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An Efficient Grey Wolf Optimization Approach for Maximum Power Point Tracking of Solar Photovoltaic Systems

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ABSTRACT: Solar photovoltaic (PV) systems are widely regarded as one of the most sustainable and environmentally friendly energy sources for power generation. In recent years, their adoption has significantly increased due to the growing demand for clean energy in electrical applications. However, the output power of a PV system is highly dependent on environmental conditions such as solar irradiance and temperature, which leads to fluctuations in its performance. To ensure maximum efficiency, it is essential to operate the PV system at its Maximum Power Point (MPP).Maximum Power Point Tracking (MPPT) techniques are therefore crucial for optimizing the energy extraction from PV systems. Conventional methods such as the Perturb and Observe (P&O) algorithm suffer from inherent limitations, particularly steady-state oscillations around the MPP, which result in power losses and reduced efficiency.To overcome these drawbacks, this work introduces a Grey Wolf Optimization (GWO)-based MPPT approach. GWO is a metaheuristic algorithm inspired by the social hierarchy and hunting behavior of grey wolves, and it is employed here to effectively track the MPP under varying environmental conditions. In this method, the PV system's voltage and current are taken as input parameters, while the duty cycle of the converter serves as the control output.

A DC-DC boost converter is integrated into the system to regulate and enhance the output voltage according to variations in input power. The proposed method is evaluated under different operating conditions and compared with the conventional P&O technique. Simulation results demonstrate that the GWO-based MPPT method achieves improved power output and exhibits faster tracking capability, especially under changing irradiance levels.

KEYWORDS: Maximum Power Point Tracking (MPPT), Grey Wolf Optimization (GWO), Metaheuristic Algorithm, DC–DC Boost Converter, Renewable Energy, Solar Irradiance, Duty Cycle Control.

I. INTRODUCTION

Green energy, clean energy, and renewable energy are often used interchangeably, but they differ in certain aspects. Renewable energy is derived from resources that are naturally replenished, such as sunlight and wind. Clean energy refers to energy sources that produce little or no environmental pollution, particularly carbon emissions. Green energy specifically emphasizes energy obtained from natural processes with minimal ecological impact.

Renewable energy sources play a vital role in ensuring a stable and diversified energy supply. They enhance energy security, reduce environmental degradation, and help preserve ecosystems and natural resources. Among the various renewable options, solar and wind energy are the most widely utilized due to their availability and scalability.

In developing regions, renewable energy offers a practical solution for electrifying remote and rural areas where extending the conventional power grid may not be economically viable. At the same time, in urban settings, it supports the growing electricity demand by supplementing existing grid systems. The potential of renewable energy is vast, and it can theoretically provide a continuous and sustainable source of power.When compared to the immense amount of solar energy reaching the Earth, human energy consumption is relatively small, highlighting the nearly limitless potential of solar-based resources. Integrating renewable energy into modern power systems is therefore essential for achieving long-term sustainability and meeting increasing energy demands.

A wide range of technologies has been developed to convert renewable resources into usable forms such as electricity, heat, and fuels. Continuous advancements in these technologies have led to improved efficiency and reduced costs, making renewable energy systems more economically competitive. As a result, renewable energy is increasingly becoming a viable alternative to conventional fossil fuel-based energy sources.

Premkumar Manoharan et al. (2020) investigated the reduction in power output of photovoltaic systems caused by variations in environmental conditions such as temperature and solar irradiance. Their study highlights the importance of effective tracking methods during rapidly changing weather conditions. The conventional Perturb and Observe (P&O) technique was considered due to its simplicity and suitability for practical implementation. The system performance was evaluated under a range of operating conditions to study its effectiveness [1].

Nathan Chris Swanepoel et al. (2017) focused on improving solar cell efficiency through Maximum Power Point Tracking (MPPT). They employed the Incremental Conductance (INC) algorithm, which is capable of locating the exact maximum power point by utilizing real-time voltage and current feedback. This method offers a faster response and operates independently of predefined PV characteristics, making it more adaptive to changing conditions [2].

Dezso Sera et al. (2013) conducted a comparative analysis of two widely used hill-climbing MPPT techniques: Perturb and Observe (P&O) and Incremental Conductance (INC). Their study examined both theoretical and practical aspects of these methods, concluding through mathematical analysis that both approaches exhibit similar operational behavior despite differences in implementation [3].

