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Design a novel SSSC based FOPID controller for the hybrid PV-DFIG-based system to enhance transient stability and dampen power oscillations

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ABSTRACT

The integration of photovoltaic (PV) and wind energy systems is becoming increasingly significant in the modern energy sector. Among various technologies, doubly fed induction generator (DFIG)-based wind power systems are extensively utilized due to their superior power control capabilities. Conventional control strategies, such as proportional-integral (PI) controllers, are commonly implemented to stabilize system waveforms. However, recent advancements highlight the potential for improved oscillation damping through optimized controller designs. This paper introduces an optimal fractional-order proportional-integral-derivative (FOPID) controller integrated with a static synchronous series compensator (SSSC) to enhance power system stability. The proposed approach incorporates the dynamic characteristics of a wind energy conversion system (WECS) connected to an infinite grid. A detailed WECS model is developed to assess the effectiveness and robustness of the proposed controller in mitigating power oscillations, particularly under varying wind conditions. The proposed FOPID controller offers enhanced flexibility for parameter tuning, enabling precise damping of power oscillations, and presents a significant advancement over traditional wind turbine systems based on permanent magnet synchronous machines (PMSM).

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1. INTRODUCTION

Voltage injection through static synchronous series compensators (SSSC) is a widely adopted method for enhancing reactive power flow and improving power transmission performance [1], [2]. As part of FACTS devices, SSSCs enhance voltage stability, system stability, and oscillation damping by regulating voltage, current, and impedance [3]-[5]. Advanced control strategies, including modified differential evolution, improved PID, and fuzzy lead-lag controllers, have been explored for stability improvement [6]-[10].

Traditional PID controllers are common in power system stabilizers (PSSs) to mitigate low-frequency oscillations (LFOs), but their fixed gains limit adaptability to dynamic conditions [11]-[13]. Fractional order PID (FO-PID) controllers address these limitations using fractional calculus; however, their complexity and lack of standardized tuning methods remain challenging [14], [15]. Decentralized PID-PSS designs using linear matrix inequality (LMI) and wide-area measurement systems (WAMS) for wide-area power system stabilizers (WAPSS) have been proposed but face communication delays and related issues [16]-[22]. FACTS-based controllers leveraging the equilibrium optimization algorithm (EOA) for FOPID design demonstrate improved oscillation damping but require further optimization to address implementation challenges [23], [24].

This study introduces an SSSC-based FO-PID controller to mitigate active (P) and reactive (Q) power fluctuations during faults, enhancing damping and stability. The proposed controller integrates wind energy conversion systems (WECS) into an infinite bus configuration, adapting to wind power variations for improved system reliability. While methods like EOA for FACTS controllers show potential, practical issues such as communication delays and load variations in wide area damping controllers (WADCs) remain underexplored [23], [25]. This study addresses these gaps, providing notable advancements in power system control and stability.

In addressing the limitations of existing methodologies, this study makes the following contributions such as analysis of fluctuations in both active (P) and reactive (Q) power at the buses, attributed to faults occurring in the power lines under investigation. Then, the implementation of an SSSC regulated by a fractional order proportional integral derivative controller (FOPIDC) to dampen power oscillations within the proposed system. Then, design an optimal FOPIDC to mitigate power system instability using a static synchronous series compensator with a dynamic voltage equivalence system. Then, integration of the dynamics of WECS into an infinite bus configuration enhances the proposed controller's effectiveness in addressing fluctuations in wind power supply and thereby improving system stability.

2. PROPOSED METHODOLOGY

2.1. System description and control algorithm

This study considers a hybrid power generation system integrating PV and wind energy. The wind power generation employs a doubly fed induction generator (DFIG), while the PV system uses a boost converter for maximum power point tracking (MPPT) and a DC-AC converter. Figure 1 illustrates the proposed system, where the DFIG generates 575 V, stepped up to 161 kV via a transformer for transmission. Similarly, PV power is generated at 0.4 kV and stepped up to 161 kV. The SSSC is connected after the point of common coupling (PCC), with the system linked to an infinite power system.

Figure 2 presents the SSSC control algorithm. The required DC-link voltage is set as V_{dcmin} and compared with the measured V_{dc}. The resulting error is processed through the FOPIDC to generate the required injection voltage. This voltage is added to the reference voltage V_{ref} and passed through a summing block. The voltage at the PCC (V_{pcc}) is synchronized using a phase-locked loop (PLL) to determine the frequency. The voltage error between the reference and measured values is again processed in the FOPIDC, which determines the phase angle, enabling pulse width modulation (PWM) generation.

