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PSO-tuned FOPID Controlled MGP System for Fault-Ride-Through of Renewable Sources

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***Abstract*-— The globe has now reached a position where Renewable Energy sources like wind, solar, etc., have a more significant role in light of the alarming rate of global warming. However, integrating renewable energy sources into the primary grid is a challenging task, with "Fault Ride Through disturbances" being one of the major issues. A Synchronous Motor Generator Pair (MGP) system can be used to ride through a fault, and it also improves inertia and network stability. This paper presents a PSO-tuned FOPID controller for the MGP system to maintain the grid voltage in the Low and High Voltage FRT scenarios in a system comprising a wind energy conversion system (WECS) and solar system. The performance of the proposed controller is then simulated and compared with the performance of the conventional PI controller. The simulation results establish the superior performance of the proposed controller in terms of settling time and peak overshoot. Further, the effect of using the Dynamic Voltage Restorer (DVR) has also been examined.**

***Keywords*---Motor Generator Pair, Voltage sag, Voltage swell, Power quality, System Stability.**

I. INTRODUCTION

Most electricity is generated by burning fossil fuels such as coal, oil, and gas. These fossil fuels have numerous serious consequences for the atmosphere. Moreover, even these fossil fuels are limited and expected to continue only until this century. These issues necessitate the search for an alternative to fossil fuels. Renewable Energy Sources (RES) are perfect alternatives to fossil fuels and are increasingly adopted to promote green energy. As a result, renewable energy sources have been increasingly integrated into the electrical grid [1]. However, the increased presence of the RES comes at the cost of issues associated with these sources. The significant challenges that come across are faults and stability of the system, which gets disturbed due to the variations in the loading conditions on the grid side. As a result, most countries have issued laws on connections to renewable energy grids requiring Fault Ride-Through (FRT) to boost grid stability [2-3]. To strengthen the FRT, there are two basic approaches: upgrading the converter's control strategy and using an extra hardware circuit. Among the improved control, approaches are counter control [3], virtual impedance control [4-5], virtual flux control [6]. Grid voltage disturbances lead to the destruction of both wind generators as well as solar systems. Therefore, implement a comprehensive FRT strategy that can counter the adverse impact of all types of grid voltage swings, namely, symmetrical and asymmetrical sags, and symmetrical and asymmetrical swells. Earlier, different auxiliary hardware circuits such as Energy Storage System (ESS) [7], crowbar circuits and dc chopper [8] and stator series impedance [9] etc., were used for achieving the condition of FRT. Though such devices may achieve FRT but still due to conditions like unreasonable switching at fault times, secondary failure may occur. In addition, there is a lack of a regulation strategy that considers all the different types of voltage fluctuations in their design and execution. The proper regulation of reactive power will ensure that grid condition remains stable even during disturbances. Consequently, this will have a positive impact on grid reliability.

The existing improvement methods mostly start with the control of the blower, such as improving the integrated properties of the converter and the angles of the blades. However, if the wind turbine control system manages the fault, the system's complexity will increase, making its implementation difficult. In [10-13], virtual inertia or virtual synchronous generator (VSG) control system is presented. A wind turbine's rotor or a photovoltaic system's energy storage system is used to provide enough inertia for the converter to emulate synchronous generators. However, when the system is subjected to severe disturbances, the VSG cannot handle the high short circuit currents.

To address the aforementioned issues, a new grid consolidation technology, namely the Motor-Generator Pair (MGP), in which a portion of renewable energy is integrated via a pair of synchronous machines rather than an inverter, was presented [14-15]. MGP improves the

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inertia and removes renewable energy from the energy grid through the mechanical axis, significantly improving power system security [16]. Additionally, the mechanical shafting separation [17] of the MGP system provides grid fault isolation on the generator side. When there is a fault, the renewable energy's power production can be maintained while the synchronous generator's excitation can be regulated to maintain the grid's voltage level. A renewable energy power grid with these capabilities can be more stable during transitory periods than without them.The current work presents a Fractional-Order PID (FOPID) controller to maintain the voltage level of the grid under the conditions of voltage sag and swell by regulating the generator's excitation. Since the controller's performance depends on the controller gains, particle swarm optimization has been employed to tun the FOPID.

