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Research Article

Optimizing Solar PV System Performance Using Self-Tuning Regulator and MPC Controlled Dc/Ac Conversion for Nonlinear Load

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A B S T R A C T

The intermittent nature of solar irradiance presents challenges for photovoltaic (PV) systems, causing fluctuations in output voltage and reducing system stability and efficiency. Conventional control methods, such as fixed Proportional-Integral (PI) controllers, struggle to handle these variations effectively. This paper proposes an advanced PV-based power conversion system that integrates a self-tuning regulator and Model Predictive Control (MPC). The self-tuning regulator adjusts the PWM duty cycle based on irradiance fluctuations, ensuring stable DC voltage regulation. MPC is used to optimize system performance by minimizing voltage deviations and controlling duty cycle variations. The regulated DC voltage is converted to AC by the inverter to drive an induction motor efficiently. The expected results include stable boosted DC output voltage, minimized fluctuations in inverter output and efficient motor operation under varying irradiance conditions. The system is expected to improve both transient and steady-state performance. Simulations will be conducted using MATLAB/Simulink to model and validate the system. This proposed methodology provides an adaptive and optimized solution to the challenges of solar power conversion, enhancing system stability, efficiency and performance in dynamic environmental conditions.

Keywords: Self tunned Controller, Model Predictive Controller, Boost converter, Inverter, PV panel

1. Introduction

The global shift toward renewable energy sources is crucial in the face of climate change, fossil fuel depletion and the need for energy security. Among the most promising renewable energy sources, solar energy stands out due to its abundance, accessibility and minimal environmental impact. These systems can be applied in various sectors, from residential power generation to large-scale installations, significantly contributing to reducing carbon emissions and promoting sustainability. However, solar energy faces challenges due to the intermittent and variable nature of solar irradiance. Solar power generation is dependent on environmental factors such as time of day, weather conditions and geographic location, which can lead to fluctuations in voltage and power output[1]. To optimize energy utilization and ensure reliable power supply, advanced power conversion technologies are necessary. A key component in this context is the DC-DC boost converter, which regulates and converts the variable output from solar panels into stable, usable electricity.

PVs generate low DC voltage that needs to be increased to a higher voltage for powering appliances or integrating with the grid. DC-DC boost converters are used to step up the voltage while maintaining the power balance. However, the performance of these converters can be compromised by fluctuations in solar irradiance. When solar irradiance decreases, the output from the panels drops, leading to instability in the input voltage supplied to the boost converter, resulting in inefficiencies. self-tuned regulators are integrated into modern solar power systems. These regulators dynamically adjust the boost converter's operation based on real-time feedback from solar panel output and irradiance levels[2]. By continuously monitoring these conditions and adjusting the converter's duty cycle or other operational parameters, self-tuned regulators ensure that the system operates optimally, maintaining stable voltage and maximizing energy harvesting even under fluctuating solar irradiance.

A high-quality inverter ensures that the AC output is stable, with minimal harmonic distortion and matches the voltage and frequency required for appliances or grid integration. Pulse Width Modulation (PWM) techniques, which control the inverter's output waveform precisely. This reduces harmonics and improves the overall power quality. The boost converter steps up the low DC voltage from the solar panels and the inverter then converts this DC into AC to drive the induction motor. This integration reduces operational costs and provides a clean energy solution. Effective control strategies are essential for optimizing the performance of solar power systems. Model Predictive Control (MPC), which predicts the system's future behaviour based on current and past data, adjusting control parameters accordingly. MPC can be used to forecast changes in solar irradiance and adjust the operation of the boost converter and inverter in real time[3,4]. This ensures efficient energy conversion even when solar irradiance fluctuates, maintaining voltage stability.

In addition to MPC, Maximum Power Point Tracking (MPPT) algorithms are often used to ensure that solar panels operate at their maximum power point, despite changes in environmental conditions[5]. MPPT dynamically adjusts the operating point of the solar panels, ensuring the system extracts the maximum available energy, thus improving the overall efficiency of the system[6].

