Intelligent Optimized Voltage Control for Hybrid Off-Grid Power Systems

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Abstract

Hybrid off-grid power systems with different renewable and non-renewable energy sources, such as wind, photovoltaics, and diesel generation, have a wide application scope in regions where grid extension is not possible. To supply quality power, hybrid off-grid power systems need proper reactive power management to deal with randomly changing load and supply. In particular, to realize dependable and quality power supply, hybrid off-grid power systems require suitable and efficient control techniques. A properly tuned controller of reactive power sources is crucial to maintain a prescribed voltage profile. Computational intelligence techniques such as particle swarm optimization can provide desired and acceptable solutions for optimization problems. In this study, we applied computational intelligent techniques for optimal control of reactive power sources, such as photovoltaic inverters and automatic voltage regulators for synchronous generators in diesel engines, to investigate dynamic voltage profile stability through reactive power management.

Keywords: hybrid off-grid power system, voltage control, reactive power management, computational intelligent techniques, optimal control

1. Introduction

Rural electrification contributes to economic, social, environmental, and health benefits. In South Asia, a considerable part of the population does not have access to electricity. Off-grid electrification based on renewable energy sources offers a feasible electrification option for rural areas of developing countries that do not have reactive power support from the main grid owing to their remote or isolated locations [1]. In this context, off-grid electrification is cheaper than grid extension, and could also entail less environmental impact and easier adaptation to local needs and conditions.

Hybrid off-grid power systems (HOPSs) integrate a number of renewable and non-renewable energy sources. Power quality is important for reliable load operation. Maintaining a constant voltage is a fundamental indicator of the good quality of power supply. However, the voltage may fluctuate as a result of excess or deficit of reactive power. System reactive power unbalances in the

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Received: 17 Jan 2023 Accepted: 31 Jan 2023 Published: 8 Feb 2023
Journal of Asian Energy Studies (2023), Vol 7, 39-47, doi:10.24112/jaes.070003

generation and consumption cause voltage fluctuations. Therefore, control systems to manage reactive power and eliminate voltage deviations are crucial.

Inadequate tuned parameters may result in slow, oscillatory responses of the system or, in a worse scenario, may lead to instability [2, 3]. Optimal tuning of controller parameters is an optimization problem. There are many classical tuning methods available in the literature, but computational intelligence optimization techniques have been useful and successful compared to conventional approaches [4]. Computational intelligence approaches have motivated researchers to find solutions for a variety of complex real-world problems, predominantly in the area of optimization. Computational intelligence techniques can provide desired and acceptable solutions for optimization problems [5, 6].

In this study, we investigated the application of computational intelligence algorithms to design an optimal controller for photovoltaic (PV) inverters and automatic voltage regulators (AVRs) for voltage control in hybrid off-grid power systems. The dynamic performance of an off-grid power system is greatly influenced by disturbances during its operation. Hence, in this study we aimed to improve the dynamic performance of such systems under disturbances by optimizing the inverter and AVR controller parameters using computational intelligence algorithms such as particle swarm optimization (PSO). The advantage of PSO is its simplicity. It is fast and applicable to a wide range of problems [7]. In PSO, the candidate solution is called particle. Each particle is characterized by two parameters: velocity and position. Each particle has its fitness values, which is calculated by the fitness function to be optimized. The particle moves in the feasible region by following the current optimum particles. An inverter control for reactive power within the bounds enforced by its apparent power size to control the feeder voltage in the distribution system has been suggested in previous studies—the inverter can supply reactive power, hence precluding the need for an extra reactive power device and saving extra investment. However, few studies have been conducted to explore PV inverters as a reactive power source for distribution networks. The novelty of this research study is the use of reactive power capacity from the PV inverter for reactive power management in hybrid off-grid power systems.

2. Test System Configuration

A HOPS consists of power generation from wind, PV, and diesel engine, as shown in Fig. 1. The system components are an induction generator (IG) for wind, synchronous generator (SG) as diesel engine generator, inverter for PV, capacitor bank, and load. In this configuration, the diesel engine acts as the local grid in this system. Loads are assumed to be located close to the generator that pumps power to the common bus which all loads are connected to. All these components are connected to a common AC bus. HOPSs are in operation in small islands and isolated communities [8].