The structure of the paper is as follows. Section II presents the essential principles and structure of the MGP system. Section III discusses the control strategy and test system. Further, isolation, dampening, the advantage of using DVRs, and protection measures for renewable energy sources are examined. Section IV discusses the simulation results of the investigations made regarding the performance of the proposed controller in situations of voltage sag and swell. Section V is a summary of the significant findings and conclusions.

II. STRUCTURE OF MGP SYSTEM

Renewable energy units require sufficient driving capacity to avoid widespread disconnection due to grid faults. A benefit of renewable energy connected to the grid via MGP is grid isolation, which is achieved through superior voltage capacity and the current resistance of synchronous generators. Since synchronous generator synchronization is crucial for system stability, an MGP system provides an entirely new way to connect RES to the grid that increases system stability. MGP can provide inertia for stability in one part of renewable energy, while another component can still be linked directly to the grid in the traditional method.

As shown in Fig.1, the MGP system consists of two synchronous machines that are coaxially linked, with each machine having its excitation system. The renewable power is generated and fed into a synchronous motor via its inverter. The shafts of both machines are connected so that the motor can operate the generator, thereby replacing conventional steam turbines or water turbines with a synchronous motor as the primary mover. The same rated speed operates both the machines so that the generator can be connected directly to the electricity grid like a conventional power plant.

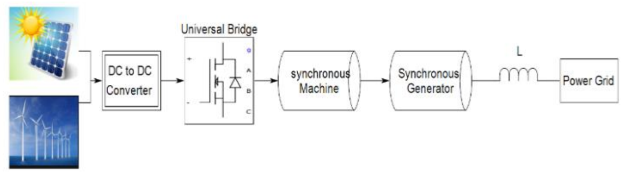

Fig.1: Grid-connected through MGP

Because the MGP system's motor and generator are coupled with the same axis, both machines' speed and change in speed are considered to be the same. For one machine electromagnetic torque equation is written as:

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = 2H\frac{d\omega_m^*}{dt} = T_m^* - T_e^* - K_D\Delta\omega_m^* \quad (1)$$

Both machines are coaxially linked, and the mechanical torques of their rotors are also the same, suggesting that the two machines utilize their electromagnetic equations and mechanical systems. The inertia time constant of both machines is presumed H_G,H_M and the electromagnetic torque is T_eG,T_eM the rotor angle is δ_G,δ_M then Eq. "(1)" for two machines can be rewritten as:

$$2(H_M + H_G)\frac{d\omega_m^*}{dt} = |T_{eM}^*| - |T_{eG}^*| - (K_{DG} + K_{DM})\Delta\omega_m^*$$
$$\frac{d\delta_M}{dt} = \frac{d\delta_G}{dt} = \omega_0\Delta\omega_m^* \quad (2)$$

Where, the damping coefficients of the motor and generator is K_DM " and " K_DG and Δω_m is the difference between the electric angular velocity and mechanical angular velocity.

III. TEST SYSTEM

The joint operation of photovoltaic systems, wind energy, and grid hybrid systems are used to deliver continuous, high-quality power and, at the same time make the largest contribution to intermittent renewable energy.