In this paper, the integration of DC-DC boost converters, self-tuned regulators, inverters and induction motors into solar power systems presents a highly efficient and sustainable solution to the challenges posed by intermittent solar energy. These systems not only enhance energy efficiency by stabilizing voltage outputs but also provide a scalable solution for diverse applications, from off-grid agricultural systems to large-scale grid-connected installations. The incorporation of advanced control strategies such as MPC and MPPT further optimizes system performance, ensuring that solar energy is harnessed with maximum efficiency.

2. Proposed MPC Based STR

The fig.1 shows that the proposed solar panel connected to boost converter and pwm generated with tunned PI controller and MPC.

2.1. PV Cell Equivalent and Irradiance Effect

The photovoltaic effect energy conversion process can be mathematically modelled using the single-diode equivalent circuit. The output current of a PV cell depends on light intensity (irradiance), temperature and material characteristics. The equation for the output current of a PV cell is **(Figure 1).**

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (1)$$

Where, I_{pv} is the output current of the solar cell at a given voltage V. I_{ph} is the photocurrent generated due to incident sunlight depends on solar irradiance. I_d is the current through the diode, given by the Shockley diode eqn (2). I_{sh} is the current through the shunt resistance leakage current.

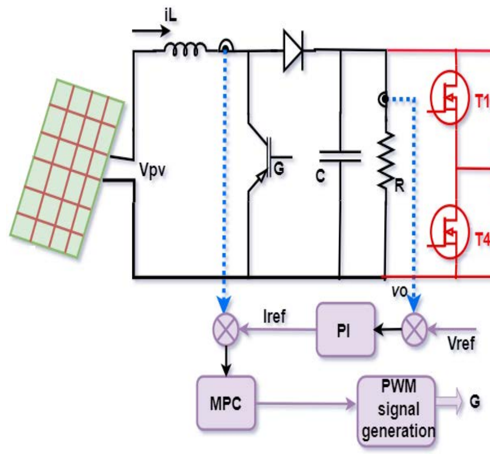

Figure 1: Proposed MPC controller-based DC to AC converter.

The Shockley diode equation for the diode current is

$$I_d = I_0\left(exp\left(\frac{q(V+I_L R_{sh})}{nk_B T}\right) - 1\right) \quad (2)$$

Where, I_0 is the reverse saturation current of the diode. V is the voltage across the solar cell q is the electron charge (1.602×10^{-19} C). n is the ideality factor of the diode (between 1 and 2). k_B is the Boltzmann constant (1.38×10^{-23} J/K). T is the temperature in Kelvin. R_{sh} is the shunt resistance.

Solar irradiance G(t), the power per unit area from the Sun, affects the PV cell's output. The photocurrent I_{ph} is directly proportional to the irradiance G and is given by

$$I_{ph} = I_{ph0}\, X \left(\frac{G}{G_0}\right) \quad (3)$$

Where, I_{ph} is the photocurrent under standard test conditions (typically at G_0=1000 W/m^2). G is the instantaneous solar irradiance. G_0 is the reference irradiance.

Fluctuations in solar irradiance directly impact the voltage Vin(t) of the PV system, which affects the entire power system, including the boost converter and induction motor. As solar irradiance G(t) fluctuates, it directly impacts the input voltage Vin(t) to the boost converter in eqn (3). This, in turn, affects the performance of the boost converter, the operation of the inverter and the speed and torque of the induction motor. This disturbance, modeled as variations in G(t), requires the self-tuning regulator and PWM control to adapt dynamically and maintain stable motor operation.

2.2. Self-Tuning Regulator for PWM Generation

A self-tuning regulator adjusts the duty cycle of the PWM signal based on the error between the desired output voltage Vref and the actual output voltage Vout(t) is

$$E(t) = V_{ref} - V_{out}(t) \quad (4)$$

The self-tuning regulator adjusts the duty cycle D(t) based on the error signal using a Proportional-Integral (PI) controller:

$$D(t) = D_0 + K_p E(t) + K_i \int E(t)dt \quad (5)$$

Where, D(t) is the duty cycle at time t, D_0 is the initial duty cycle, Kp and Ki are the proportional and integral gains. PWM signals are generated by comparing the adjusted duty cycle with a triangular or sawtooth waveform. The dynamic response of the boost converter with a self-tuning regulator can be analyzed using state-space modelling in eqn (6). The state-space equations are

$$\begin{bmatrix} i_L(t) \\ V_{out}(t) \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L(t) \\ V_{out}(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} . D(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} . V_{in}(t) \quad (6)$$

Where, R is the load resistance, C is the output capacitance and Vin(t) is the fluctuating input voltage influenced by solar irradiance G(t).