In HOPS test systems, the IG and loads need reactive power. The reactive power required by HOPSs varies with the reactive power load and input wind power to IG. Reactive power is also needed in the power system for improvement of voltage regulation, to enhance the steady state and dynamic stability, and to reduce voltage unbalance. Therefore, the reactive power source is a requisite to balance the generation and consumption of reactive power. If a wind turbine system is connected to the grid, then the reactive power requirement of IG is fulfilled by a grid/capacitor.

In HOPSs, the reactive power can be compensated by the capacitor bank and/or flexible alternating current transmission system devices. Previous studies suggested different methods based on a fixed capacitor bank to supply the reactive power under steady-state conditions [9–12]. The PV inverter can compensate the reactive power when its apparent power capacity is increased more than the PV active power. In this study, we considered the inverter as a reactive power compensator [13,14].

The HOPS test system has two control structures, one for reactive power compensation and other structure for SG excitation control. Both control structures have proportional-integral (PI) controllers.

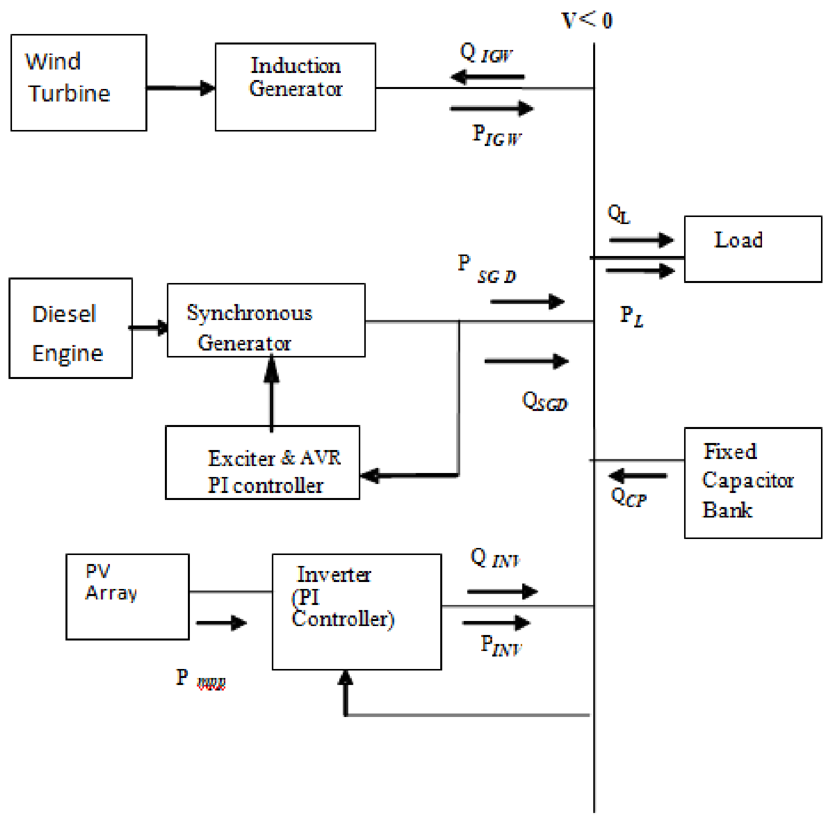

Figure 1: *HOPS configuration*

3. Optimal Controller Design Based on PSO

In optimization problems, it is required to explore the whole domain to obtain an area including a global minimum and find the optimum as fast as possible. Optimization problems are formulated here in terms of finding optimum parameters for the PI controller of the inverter and AVR. The objective function is defined as the integral time multiplied squared error (ITSE). The error is expressed in terms of voltage deviation, ΔV. An optimization problem aims to minimize the ITSE to obtain optimal controller parameters. In this study, we implemented the PSO algorithm to minimize the ITSE (Fig. 2).