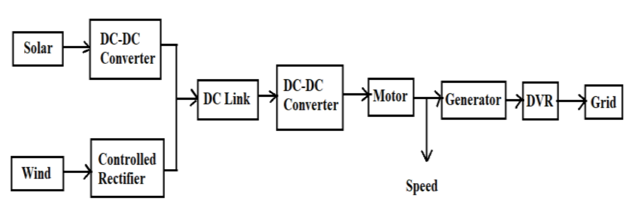

Fig.2: Overall system block diagram

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The system under consideration is a combination of solar and wind systems and together produces 5 KW of power, which is converged to drive a synchronous motor via the inverter. As the shafts of the two machines are connected, the motor will drive the generator. Fig.2 depicts a block diagram representation of the system under consideration. The advantage of renewable energy connected to the grid via the MGP technology is the isolation of grid faults, which varies considerably from conventional fault-ride-through techniques for such systems. Because the voltage phase difference between the MGP system's two terminals is equivalent to the real power P delivered through the MGP system, P rises as the phase difference rises. The MGP system's characteristics described above serve as the physical foundation for achieving stable operation control. To ensure proper failure driving, both sides of the DC bus must use the MGP system. This is followed by a unique control technique based on DC link voltage feedback. The supervisory control system is built to ensure maximum power point tracking (MPPT). Depending on the amount of power generated by each energy source and the load requirement, two possibilities are evaluated and categorized. As MPPT control logic in PV systems, the Perturb and Observe (P&O) algorithm is utilized; as MPPT control logic in wind generation systems, the Hill Climb Search (HCS) approach is employed. The generation of wind energy and photovoltaic electricity changes with time at its source; however, the superposition of wind energy and photovoltaic power generation is substantially stable throughout the day.

A FOPID control mechanism is proposed here, which aids in synchronization with the main grid. The FOPID controller gives greater design flexibility than the conventional PI controller, which boosts the controller's quality and robustness. Fig.3 shows a block schematic of a FOPID controller.

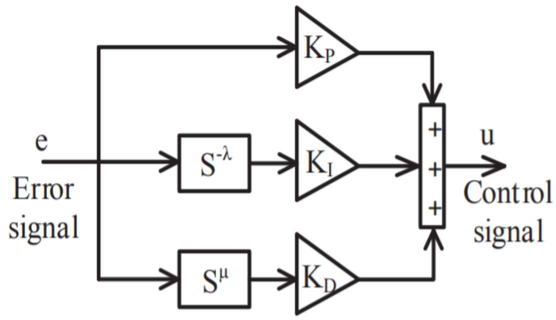


Fig.3: FOPID controller block diagram

The differential equation of FOPID is given by:

$$u(t) = K_p e(t) + K_i D_t^{-\lambda} e(t) + K_d D_t^{\mu} e(t) \quad (3)$$

Equation (4) represents the Laplace transform of equation (3)

$$C(s) = K_p + K_i s^{-\lambda} + K_d S^{\mu} \quad (4)$$

PID controller can be simply obtained taking λ=1 and μ=1 Accordingly, FOPID can be positioned at any location on or in the plane, depicted in Fig. 4.

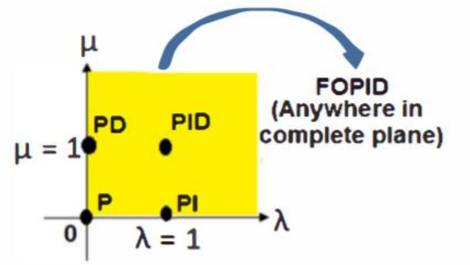


Fig.4: Point to plan expansion [18]

The controller gains affect the performance of a controller. The advantage of greater design flexibility in a FOPID controller can be exploited only if the controller parameters are appropriately selected. In this work, the tuning of FOPID controller is done by using the Particle Swarm Optimization (PSO) Technique, a well-established algorithm that optimizes a problem by iteratively enhancing a solution.

To reduce time-domain integral performance indices, which are considered as objective functions, in a PSO method. The following time-domain performance criteria can be used to tune controller parameters in the time domain and to evaluate their effectiveness:

Integral Absolute error (IAE)

$$IAE = \int_0^{\infty} |e(t)| dt \quad (5)$$

Integral Time Absolute Error (ITAE)

$$ITAE = \int_0^{\infty} t|e(t)| dt \quad (6)$$

Integral of Square Error (ISE)

$$ISE = \int_0^{\infty} e^2(t) dt \quad (7)$$

As soon as the stopping requirement has been reached, the algorithm is stopped. One of the generally used performance indices, the ISE criterion, is used in this study as a fitness function. By minimizing the ISE criteria, the PSO algorithm identifies controller parameters. Since more adjustment choices are available for the PID controller, the error signal can be reduced to zero faster. As a result, FOPID handles the grid response without any effort on the part of the renewable unit.