2.1.1. Mathematical modeling of the proposed SSSC controller

The (1) and (2) illustrate the direct and quadrature components of the series injection voltage.

$$V_{dse} = n_c K_{inv} V_{dc,sssc} \cos \alpha_{se} \tag{1}$$

$$V_{qse} = n_c K_{inv} V_{dc,sssc} \sin \alpha_{se} \tag{2}$$

Where n_c is the coupling transformer ratio, $V_{dc,sssc}$ is the DC link voltage, α_{se} is the series injected phase angle, and K_{inv} is the DC-AC conversion constant.

The real and reactive power equations simplify as (3) and (4).

$$P = \frac{V_s V_r}{X_L} \sin(\delta), \quad Q = \frac{V_s V_r}{X_L}(1 - \cos(\delta)) \tag{3}$$

Assuming equal voltage magnitudes ($V_s = V_r = V$) as (4).

$$P_q = \frac{V^2}{X_{eff}} \sin \delta, \quad Q = \frac{V^2}{X_{eff}}(1 - \cos \delta) \tag{4}$$

Where X_{eff} is the effective reactance and δ represents the phase angle difference. The simplified expressions for real and reactive power using X_q and X_l are as (5).

$$P_q = \frac{V^2}{X_l\left(1 - \frac{X_q}{X_l}\right)} \sin\delta, \quad Q = \frac{V^2}{X_l\left(1 - \frac{X_q}{X_l}\right)} \sin\delta \tag{5}$$

2.1.2. Structure of the proposed SSSC-FOPID controller

The SSSC functions in a capacitive mode to inject voltage and regulate power flow within the transmission line. The measured DC voltage is compared against the reference voltage, and the resulting error is processed by a proportional-integral controller (PIC), which calculates the alpha angle required for voltage injection. Figure 3 depicts the mathematical modeling of the PI and FOPID controllers' functional block diagram. In this work, the PIC controller is replaced by an FOPIDC.

The PIC output is given by (6).

$$Out(t) = K_p(V_{dc} - V_{dc}) + K_i \int (V_{dc} - V_{dc})dt \tag{6}$$

Where K_p and K_i are the proportional and integral constants, V_{dc}^* is the reference voltage, and V_{dc} is the measured voltage. The parameters are manually tuned. In the FOPIDC, integration is applied twice, as shown in (6).

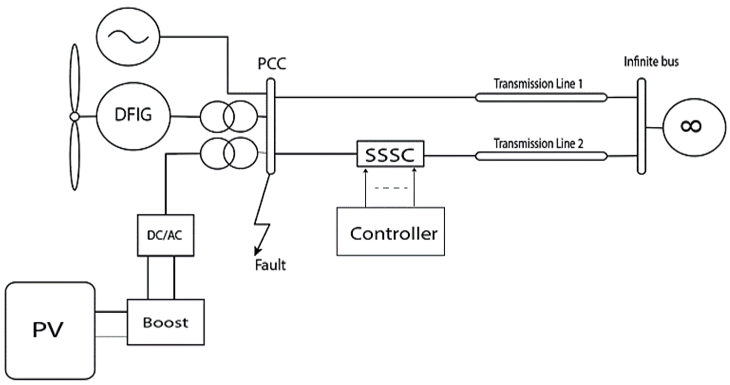


Figure 1. Hybrid PV-wind power generation with SSSC

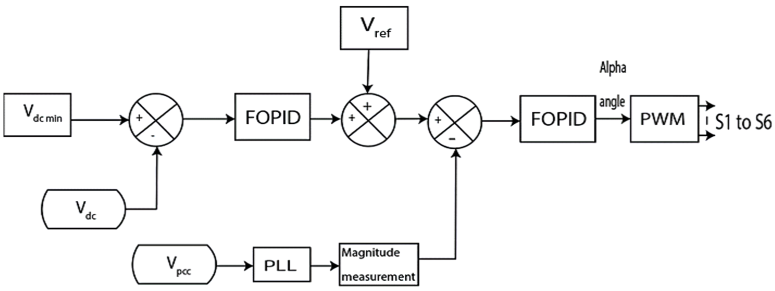


Figure 2. FOPID controller for SSSC

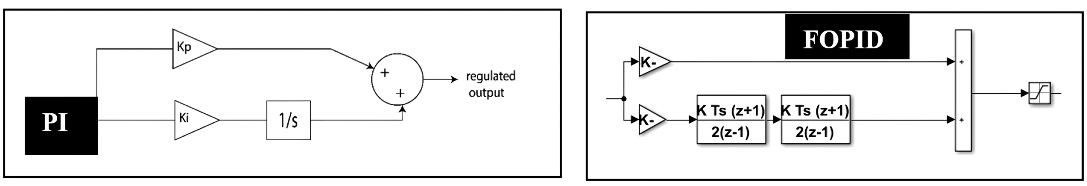


Figure 3. Mathematical modeling of PI and FOPID controllers functional block diagram