Seyedali Mirjalili et al. (2014) introduced the Grey Wolf Optimizer (GWO), a metaheuristic algorithm inspired by the leadership hierarchy and hunting strategy of grey wolves. The algorithm demonstrated strong performance when compared to other optimization techniques and proved effective in solving complex problems with unknown or nonlinear search spaces [4].Based on these studies, the Grey Wolf Optimization technique is applied in this work to achieve maximum power extraction from solar photovoltaic systems under both uniform and partial shading conditions. Its adaptive and intelligent search capability makes it suitable for handling variations in environmental parameters.

II. PROPOSED BLOCK DIAGRAM

The overall configuration of the proposed system is illustrated in Figure 1. The solar photovoltaic panel generates electrical power under varying conditions of irradiance and temperature. The output voltage and current from the PV panel are continuously monitored and provided as input signals to the Grey Wolf Optimization (GWO) algorithm. Based on these inputs, the algorithm determines the optimal duty cycle required for maximum power extraction.This duty cycle is then applied to the Pulse Width Modulation (PWM) controller, which drives the DC–DC boost converter. The boost converter adjusts the voltage level according to the input power variations, ensuring efficient energy transfer. As a result, the system operates at or near the maximum power point, and the optimized output power is delivered to the connected load.

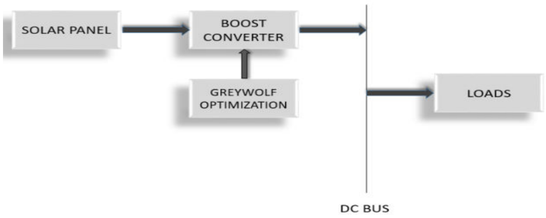

Fig.1 Block diagram

III. SOLAR PANEL

Solar panels convert sunlight, a clean and renewable energy source, into electrical power that can be used to supply various loads. A solar panel is composed of multiple solar cells, typically fabricated from semiconductor materials such as silicon. These cells are formed by doping silicon with elements like phosphorus, which introduces negative charge carriers, and boron, which creates positive charge carriers.

When sunlight strikes the surface of a solar cell, photons transfer their energy to electrons within the material. This energy excites the electrons, causing them to break free from their atomic bonds. The internal electric field present in the cell then drives these free electrons in a specific direction, generating an electric current. This phenomenon is known as the photovoltaic effect. In residential applications, rooftop solar installations can often generate sufficient electricity to meet daily energy demands, with surplus energy sometimes supplied back to the grid.

Photovoltaic (PV) cells are available in several types, including monocrystalline, polycrystalline, and thin-film technologies. Monocrystalline cells are manufactured from a single, pure crystal structure and offer higher efficiency, typically in the range of 18–20%. Polycrystalline cells are made from multiple silicon crystals, making them more cost-effective but slightly less efficient, generally around 16–17.5%.

PV systems operate silently and do not produce environmental pollutants, making them reliable and sustainable energy solutions. A PV module consists of multiple interconnected solar cells arranged to deliver practical levels of voltage and current. These cells are encapsulated within protective layers to ensure durability and resistance to environmental conditions.Silicon plays a crucial role as the primary material in solar cells due to its semiconductor properties. Although it is not a strong conductor under normal conditions, its electrical behavior can be controlled through doping. The foundation of photovoltaic technology dates back to the discovery by Edmond Becquerel in 1839, who observed the generation of electric current from light exposure in certain materials.

The working principle of a solar cell is based on the interaction between photons and a semiconductor material. When photons with sufficient energy strike the PN junction of the cell, they generate electron–hole pairs. The built-in electric field at the junction separates these charge carriers, resulting in a flow of current proportional to the intensity of incident sunlight.

Solar PV systems generate direct current (DC) electricity in a clean, noiseless manner without harmful emissions. To achieve higher output voltages, solar cells are connected in series, forming modules that typically contain 60 or 72 cells. These modules are enclosed in robust protective materials through encapsulation, ensuring long-term performance and protection against mechanical and environmental stresses and Show in the fig 2.