The inverter converts the DC voltage from the boost converter into AC voltage for driving the induction motor[7-9]. The inverter's output voltage is controlled by the PWM technique and is given by

$$V_{ac}(t) = V_o PWM(t) \quad (7)$$

Where Vout(t) is the output voltage from the boost converter, which fluctuates due to changes in solar irradiance. The PWM signal is generated based on the desired frequency and reference voltage.

2.3. Model Predictive Control (MPC)

Model Predictive Control (MPC) is a control strategy that uses a dynamic model of the system to predict and optimize future system behavior by solving an optimization problem at each time step. The solar PV system, MPC is used to optimize the performance of the boost converter, inverter and induction motor in real-time, taking into account variations in solar irradiance and system disturbances. MPC uses the system's state-space equations to predict future behavior and calculate control actions that minimize a cost function over a prediction horizon.

a. Optimization Problem for MPC

An optimization problem where you are minimizing a cost function over a sequence of control inputs D(t), D(t+1),…, D(t+N-1). The objective is to find the sequence of disturbance or control inputs D(t) that minimizes the cost function, which is a weighted sum of two terms at each time step t, the MPC optimization problem can be formulated as

$$D(t),D(t+1),\ldots,D(t+N-1) \sum_{k=0}^{N-1}((V_o(t+k) - V_{ref})^2 + \lambda_1 D(t+k)^2) \quad (8)$$

Where, N is the prediction horizon. $Vo(t+k)$ is the predicted output voltage at time step (t+k). V_{ref} is the desired reference voltage. $D(t+k)\lambda_1$ is a regularization parameter that penalizes large control inputs to avoid excessive duty cycle changes. s a regularization parameter that controls the trade-off between minimizing the voltage error ($Vo(t+k) - V_{ref}$) and minimizing the disturbance input D($t+k$).

This objective function aims to minimize the difference between the predicted output voltage ($V_o(t+k)$) and the reference voltage V_{ref} over the prediction horizon, while also penalizing large control inputs duty cycles to avoid oscillations or overcompensation. λ_1 is a weight that controls how heavily the disturbance input is penalized. A higher value of λ_1 leads to a greater penalty for using large inputs, thus promoting smaller disturbance inputs. The magnitude of the control or disturbance input D(t),D(t+1),…,D(t+N-1), which penalizes large inputs to avoid excessive control actions. If λ_1 is large, the optimization will prioritize minimizi ng D(t), D(t+1) ,…,D(t+N-1) over minimizing the voltage error. If λ_1 is small, the optimization will prioritize minimizing th e voltage error, potentially leading to larger disturbance inputs.

b. Constraints for MPC

In addition to the objective function, the MPC must account for the physical constraints of the system, such as the limits on the duty cycle and the output voltage

Step 1: Duty Cycle Constraints

$$0 \le D(t+k) \le D_{max}, \forall k \in [0, N-1] \quad (9)$$

D_{max} is the maximum allowed value for the control input at each time step. Typically, D_{max} is set to 1 (or 100%), which means that the control input is bounded between 0 and 1 (or 0% and 100%).

Step 2: Output Voltage Constraints

$$V_{min} \le V_o(t+k) \le V_{max}, \forall k \in [0, N-1] \quad (10)$$

This imposes bounds on the output voltage V_o(t+k) at each time step (t+k), ensuring that the output voltage stays within a feasible range between a minimum voltage V_{max} and a maximum voltage V_{max}.

Step 3: Input Voltage (Irradiance Effect) Constraints

$$V_{in}(t+k) = V_{ph}(G(t+k)) - I_d(t+k)R_s \quad (11)$$

describes the input voltage V_{in}(t+k) at time step (t+k), where the voltage depends on two key factors of G(t+k). The solar irradiance at time step (t+k), which affects the photovoltaic (PV) panel's output. I_d(t+k) The current drawn by the system at time step (t+k). Rs is the series resistance of the photovoltaic system.

