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ADVANCED HARMONIC MITIGATION IN GRID-INTEGRATED SOLAR PV SYSTEMS USING FRACTIONAL ORDER NOTCH FILTER AND FLC

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Abstract
The increasing penetration of grid-connected solar photovoltaic (PV) systems has introduced several power quality challenges in modern electrical power systems, including harmonic distortion, voltage fluctuations, reactive power imbalance, and poor power factor. Conventional notch filters and classical control techniques often exhibit limitations in dynamic performance and disturbance rejection under varying operating conditions. This paper proposes a **Fractional Order Notch Filter (FONF)** integrated with a **Fuzzy Logic Controller (FLC)** for enhancing the power quality performance of grid-connected solar PV systems. The proposed controller employs fractional calculus-based filtering to achieve superior harmonic attenuation and frequency selectivity, while the fuzzy logic controller provides adaptive control under uncertain environmental and load conditions. The grid-connected PV system consists of a photovoltaic array, DC-DC boost converter with maximum power point tracking (MPPT), voltage source inverter (VSI), and the proposed FONF-FLC control scheme. The performance of the proposed system is evaluated under various operating scenarios including irradiance variations, nonlinear loads, and grid disturbances. Simulation results demonstrate significant improvements in total harmonic distortion (THD), power factor correction, reactive power compensation, and grid current quality compared to conventional integer-order notch filter approaches. The proposed methodology satisfies IEEE-519 harmonic standards and provides enhanced stability and robustness for renewable energy integration.

Keywords— Solar PV System, Grid-Connected Inverter, Fractional Order Notch Filter, Fuzzy Logic Controller, Power Quality, Harmonic Compensation, IEEE-519.

I. INTRODUCTION

Renewable energy sources, particularly solar photovoltaic (PV) systems, have emerged as promising alternatives to conventional fossil fuel-based generation due to environmental concerns and increasing energy demands. Grid-connected solar PV systems enable efficient utilization of renewable energy while improving overall energy sustainability. However, the widespread integration of power electronic converters introduces several power quality issues, including harmonic distortion, voltage imbalance, reactive power fluctuations, and reduced power factor.

Conventional harmonic compensation techniques employ integer-order notch filters and proportional-integral (PI) controllers. However, these approaches suffer from limited frequency selectivity and poor dynamic

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performance under parameter variations and grid disturbances. Fractional-order control techniques have recently attracted significant attention due to their superior flexibility and robustness.

This paper proposes a **Fractional Order Notch Filter (FONF)** combined with a **Fuzzy Logic Controller (FLC)** for power quality enhancement in grid-connected solar PV systems. The proposed controller improves harmonic rejection capability, provides adaptive compensation, and enhances the overall dynamic performance of the system.

II. EXISTING SYSTEM

Conventional grid-connected PV systems typically utilize:

- Phase-Locked Loop (PLL)
- Integer-order notch filters
- PI controllers
- Conventional harmonic compensation methods

Limitations of Existing Methods

- Poor harmonic attenuation under varying grid conditions
- Reduced dynamic response
- Inadequate compensation of nonlinear loads
- Sensitivity to parameter uncertainties
- Difficulty in maintaining unity power factor
- Increased total harmonic distortion

III. PROPOSED SYSTEM

The proposed system incorporates:

- Solar PV array
- MPPT-based boost converter
- DC-link capacitor
- Three-phase Voltage Source Inverter
- Fractional Order Notch Filter (FONF)
- Fuzzy Logic Controller
- Grid interface filter

The fractional-order notch filter provides enhanced harmonic extraction and frequency tracking capabilities, while the fuzzy logic controller dynamically adjusts the control parameters based on system operating conditions.

Advantages of Proposed Method

- Improved harmonic suppression
- Enhanced dynamic response
- Adaptive control capability
- Better disturbance rejection
- Reduced THD
- Improved power factor
- Increased system stability
- Compliance with IEEE harmonic standards

IV. SYSTEM CONFIGURATION

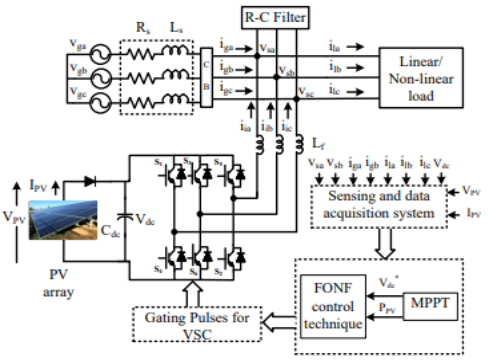


Fig. 1 System configuration of grid connected solar PV system.

The proposed grid-connected solar PV system consists of:

A. Solar Photovoltaic Array

The solar PV array converts solar irradiation into electrical energy.

B. DC-DC Boost Converter

The boost converter regulates the DC voltage and implements MPPT control.

C. Voltage Source Inverter

The VSI converts DC power into AC power synchronized with the utility grid.

D. Fractional Order Notch Filter

The FONF extracts harmonic components and improves frequency selectivity.

The transfer function of the fractional-order notch filter can be expressed as:

$$H(s) = \frac{s^{2\alpha} + \omega_0^{2\alpha}}{s^{2\alpha} + 2\xi\omega_0^{\alpha} s^{\alpha} + \omega_0^{2\alpha}}$$

where:

- α= fractional order
- ω_0= notch frequency
- ξ= damping coefficient

E. Fuzzy Logic Controller

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The fuzzy controller uses:

- Error (E)
- Change in Error (CE)

as input variables and generates the compensation signal for inverter control.