Control strategy

Firstly, a comparison is made between the output power and the reference power in the proposed control, and the error, which is the phase difference, is given to the Fractional Order PID controller, as shown in Fig 5. In addition, a Phase-Locked Loop (PLL) is utilized to identify a generator's frequency and phase change. When the source-grid phase difference Δθ changes, the output varies to follow the set point [17]. Three-phase voltages are estimated using a Space Vector Modulation (SVM). When compared to other approaches, SVM is faster in detecting voltage dips. The output of the SVM is sent to the Sine PWM and then to the frequency converter, where it is converted to a frequency. This method offers a rapid response time and substantial sag and swells correcting capabilities. To have a ripple-free voltage profile, a DVR is used after MGP. DVR is used to absorb/supply the extra or the deficit voltage to the system. This helps in diminishing the harmonics in the voltage and current of MGP efficiently and precisely. This further reduces the Total Harmonic Distortion (THD) as well. Simulation results show that the distribution system's balance sags and swells can be effectively minimized by using the proposed technique.

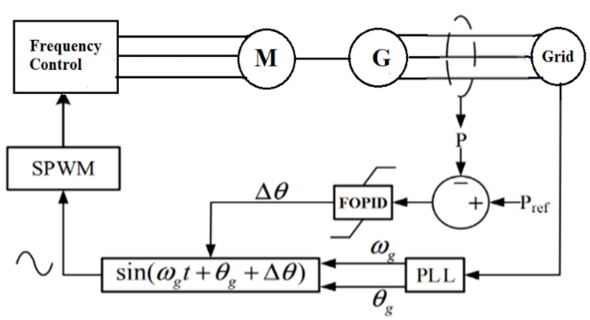


Fig.5: Control system block diagram of MGP system

IV. SIMULATION ANALYSIS AND RESULT

The study employs an MGP system to connect renewable energy to the power grid, as shown in Fig.2. Modeling and simulation of this system were performed using MATLAB/SIMULINK. Table I lists the simulation parameters.

Table I: Simulation Parameter

Parameter	Value	Parameter	Value
Renewable power	5 KW	Stator resistance	0.5 ohm
Motor rating	5 KVA	Stator inductance	0.00198 H
Generator Rating	5 KVA	Rotor resistance	0.45 ohm
Nominal line voltage	220 V	Rotor inductance	0.00132 H

The power extracted from the solar PV and wind systems is fed to the DC link, as shown in fig. 2. Fig.6 depicts the voltage and current waveform of the DC link. This power is then passed on to the two synchronous machines configured to feed the grid.

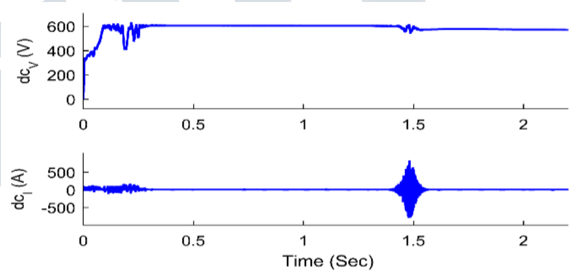


Fig.6: Voltage and current output of the renewable unit

The system's performance equipped with the proposed PSO-tuned FOPID controller is then investigated for the under-voltage and over-voltage conditions as described below and compared with the performance of the PI controller. The effect of using a DVR is also investigated. The graph of the number of iterations versus objective function ISE is as shown in Fig. 7. Table II lists the simulation parameter.