Fig 2 Solar array

IV. BOOST CONVERTER

The boost converter is a simple and widely used DC–DC converter in solar photovoltaic systems, mainly employed to increase the output voltage from the PV panel to the required level. It is preferred over other converters due to its high efficiency, low cost, and compact design. The performance of a solar panel varies with changes in temperature and irradiance, so the converter must operate efficiently under different environmental conditions. To achieve maximum power extraction, the system works near the maximum power point (MPP). The boost converter can operate in continuous conduction mode (CCM) or discontinuous conduction mode (DCM), depending on load and input conditions. It consists of basic components such as an inductor, switch, diode, and capacitor. When the switch is turned on, the inductor stores energy, and when it is turned off, this energy is transferred to the load, increasing the output voltage. This process results in an output voltage higher than the input voltage. Although it offers advantages like simplicity and efficiency, it also has drawbacks such as high ripple current and voltage stress. Despite these limitations, it is widely used in solar energy applications due to its effectiveness and Show in the fig 3.

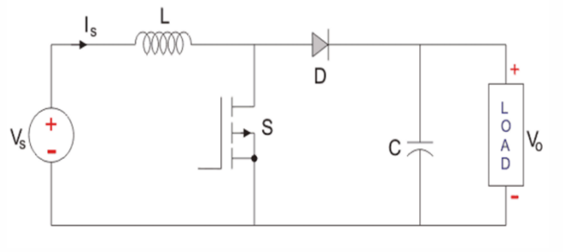

Fig 3 Boost converter circuit

V. GREY WOLF OPTIMIZATION ALGORITHM

Grey Wolf Optimization (GWO) is a nature-inspired metaheuristic algorithm developed based on the social hierarchy and hunting behavior of grey wolves in the wild. In a wolf pack, individuals are categorized into four main groups: alpha (leaders), beta (assistants), delta (subordinate leaders), and omega (followers). This hierarchical structure is mathematically modeled in the algorithm to guide the search process toward an optimal solution. The hunting mechanism of wolves—consisting of searching, encircling, and attacking prey—is translated into optimization steps, allowing the algorithm to explore and exploit the search space effectively.

In engineering applications, GWO is widely used for solving complex optimization problems due to its simplicity, flexibility, and strong convergence capability. In solar photovoltaic systems, it is applied to Maximum Power Point Tracking (MPPT) to determine the optimal operating point under varying environmental conditions such as changes in irradiance and temperature. By continuously adjusting control parameters like the duty cycle of a converter, the algorithm ensures efficient power extraction from the PV system. Compared to conventional methods, GWO offers faster convergence, reduced oscillations, and improved tracking accuracy, making it suitable for dynamic and nonlinear systems and Show in flow Chart 4.

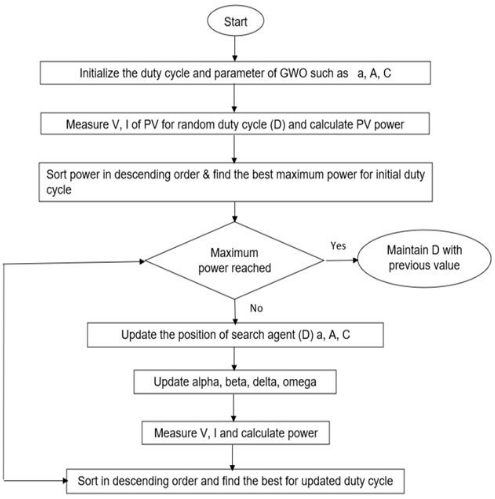

Fig 4.Flow chart of the proposed system

VI. RESULT AND DISCUSSION

The power from the PV module can be calculated by measuring the voltage and current. The PV module voltage and current is used as inputs for the GW algorithm which then adjusts the duty cycle of the switch resulting in adjustment of the reflected load impedance according to the power output of PV module. The duty cycle is the output and it is tested with the different operating conditions. The DC-DC boost converter is used to boost the output voltage to match the variations in input power.The MATLAB/SIMULINK model of PV model with boost converter using grey wolf algorithm (GWO) algorithm is shown in Fig 5.

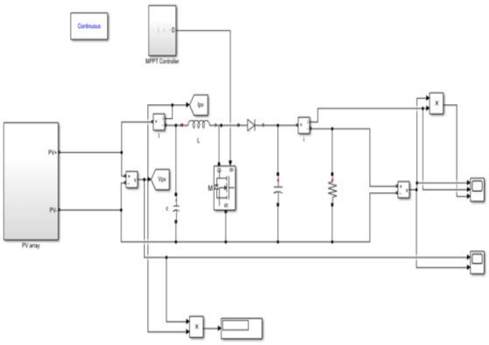

Fig .5 circuit diagram

Solar Panel Output for Grey Wolf Algorithm for Step Change in Input

Figure 6 illustrates the variation in solar panel voltage and the corresponding boost converter output voltage obtained using the Grey Wolf Optimization (GWO) technique under different irradiance levels of 1000 W/m², 800 W/m², and 600 W/m².