3. PERFORMANCE OF THE PROPOSED SSSC-FOPID CONTROLLER IN THE PV-DFIG GRID-CONNECTED SYSTEM

The analysis focuses on a hybrid power generation system combining PV and wind energy, where wind power uses a DFIG and PV power uses a boost converter for maximum power point tracking and a DC-to-AC converter. Figure 4 shows the setup, with the DFIG and PV systems connected to the PCC. The DFIG generates 575 V, stepped up to 161 kV for transmission, while the PV system produces 0.4 kV, also stepped up to 161 kV. The SSSC is connected downstream of the PCC, and the system is linked to a renewable power grid.

The parameters for the SSSC, wind power generation, grid, and transmission system are shown in Table 1, while Table 2 lists the PV power generation parameters. The wind and PV systems are connected to the PCC, with the SSSC linked through the transmission line. Fault analysis at the PCC was conducted for LLLG, LL, and LG faults.

Figure 5(a) shows the LLLG fault results, including the injected voltage (Vinj), gearbox current (Iabc), reference voltage (Vref), DC link voltage (Vdc), and real/reactive power for each line (L1, L2, L3). The system stabilizes at 1.6 seconds. Figure 5(b) shows similar results for the LL fault, with settling at 1.59 seconds. Figure 5(c) presents the LG fault, with stabilization occurring at 1.59 seconds. Using FOPIDC, Figure 6(a) shows the LLLG fault stabilizing at 1.55 seconds. Figures 6(b) and 6(c) demonstrate the LL and LG fault results, both stabilizing at 1.55 seconds.

In Table 3, the controllers compared are PI, FOPID, TLBO-PI, and GWO-PI. The performance metric is settling time after faults (LLLG, LLG, LG). The advanced controllers (FOPID, TLBO-PI, GWO-PI) show consistently lower or comparable settling times than the PI controller, with minimal variations across fault types, indicating similar effectiveness in fault response.

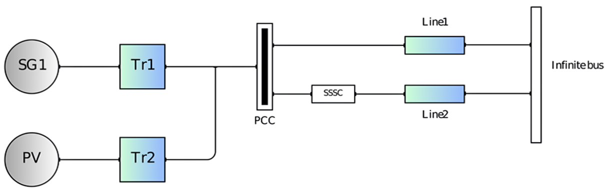


Figure 4. Hybrid PV-wind connected simulation diagram using MATLAB

Table 1. SSSC and wind power generation parameters chosen for study

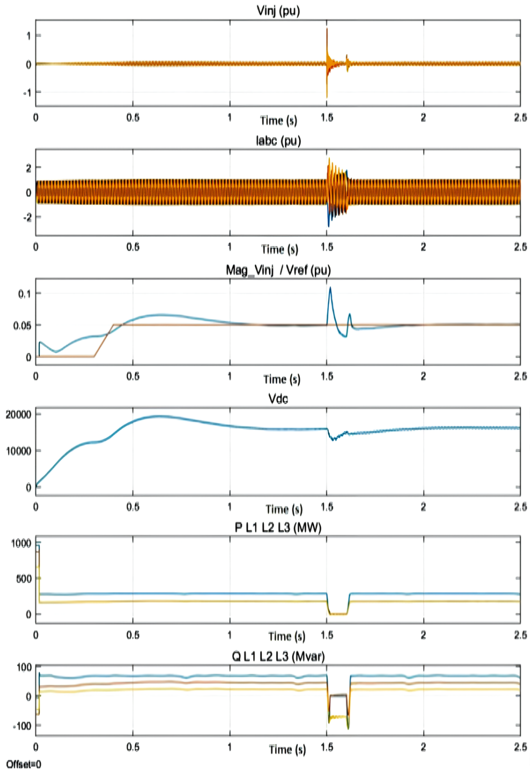
Static synchronous series compensator	GRID	Transformer
Electrical power rating: 1.0 MVA	Voltage rating: 161 kV	Type of transformer: D/Y
Percentage of compensation: 10%	Frequency: 50 Hz	Primary voltage: 575 V
Transmission line inductance: 75.5 μH		Secondary voltage: 161 kV
		Frequency: 50 Hz