At the beginning of the search process, the PSO algorithm initializes a group of random solution (particles) in the feasible region of the optimization domain. Then, the optimal solution can be obtained through iterations. In each iteration, the fitness function value of each particle is evaluated. This value is compared with the previous best value at the current iteration. The individual best (local_best) and swarm best (global_best) are thus updated. Based on these best values, the velocity '$\vartheta(t)$' and position 'cur_pos' of a particle are updated as follows:

$$\vartheta(t+1) = \Psi\vartheta(t) + C_1R_1(local\_best(t) - current\_pos(t) + C_2R_2(global\_best(t) - cur\_pos(t)) \quad (1)$$

$$cur\_pos(t+1) = cur\_pos(t) + \vartheta(t+1) \quad (2)$$

where $C1$ and $C2$ are speeding factors, $[0 \leq C1, C2 \leq 2]$, Ψ is the inertia weight, $R1$, $R2$ are random numbers, $[0 \leq R1, R2 \leq 1]$, and t is the iteration time. Factor $C1$restricts the length of the step the particle takes in the direction of its individual best. Likewise, Factor $C2$ restricts the length of the step the particle takes in the direction of the global best. The inertia weight accounts for the convergence speed and exploration of the solution space. Appropriate selection of the inertia weight is important to balance global and local explorations as follows:

$$\Psi = \Psi_{max} - (\Psi_{max} - \Psi_{min}/Iter_{max}) * Iter \quad (3)$$

where Ψ_{max} and Ψ_{min} are the maximum and minimum values of the inertia weight, $Iter$ is the current iteration, and $Iter_{max}$ is the maximum number of iterations. The algorithm continues the search process until the maximum number of iterations or minimum error tolerance is reached.

The minimum value of ITSE was obtained after 163 iterations for TS-1, as shown in Fig. 3. The optimal values of both controller parameters obtained by the PSO algorithm for the minimum value of ITSE are listed in Table 1.

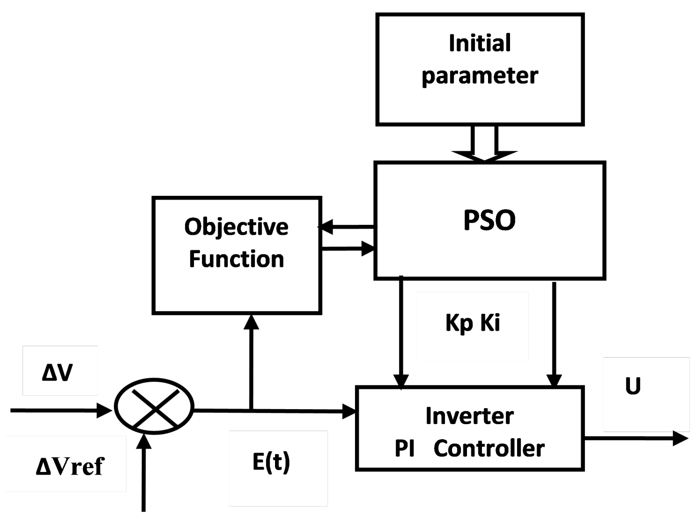

Figure 2: *Block diagram for optimal tuning of the inverter PI controller using PSO*

Table 1: *Optimal values of the inverter and AVR PI controller parameters*

Inverter PI controller parameters		AVR PI controller parameter	
Kp	Ki	Kp	Ki
29.679	7593.4	9.195	25

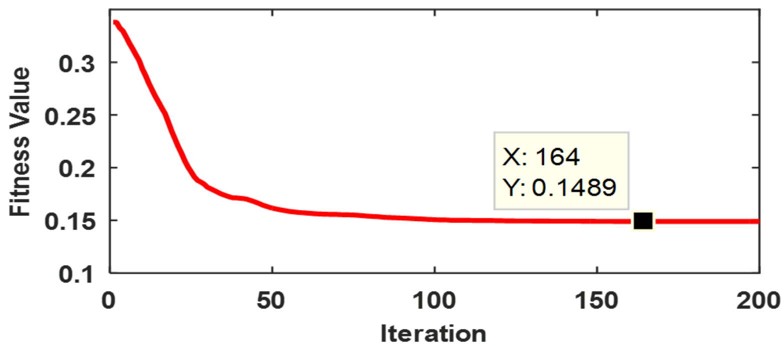

Figure 3: *Search plot of PSO for optimal values of ITSE*

4. Simulation Results

HOPS simulations were conducted using the optimal values obtained by PSO under disturbance conditions, as shown in Fig. 4. These simulations were carried out for step (sudden) increases in reactive load and wind power input to the IG, and changes in irradiance and temperature, to mimic realistic situation.

