W      |
| Open circuit voltage (V<sub>oc</sub>) | 20 V      |
| Short circuit current (I<sub>sc</sub>) | 5 A       |
| Current at maximum power point (I<sub>mp</sub>) | 4.5 A     |
| Voltage at maximum power point (V<sub>mp</sub>) | 16 V      |
| Irradiance                  | 1000 W/m<sup>2</sup> |

Figure 1 shows the power voltage characteristics of single PV panel. Using the above specification the maximum power obtained from a single PV panel is 303W. Pattern 1 has uniform irradiance value each of 1000W/m<sup>2</sup>, pattern 2 has different irradiance of 1000, 900, 800 and 700W/m<sup>2</sup>, pattern 3 has different irradiance of 900, 700, 500 and 300W/m<sup>2</sup> and pattern 4 has different irradiance of 800, 600, 400 and 200W/m<sup>2</sup>. From the figure 2, it is concluded that only one maximum power under uniform irradiance condition. Under varying irradiance condition, P-V curve has multiple power peaks.

![Figure 1. PV characteristics of Single PV panel](image1.png)

![Figure 2. Power-voltage characteristics of PV panels under different irradiance condition](image2.png)
2. Block Diagram of Existing System

![Block Diagram of Existing System](image)

**Figure 3.** Block Diagram of Existing System

In the existing system of figure 3 contains PV module is associated with MPPT boost converter to acquire extreme output and to transfer power to the attached load. The optimization of the system is made using GWO optimization technique for better performance. The MPP tracking is employed to make most of the PV array’s output power, regardless to the radiance and temperature situations. The GWO algorithm feeds the gating signals to the converter to operate at “maximum power point” voltage. The optimization technique will search for the best optimum value for duty cycle in order to achieve the objective function. In order to determine the optimum duty, an optimization technique is employed with an objective function of maximum power. MPPT requires constant voltage across the load and the power delivered to the load. To maintain the voltage constant is the major requirement in the existing system.

To overcome the limitation in existing system and to make the system more reliable, the proposed system is implemented and it is shown in figure 4. It comprises of two cascaded converters. MPPT boost converter is the first set of converter employed to maintain maximum output from the solar panel. Maximum power tracking requires optimum voltage which is maintained at constant. In order to maintain the voltage there is a second set of converter called as “Quadratic Converter” which employs a MOSFET power switch and switching ON and OFF duty cycle of the power switch will decide the voltage maintained across the load. The optimum duty cycle is decided by the GWO algorithm which is in multi objective. The two main objective of this system is Maximum Power and Minimum ISE. Here one objective is maximum and the other is minimum and so inverse of minimum ISE is considered while combining as single objective so that optimization can be performed for maximum value.

PI controller is employed to generate the ON time based on the error between set voltage and actual voltage across load. PI controller generates control signal in a feedback control loop using an error signal which is the difference between the set value and actual value achieved by the system. The controller takes the input of the best values of $K_p$ & $K_i$ from the GWO optimization. Thus, helps in minimizing the errors.

In PV power system, the power generated may not match the load demand due to changes in irradiance. Hence, a battery is connected in parallel to PV power system for power balance. The battery will deliver power to load when PV power is less than load demand. The battery will charge if PV power is more than load demand. Thus, the system is completely independent to meet the load demands.
In this system there are two objectives: one is Maximum power and another one is Minimum ISE. The two objectives are combined to single objective by converting them to per unit values by dividing the respective values by their expected maximum value (or base value) and taking sum of the two per unit objective value as single objective for optimization. Here one objective is maximum and the other is minimum and so inverse of minimum ISE is considered while combining as single objective so that optimization can be performed for maximum value.

3. Optimization Algorithm

Mirjalili et al. (2014) proposed a GWO algorithm that resembles the leadership qualities and hunting behaviour of grey wolves in nature. Grey wolves prefer to live in a group. The average wolf group size is 5-12. The leadership hierarchy consists of four types of grey wolves called alpha (α), beta (β), delta (δ), and omega (ω). Among these alpha is the leader and it may be a male or a female. Alpha wolf may not be the strongest wolf among the group but it must have the capability to manage the group. The next level of hierarchy in the grey wolves is beta and it may be either a male or female.

3.1 Mathematical Model of GWO Algorithm

The mathematical model of the social hierarchy, tracking, encircling and attacking prey of GWO algorithm is outlined below.

(a) Social hierarchy
In order to model the social hierarchy of wolves in MGWO technique, Assume the fittest solution as the alpha (α) and it is followed by the second and third best solutions, namely, beta (β) and delta (δ), respectively. The rest of the candidate solutions are assumed to be omega (ω). The hunting mechanism is guided by alpha, beta and delta. The omega wolves follow these three wolves.