Table 2. PV Power generation parameters used for simulation

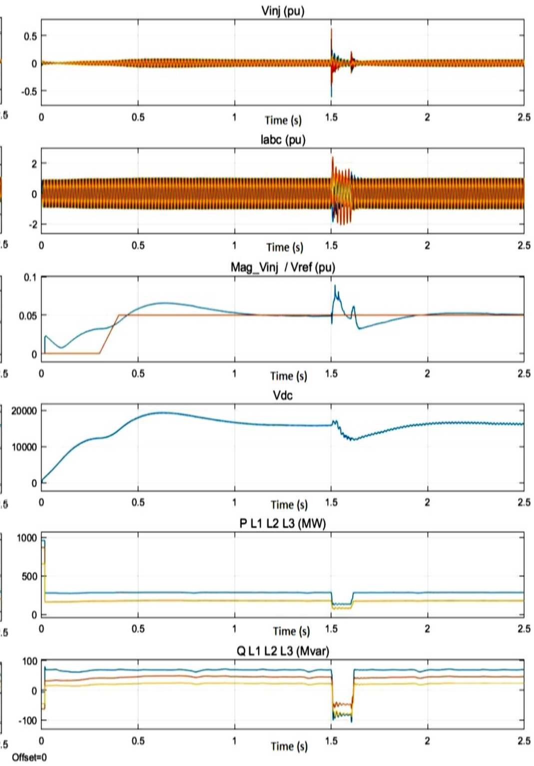
Sl. No	Components	Ratings
i	Solar photovoltaic	Voc = 64.2 V, Vmp = 54.7 V, Isc = 5.96A, Imp = 5.58 A, 6 modules in series, 48 modules in parallel
ii	Electric grid	V = 0.440 kV, F = 50.0 Hz
iii	Transformer	100 KVA, 50 Hz, 1:1
iv	Linear load	80 kW
v	Non-linear load	Bridge Rectifier: R = 50 Ω, L = 2 mH
vi	Boost converter	Vin = 300 V, Vout = 700 V
vii	Inverter	SPWM, two-level

Table 3. Comparison of various controllers with respect to real and reactive power settling time for different fault conditions

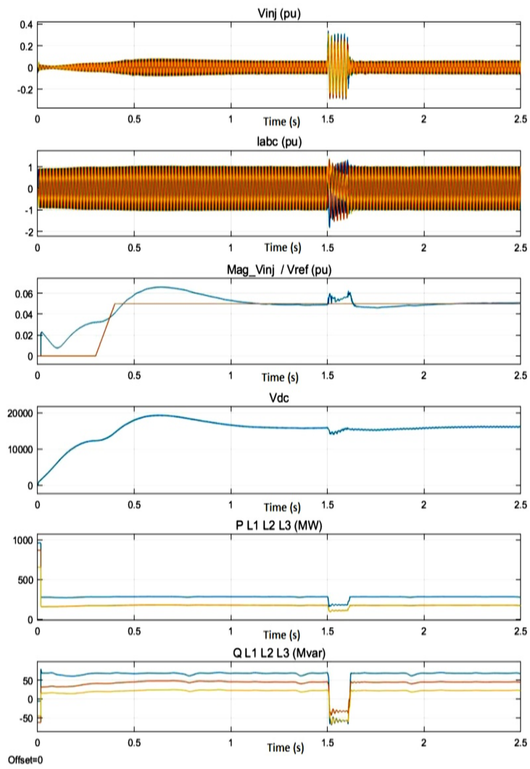
Fault types	Settling time in s			
	PI controller	FOPID controller	TLBO-PI	GWO-PI
LLLG	1.6	1.55	1.54	1.53
LLG	1.59	1.55	1.54	1.53
LG	1.59	1.55	1.54	1.53



(a)