The small-signal disturbances considered in the simulations were a step increase of 2% (0.02 p.u) in reactive load demand QL applied at t = 0 s (without change in wind power input to IG, irradiance, and temperature). The dynamic responses of ΔV, $\Delta QINV$, $\Delta QSGD$, and $\Delta QIGW$ depicted in Figs. 5 to 7, respectively, correspond to PSO and the conventional method.

As a result of the sudden disturbance in reactive power load demand introduced at t = 0 s, a sharp voltage deviation at $t = 0s$ occurs, as can be seen in Fig. 5. Note from Fig. 6 that the inverter compensates for reactive power during both transient and steady-state conditions. Note also from Fig. 7 that because of the sudden voltage deviation at the SG terminal, SG supplies reactive power during the transient condition. Step (sudden) increase in reactive power absorbed by the load causes an imbalance in reactive power; the reactive power absorbed by $IG(Q_{IGW})$ becomes disturbed during the transient condition, as shown in Fig. 8. Note that ΔV, ΔQ_{SGD}, and ΔQ_{IGW} decayed quickly for the PSO-tuned PI controller, in contrast with the conventional tuned PI controller of the inverter and AVR.

Table 2 shows that the maximum deviation of state variables increases as the magnitude of disturbance increases. The peak deviation of the dynamic response of the system variables is greater for controller parameters tuned with the conventional method. The increase in irradiance and temperature of the PV generator increases the PV real power, but it causes no change in its reactive power under steady-state conditions.

Table 3 shows that the settling time of the system variables is almost the same, irrespective of the disturbance, for PSO optimal PI controllers (inverter and AVR). The settling time of the state variables is also almost the same for the PI controller of the inverter and AVR tuned by conventional method under all disturbance conditions. However, the settling time was reduced for the PSO optimal PI controllers (inverter and AVR) with respect to the settling time achieved by the conventional method.