At each time step, the MPC controller calculates the optimal duty cycle sequence [D(t), D(t+1),…, D(t+N−1)] that minimizes the cost function, subject to the constraints. The first value D(t) is applied to the system and the process is repeated at the next time step, forming a closed-loop control system. By combining the solar PV equations, boost converter dynamics, inverter control and the Model Predictive Control (MPC) strategy, the system ensures stable operation despite disturbances from solar irradiance fluctuations. This integration enables the power conversion system to continuously adapt, optimizing the performance of the motor and ensuring efficient energy use from the solar panels.

3. Simulation Results and Discussion

The simulation results focus on the performance of a solar panel system and the output characteristics after a DC-DC boost converter. The voltage fluctuates with disturbances, likely caused by environmental conditions such as changes in solar irradiance, temperature or other system disturbances. The voltage output starts around 100 V and shows periodic variations over the simulation duration (0–100 seconds). The voltage initially increases slightly and then decreases after approximately 40 seconds, demonstrating a dynamic response. Noise is visible in the voltage waveform, which may result from non-idealities in the solar panel or external disturbances. The second plot illustrates the **DC-DC boost converter output voltage**, which processes the raw solar panel voltage to achieve a higher, regulated DC output. The boosted voltage output maintains a relatively stable waveform compared to the raw solar panel output. Despite disturbances in the input voltage, the converter successfully steps up the voltage to approximately **150 V** to **200 V**, depending on the time **(Figure 2)**.

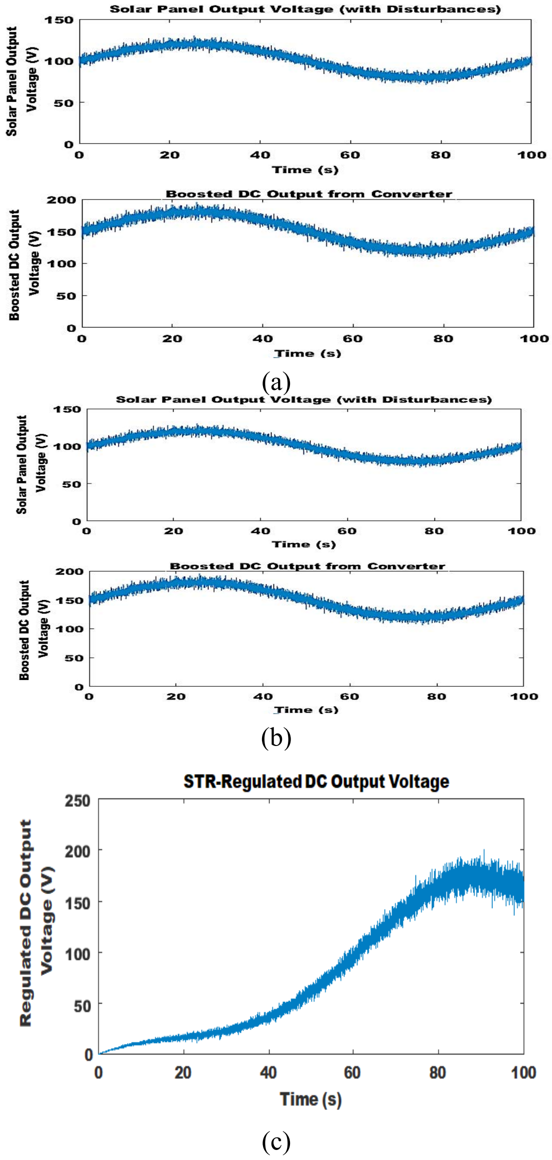

Figure 2: Solar and Boost Converter Output (a). Solar panel output voltage with disturbances (b) boost converter output voltage (c) Regulated Boost converter voltage.

The fluctuations in the boosted voltage are minimal compared to the input, indicating that the boost converter mitigates disturbances and improves voltage stability. The DC voltage starts from approximately **0 V** and rises progressively over the duration of **100 seconds**. The regulation process results in a smooth, controlled increase, with the voltage reaching a peak of approximately **250 V**. The observed response demonstrates the effectiveness of the regulator in achieving a steady and controlled DC voltage output. The smoothness of the output suggests that the STR regulator effectively suppresses disturbances and stabilizes the voltage as needed for further processing by the inverter.