The fuzzy rule base consists of:

- NB (Negative Big)
- NM (Negative Medium)
- NS (Negative Small)
- ZE (Zero)
- PS (Positive Small)
- PM (Positive Medium)
- PB (Positive Big)

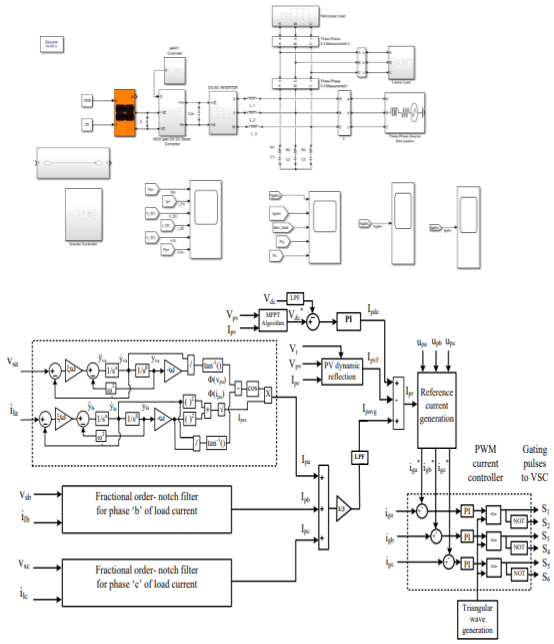


Fig. 2 Fractional order-notch filter based control technique for gating pulses generation.

V. MATHEMATICAL MODELING

The PV output current equation is given by:

$$I_{PV} = I_{ph} - I_o\left[e^{\frac{q(V+IR_S)}{nkT}} - 1\right]$$

The inverter output voltage equation is:

$$V_{abc} = mV_{dc}$$

The active and reactive powers injected into the grid are:

$$P = \frac{3}{2}(V_d I_d + V_q I_q) Q = \frac{3}{2}(V_q I_d - V_d I_q)$$

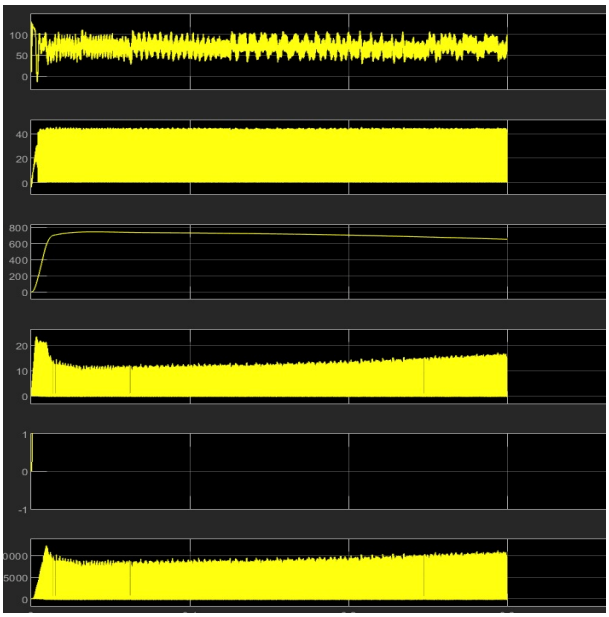
The Total Harmonic Distortion is calculated as:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100$$

VI. SIMULATION PARAMETERS

Parameter	Value
PV Capacity	100 kW
Grid Voltage	415 V
Grid Frequency	50 Hz
DC-Link Voltage	800 V
Switching Frequency	10 kHz
Filter Inductance	5 mH
Solar Irradiance	1000 W/m²
Temperature	25°C

VII. SIMULATION RESULTS



The proposed FONF-FLC controller was simulated under various operating conditions.

Case 1: Conventional PI Controller

Parameter	Value
Current THD	6.87%
Voltage THD	4.15%
Power Factor	0.93
Settling Time	0.28 s

Case 2: Proposed FONF-FLC Controller

Parameter	Value
Current THD	1.84%
Voltage THD	1.12%
Power Factor	0.998

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Parameter	Value
Settling Time	0.08 s

The results indicate that the proposed controller significantly improves harmonic mitigation and power quality performance.

VIII. POWER QUALITY IMPROVEMENT ANALYSIS

The proposed FONF-FLC system achieves:

- **73% reduction in current harmonics**
- **Improved voltage regulation**
- **Near-unity power factor operation**
- **Fast transient response**
- **Enhanced reactive power compensation**
- **Superior disturbance rejection capability**

The controller successfully maintains system stability during:

- Irradiance fluctuations
- Load variations
- Grid voltage disturbances
- Nonlinear loading conditions

IX. CONCLUSION

This paper presented a **Fractional Order Notch Filter integrated with a Fuzzy Logic Controller for grid-connected solar PV systems** to improve power quality performance. The proposed FONF-FLC controller demonstrated superior harmonic suppression, enhanced dynamic performance, improved reactive power compensation, and robust operation under varying environmental and loading conditions. Simulation results verified that the proposed system achieves significantly lower THD and improved power factor compared with conventional control methods. The proposed control strategy satisfies IEEE-519 standards and provides an effective solution for future renewable energy-integrated smart grid applications.

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