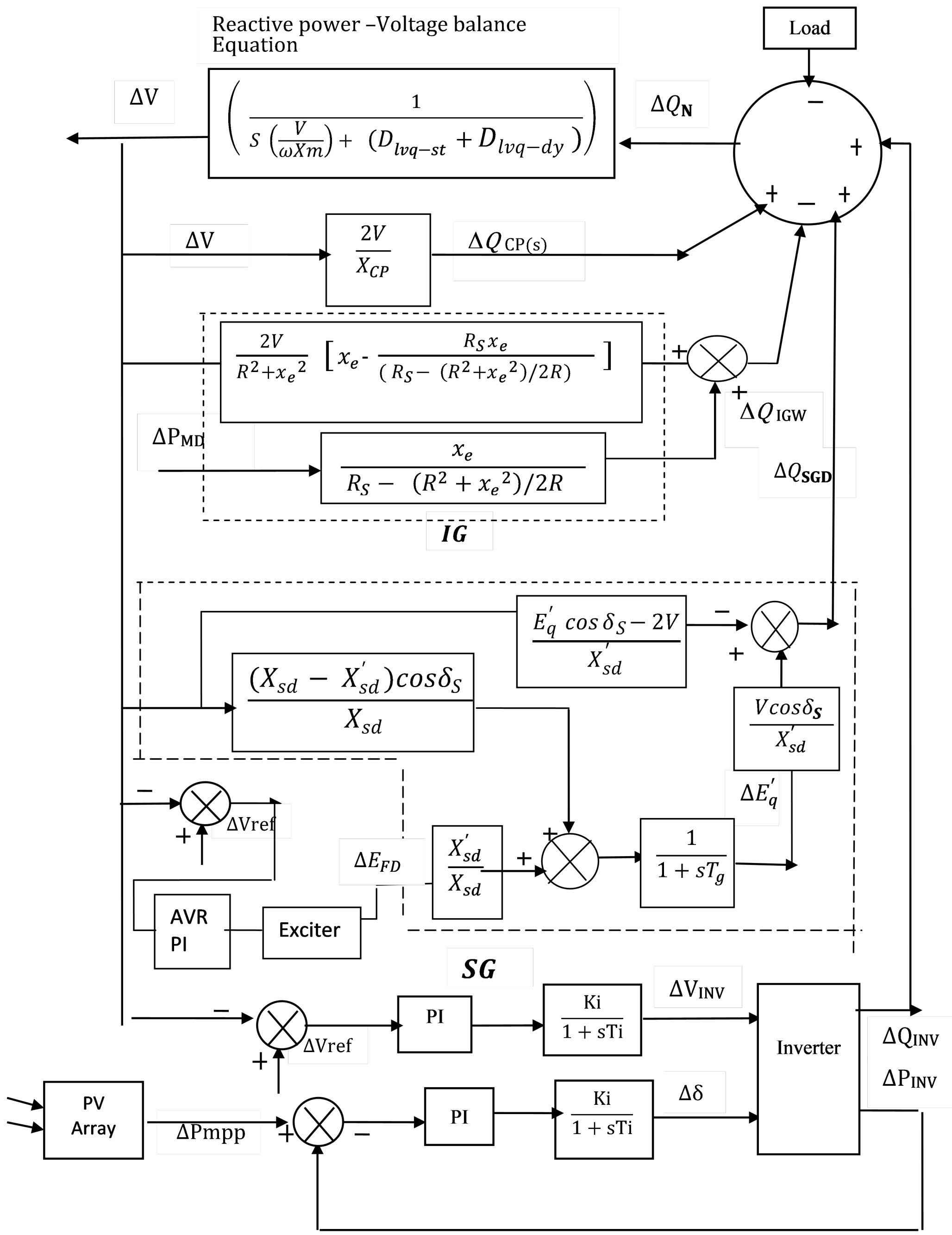

Figure 4: *Simulink system model*

5. Conclusion

Hybrid off-grid power systems can play an important role in providing clean and affordable energy to remote communities in South Asia [15,16]. However, there are technological challenges to their application, especially regarding voltage stability and power quality. In this study, we investigated

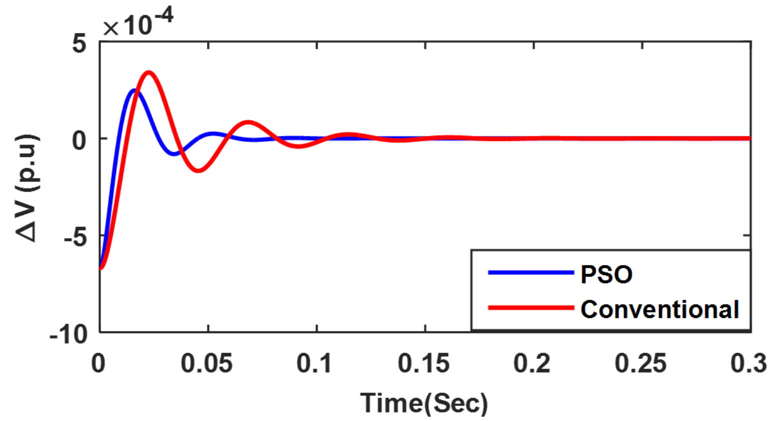

Figure 5: *Dynamic response of load voltage deviation (ΔV)*

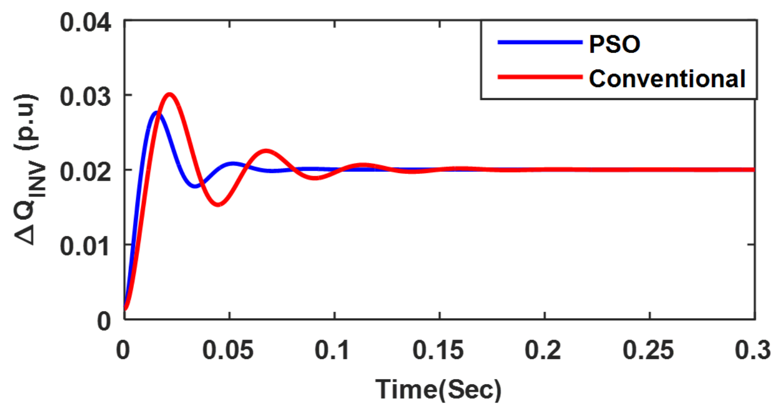

Figure 6: *Dynamic response of the deviation in the inverter reactive power (ΔQ_{INV})*