Figure 3. Shows that the AC output voltage begins at zero and increases in amplitude over time, achieving a peak of approximately **±300 V**. The waveform is **sinusoidal** in nature, with a gradually increasing amplitude that corresponds to the rising regulated DC voltage. This behavior demonstrates the inverter's ability to convert DC into AC while maintaining sinusoidal output characteristics, which are essential for driving AC loads such as motors. The waveform exhibits minimal noise, indicating that the inverter operates efficiently and generates a clean AC output voltage.

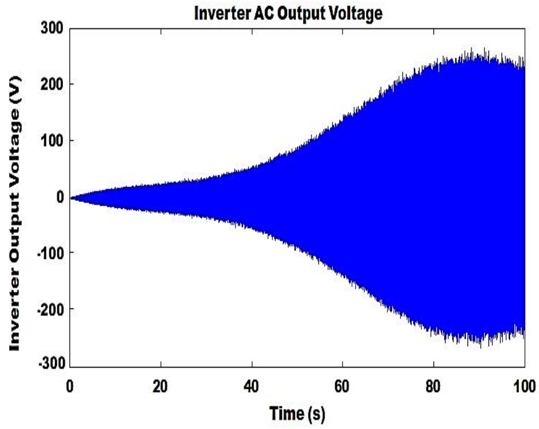

Figure 3: Inverter output voltage.

The current starts from zero and gradually increases, consistent with the inverter output voltage in **(Figure 4)**. The current waveform exhibits a sinusoidal profile, with its amplitude rising in proportion to the inverter voltage over time. At steady state (around **85–100 seconds**), the motor current reaches a peak amplitude of approximately **±3.5 A**. The zoomed-in portion of the plot (85–85.5 seconds) clearly shows the sinusoidal nature of the motor current, emphasizing the phase relationship between the inverter voltage and the motor current.

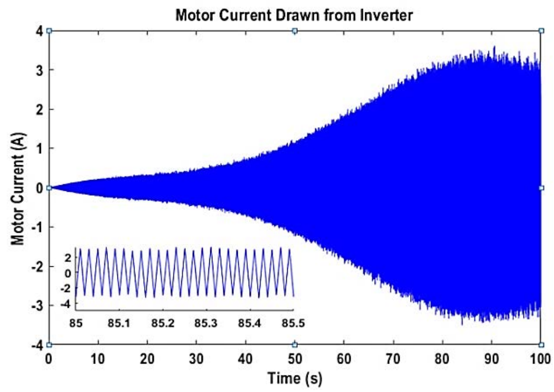

Figure 4: Inverter output current with Induction motor load.

4. Conclusion

The simulation results demonstrate the efficient operation of a PV-based power conversion system, integrating a boost converter, inverter and motor load, with effective control strategies ensuring stable performance. **The PV cell output voltage** fluctuates due to irradiance disturbances, as seen in the solar panel output voltage ranging **between 50 V and 150 V**. The boost converter successfully regulates this varying input voltage, producing a **boosted DC output of up to 200 V**, despite the irradiance effect. A self-tuning regulator using a PI controller dynamically adjusts the PWM duty cycle, stabilizing the boost converter's output voltage. This stability is evident in the inverter output, where the **AC voltage amplitude rises to ±300 V** over time. The motor current drawn from the inverter reflects smooth sinusoidal behaviour, peaking at **3.5 A**, showcasing efficient energy transfer and motor operation. The dynamic adaptability of the system under disturbances is further enhanced by Model Predictive Control (MPC). MPC optimizes the duty cycle to minimize output voltage error while avoiding excessive control inputs. By predicting future states, MPC ensures minimal deviations in voltage and current under varying irradiance. This is particularly critical as fluctuations in solar irradiance directly affect the **input voltage Vin(t)**, boost converter operation and motor performance. Harmonic reduction techniques and energy storage integration can enhance power quality and continuity. Real-time hardware implementation and thermal analysis will ensure practical feasibility and robust operation. The results validate the system's ability to deliver stable and optimized performance, adapting effectively to disturbances and ensuring efficient energy utilization in renewable energy applications.

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