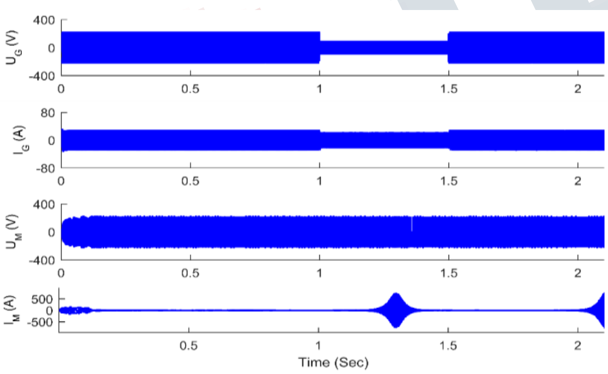
TABLE II: PSO Parameter

PSO Parameter	Value
Population size	10
No. of iterations	40
Maximum inertia weight (w_{max})	0.99
Minimum inertia weight (w_{min})	0.02
Local weight (c_1)	1.9
Local weight (c_2)	1.8

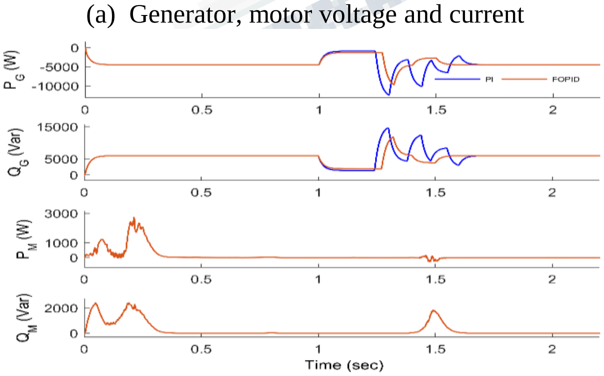
Fig.7: Convergence of objective function ISE

A. Under Voltage Condition

The grid voltage is designed to drop from 220 V to 72 V (0.4pu) at t = 1 second and to rebound to 220 V at t = 1.5 seconds. Fig.8 depicts the results of the voltage sag condition. As shown in Fig.8, the generator voltage decreases rapidly, creating an imbalance in power. Because of the damping effect, the power of the synchronous generator oscillates. Due to shafting isolation, the synchronous motor's power swing amplitude is significantly less than that of the synchronous generator. In Fig.8(a), the variations in the motor's voltage and current are minimal compared to the variations in the voltage and current on the generator side. Because of the MGP system's isolation effects, the voltage and current changes caused by rotor shafting torque imbalance are minimal, and the motor's output power can be kept steady. The PI waveform exhibits more changes than the FOPID waveform, as illustrated in fig.8(b), and will take longer to settle. This means that the active output power of the MGP system equipped with the proposed FOPID controller reaches its steady point before the MGP system equipped with the conventional PI controller during the voltage recovery process.