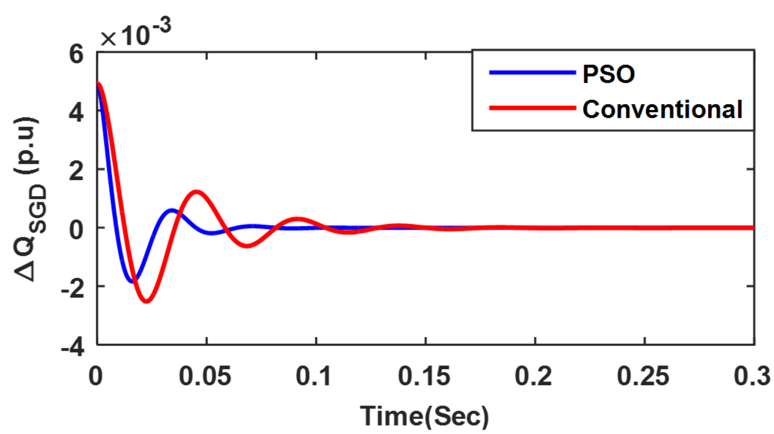

Figure 7: *Dynamic response of the deviation in the reactive power of SG (ΔQ_{SGD})*

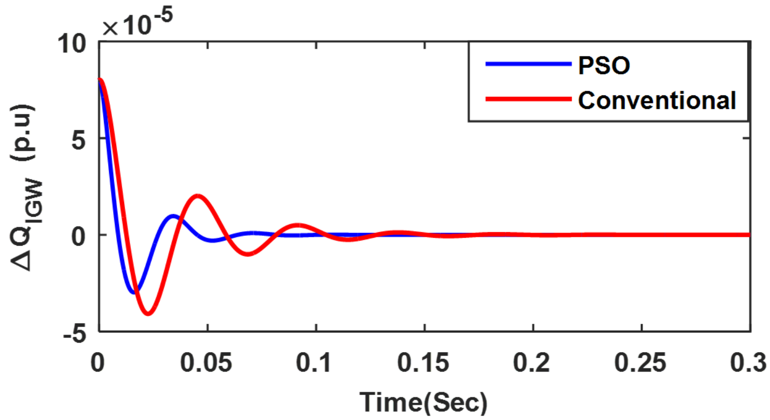

Figure 8: *Dynamic response of the deviation in the reactive power of IG (ΔQ_{IGW}).*

Table 2: *Maximum deviation (P.U.) under different disturbance conditions*

Disturbance (%)				Optimization	System state variables			
ΔQ_L	ΔP_{MD}	ΔI_r	ΔT_e	method	ΔV	ΔQ_{INV}	ΔQ_{SGD}	ΔQ_{IGW}
2	0	0	0	PSO	0.000276	0.0282	0.002004	8.0031e-05
				Conventional	0.00034	0.0301	0.00252	8.0131e-05
5	5	0	0	PSO	0.001012	0.1056	0.00749	0.02497
				Conventional	0.001273	0.1126	0.00943	0.02501

Table 3: *Settling time (s) for different disturbance conditions*

Disturbance (%)				Optimization	System state variables			
ΔQ_L	ΔP_{MD}	ΔI_r	ΔT_e	method	ΔV	ΔQ_{INV}	ΔQ_{SGD}	ΔQ_{IGW}
2	0	0	0	PSO	0.0596	0.0598	0.0597	0.0596
				Conventional	0.1213	0.1213	0.1217	0.1213
5	5	0	0	PSO	0.0595	0.0598	0.0597	0.0595
				Conventional	0.1213	0.1213	0.1217	0.1213

the dynamic performance of HOPS when subjected to disturbances of different magnitudes. We explored computational intelligent optimization methods such as PSO for optimizing controller parameters. These methods have excellent global search capacity. They are implemented in MATLAB to solve optimization problems formulated for an objective function (ITSE). In our case, the ITSE is expressed as a function of voltage deviation, which in turn is related to controller parameters. The minimization of ITSE by PSO was implemented.

With optimized values of the controller obtained by PSO, we conducted simulations of test systems under different step disturbances for the reactive power load and/or wind power input to IG and for optimal controllers designed by all the proposed methods. We conclude from the simulation results that it is evident that the system dynamic performance is considerably improved with inverter and AVR controller parameters optimized by PSO compared to conventional methods.

Declaration of interest: None

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