(b) Exploration and Encircling prey
Grey wolves encircle a prey during the hunt and the encircling behaviour is modelled by the following equations. The distance D of a wolf from the prey can be estimated by Equation (1.1).

\[
\Delta D = |\tilde{C} \times \tilde{X}_p(n) - \tilde{X}(n)|
\]

\[
\tilde{X}(n+1) = \tilde{X}_p(n) - \tilde{A} \times \Delta D
\]

Where, \(n\) denotes the current position, \(A\) and \(C\) are coefficient vectors, \(X_p\) is called the position vector of the prey, and \(X\) is the position vector of the grey wolf. The value of \(A\) and \(C\) are calculated by using the Equations (1.3) and (1.4).
During the iterations ‘α’ linearly decreases from 2 to 0 and \( r_1, r_2 \) are random vectors and the value lies between 0 and 1. The best solution can be achieved with the help of current position by varying the value of \( \alpha \), and \( \beta \) vectors. A Wolf can reach any position between the points based on the random vector \( r_1 \) and \( r_2 \). Therefore, a grey wolf can update its position in any random location by using Equations (1.1) and (1.2). The below equations are used to update the position of alpha, beta and delta wolf.

\[
\bar{D}_\alpha = \left| C_1 \times X_\alpha - \bar{X} \right| \\
\bar{D}_\beta = \left| C_2 \times X_\beta - \bar{X} \right| \\
\bar{D}_\delta = \left| C_3 \times X_\delta - \bar{X} \right| \\
\bar{X}_1 = X_\alpha - \alpha \times \bar{D}_\alpha \\
\bar{X}_2 = X_\beta - \beta \times \bar{D}_\beta \\
\bar{X}_3 = X_\delta - \delta \times \bar{D}_\delta \\
\bar{X}(n+1) = (\bar{X}_1 + \bar{X}_2 + \bar{X}_3)/3
\]

(c) Fitting GWO for PSC PV MPPT tracking

In general, MGWO algorithm is applied to optimize the positions of a group of wolves or particles (N) moving towards a prey or objective. Therefore, the algorithm starts with the initial actual position (X) of a wolf and an assumed best position (G) of wolf. The optimization process involves k iterations to determine the best position of the wolf. Hence, in an iteration called \( n^{th} \) iteration, there will be \( n^{th} \) iteration value for position on N wolf, is namely, \( X_{1,n}, X_{2,n}, \ldots, X_{n,n} \). The algorithm has to determine \( n+1^{th} \) iteration value of the position, which is determined using equations (1.1) and (1.2). In this work, MGWO algorithm is applied to optimize the duty of number of wolves (N) moving towards an objective which is maximum power. Therefore, the algorithm starts with initial duty (X) of a wolf and an assumed best position (G) of wolf. In iteration the duty is updated and the search process ends after k iterations. Here one objective is maximum and the other is minimum and so inverse of minimum ISE is considered while combining as single objective so that optimization can be performed for maximum value.

4. Simulation Results

Figure 5 shows the simulink model of proposed system. Using the specifications of PV indicated in table simulation results are tabulated in table 3.
Figure 5. Simulink model of proposed system

Table 2. Specification of PV panel

| Parameters                        | Rating  |
|-----------------------------------|---------|
| Maximum power                     | 50 W    |
| Open circuit voltage ($V_{oc}$)   | 8.7 V   |
| Short circuit current ($I_{oc}$)  | 8.01 A  |
| Current at maximum power point ($I_{mp}$) | 7.46 A |
| Voltage at maximum power point ($V_{mp}$) | 6.7 V  |
| Irradiance                        | 1000 W/m² |

Figure 6. Load voltage, Current and Power
Figure 7. PV Voltage, Current and Power

Figure 8. Battery Voltage, Current and Power

Table 3. Simulation result of the proposed system

| S. No. | Irradiance (W/m²) | Battery Voltage (V) | Battery Power (W) | Load Voltage (V) | Load Power (W) |
|--------|------------------|---------------------|-------------------|------------------|----------------|
| 1.     | 900              | 12.78               | 46.46             | 48.17            | 48.33          |
| 2.     | 700              | 12.74               | 46.69             | 48.17            | 48.34          |
| 3.     | 500              | 12.74               | 46.55             | 48.16            | 48.36          |
5. Hardware Model

Figure 9. Hardware Model of proposed system

MPPT boost converter employ a MOSFET power switch and switching ON and OFF duty cycle of the power switch will decide the power output from PV panel. Duty or duty cycle is ratio of ON time and Total Time Period of switching signal. Therefore, the value of the Duty should be at an optimum value in order to achieve MPPT. In order to determine the optimum Duty an optimization technique can be employed with an objective function of maximum power. The optimization technique will search the best optimum value for Duty in the range 0 to 1 in order to achieve the objective function. A number of optimization techniques are developed in the past. The proposed Grey Wolf Optimization technique is the best technique in selecting the best optimum duty for achieving the maximum power from the solar panel.

5.1 Minimum ISE

Quadratic boost converter employ a MOSFET power switch and switching ON and OFF duty cycle of the power switch will decide the voltage maintained across the load. PI controller is employed to generate the ON time based on the error between set voltage and actual voltage across load. The best values of $k_p$ and $k_i$ are estimated using GWO optimization technique for minimum error (minimum ISE).

5.2 Multi Objective GWO

Multi objective optimization techniques are objective functions or variables more than one. In this system there are two objectives: Maximum power and Minimum ISE. The two objectives are combined to single objective by converting them to per unit values by dividing the respective values by their expected maximum value (or base value) and taking sum of the two per unit objective value as single objective for optimization. Here one objective is maximum and the other is minimum and so inverse of minimum ISE is considered while combining as single objective so that optimization can be performed for maximum value.

6. Conclusion

Closed loop control of PV-Battery system by using multi objective GWO (Grey Wolf Optimization) technique is performed and implemented in hardware. Thus, maximum power is extracted even under partial shading condition. In future the system can be integrated to standalone micro-grid as part of hybrid power system.
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