(a) Generator, motor voltage and current

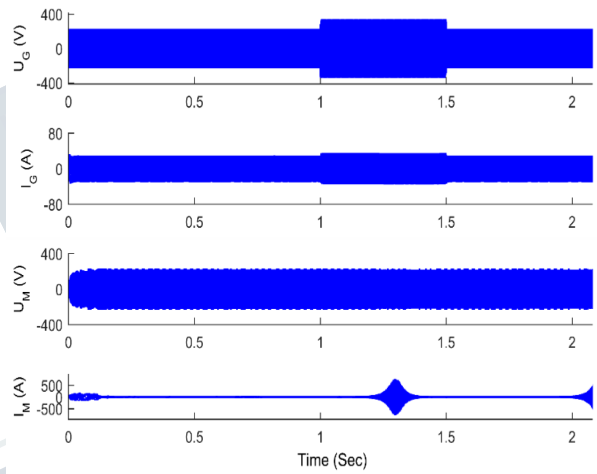


(b) Generator, motor real and reactive power

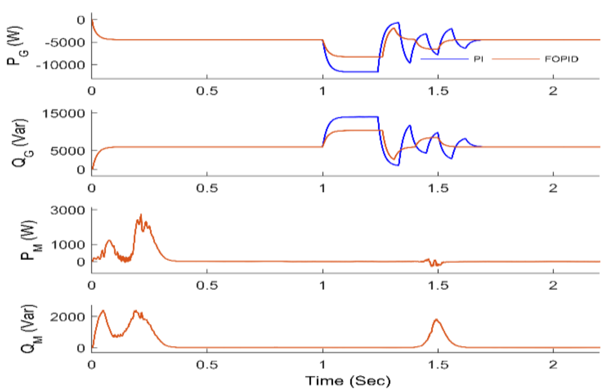
Fig.8: Under-voltage waveform

B. Over Voltage Condition

The grid voltage is designed to swell from 220 V to 327 V (1.5pu) at t = 1 second and then return to 220 V at t = 1.5 seconds. Fig.9 depicts the results of the voltage swell condition. The generator can withstand the impact of voltage spikes and current surges if grid voltage is increased. At the same time, oscillation may be prevented on the side of the motor using a synchronization controller. As shown in Fig.9(a), as voltage rises on the grid side, generator voltage and current come under the unbalanced condition, resulting in an imbalanced active power on the generator side. In contrast, the isolation mechanism of the MGP has a relatively more minor influence on motor side power.



(a) Generator, motor voltage, and current



(b) Generator, motor real and reactive power

Fig. 9: Overvoltage waveform

The generator consumes reactive power and improves grid voltage recovery due to the voltage difference. Compared to the FOPID waveform, the PI controller waveform shows more variations and requires more cycles to reach a stable state after a fault occurs, as seen in fig.9(b). The peak overshoot values and settling times for the MGP system equipped with the FOPID and PID controllers under the conditions of voltage sag and swell are given in Table III. The simulation results show that utilizing the FOPID controller provides a faster and improved transient operation than the PI controller.

TABLE III: Comparison of PID and FOPID during the faulty condition

Controller	Under Voltage		Over Voltage	
	Peak undershoot (%)	Settling time (ms)	Peak overshoot (%)	Settling time (ms)
PID	5.45	320	5.90	320
FOPID	3.63	170	4.09	170

C: Analysis of THD

The measurement of harmonic distortion in any signal is represented in terms of Total Harmonic Distortion (THD). The higher value of THD degrades the system's quality by giving higher peak currents, core loss in motor, and electromagnetic emission; therefore, we need to reduce it to have lesser voltage harmonics. In this work, we have used DVR for this purpose. DVRs are a FACTS (Flexible AC Transmission System) device installed in distribution systems to correct non-standard voltages, currents, or frequencies. By injecting voltages into the distribution line, it maintains voltage stability. When used in conjunction with MGP, this DVR has been able to minimize voltage distortion.

We have simulated our model without DVR and got 21.70% THD which is relatively high and will affect the system adversely, as discussed above. Again, the system has been simulated with DVR, and we get the value of THD as 2.88 %, which is less enough to get better power quality.

V. CONCLUSION

This paper exploits the MGP system's isolation and protection mechanisms by utilizing rotor motion equations. A PSO-tuned FOPID controller has been proposed to maintain the voltage level of the renewable sources under conditions of voltage sag and swell. The findings show that the suggested controller outperforms the traditional PI controller in performance and efficiency. Further, the effect of using a DVR in combination with the MGP system was also discussed.

Simulation results have led to the following conclusions:

1) A grid fault can be isolated at the grid side, and renewable energy units can be protected from disconnections with the MGP system. Due to the low inertia of the MGP shaft, power imbalances on either side can have relatively small voltage and current fluctuations. As a result, both sides of the output power are relatively stable.

2) When the DVR is used in conjunction with the MGP, it was found that the harmonics were reduced, resulting in a lower Total Harmonic Distortion (THD).

Further studies may focus on stable operation and feedback control strategies of MGP to deal with the randomness of renewable energy, quantitative cost estimation compared with other solutions, capacity optimization for renewable energy using MGP to achieve grid-connection, excitation system, and reactive power control for both sides.

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