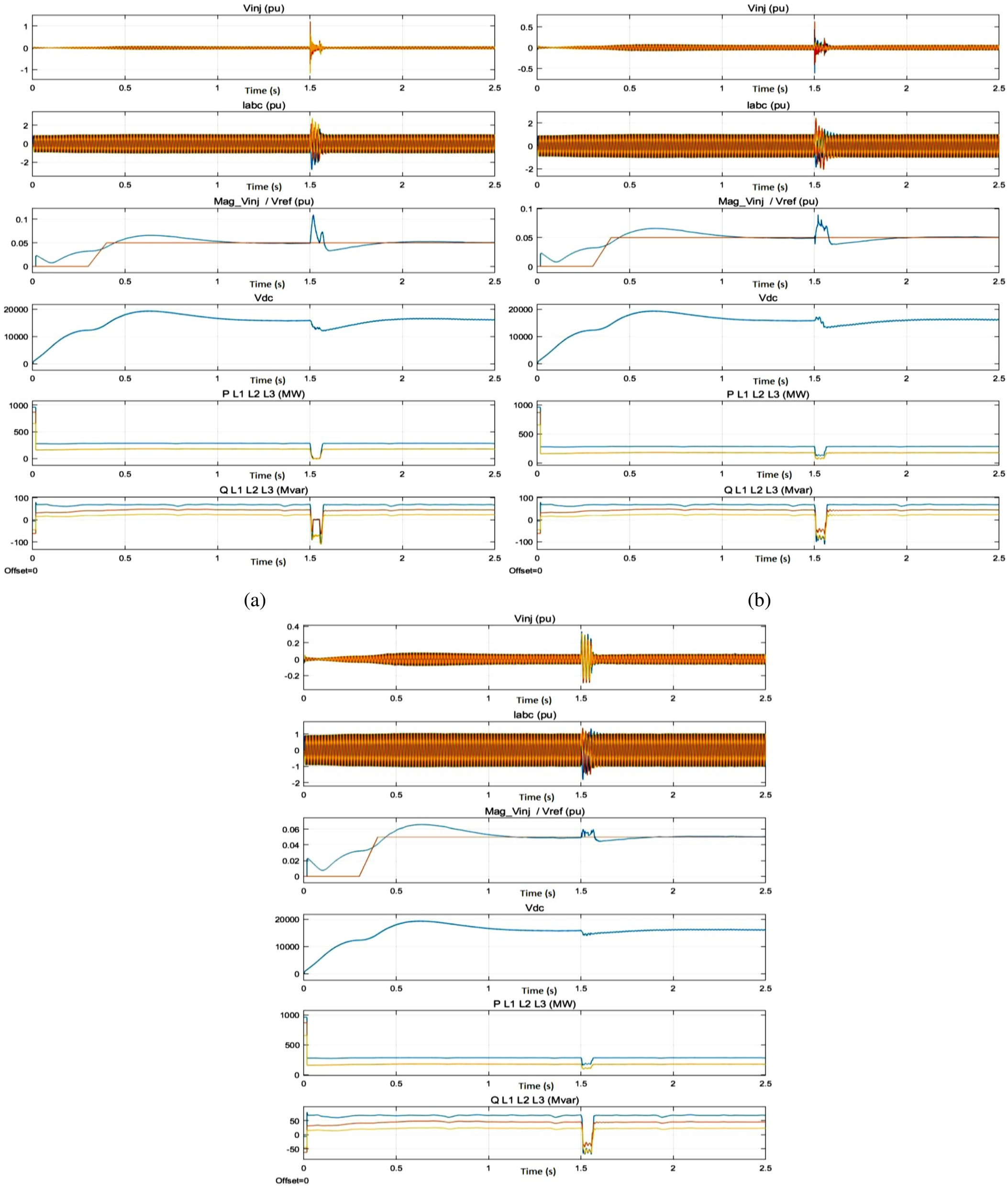


(b)



(c)

Figure 5. Time response of various parameters under: (a) LLLG fault with PI controller, (b) LLG fault with PI controller, and (c) LG fault with PI controller



(a) (b)

(c)

Figure 6. Time response of various parameters under: (a) LLLG fault with FOPID controller, (b) LLG fault with FOPID controller, and (c) LG fault with FOPID controller

4. CONCLUSION

In the proposed work, an efficient FO-PID controller is integrated with an SSSC to address instability risks in power systems. The approach also accounts for the dynamic behavior of hybrid photovoltaic (PV) and WECS connected to an infinite grid. A detailed model of the PV and WECS has been created to evaluate the performance of the enhanced controller in reducing oscillations within the power system. The model incorporates variations in wind supply to the wind turbine, recognizing that fluctuations in wind input can destabilize the grid when regulating power supply. To address this challenge, the controller is specifically designed to account for the dynamic behavior of the power system and mitigate instability induced by wind supply variations. The new controller incorporates a corrective mechanism aimed at damping oscillations, thereby enhancing system stability. A key advantage of this proposed controller is its flexibility in adjusting controller parameters, which significantly contributes to achieving power oscillation damping objectives. By introducing the proposed controller, the study aims to enhance system stability and mitigate the impact of wind variability on power grid operations.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Chethan Hiremarali Ramalingegowdam	✓	✓	✓	✓				✓	✓					
Mageshvaran Rudramoorthy	✓		✓	✓						✓		✓		
K. M. Mahesh Kumar	✓		✓	✓						✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal Analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY

All data produced/examined throughout this study are fully incorporated within this published article.

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