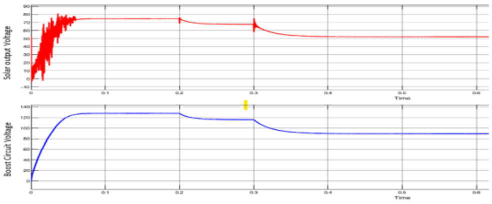

Fig .6 Voltage and boost circuit Voltage for GWO

Solar Panel Output for P&O Algorithm for Step Change in Input

Figure 7 illustrates the variation in solar panel voltage and the corresponding boost converter output voltage obtained using the P&O technique under different irradiance levels of 1000 W/m², 800 W/m², and 600 W/m².

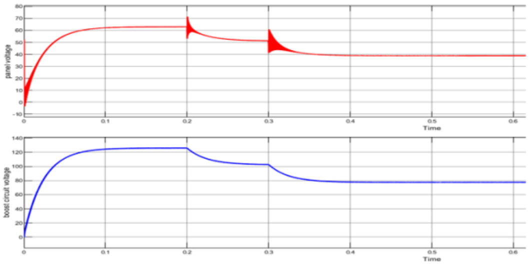

Fig 7 Voltage and boost circuit Voltage for P&O

Output Voltage, Current and Power for Grey Wolf Algorithm

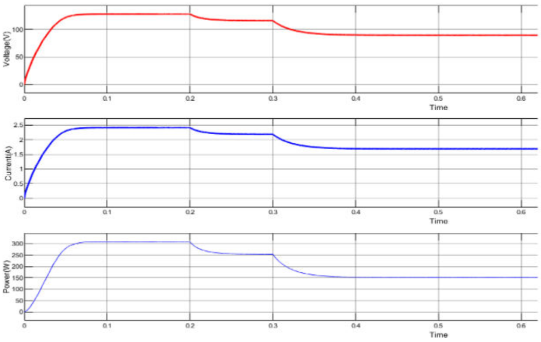

Fig 8 Output for GWO

Output Voltage, Current and Power for P&O Algorithm

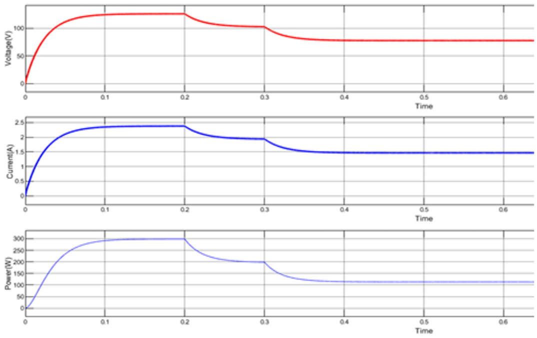

Fig 9 Output for P&O

Comparison between Grey Wolf and P&O for Different Irradiation

Parameters	**P&O (1000 W/m^2)**	**P&O (800 W/m^2)**	**P&O (600 W/m^2)**	**GWO (1000 W/m^2)**	**GWO (800 W/m^2)**	**GWO (600 W/m^2)**
Voltage (V)	125	100	80	130	118	90
Current(A)	2.4	2.0	1.5	2.45	2.3	1.7
Settling Time (s)	0.1	0.27	0.4	0.06	0.2	0.31
Power (W)	300	200	113	310	250	150
Theoretical Power (W)	320	256	160	320	256	160
Power Difference (W)	20	56	47	10	6	10

VII. CONCLUSION

The Grey Wolf Optimization (GWO) algorithm is a meta heuristic technique employed to achieve maximum power extraction from photovoltaic systems. In this work, the proposed approach is implemented and analyzed using the MATLAB/Simulink environment under various operating conditions. The algorithm utilizes the PV module's voltage and current as input parameters, while the duty cycle of the DC–DC converter is generated as the control output for MPPT operation.

The effectiveness of the GWO-based MPPT method is evaluated by comparing it with the conventional Perturb and Observe (P&O) technique. Simulation results indicate that the proposed approach delivers improved performance, achieving approximately 3.22% higher power output and about 4% faster settling time. These improvements are consistent even under varying irradiance levels and partial shading conditions. Hence, the GWO-based MPPT method demonstrates superior efficiency and dynamic response compared to the traditional P&O algorithm.

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