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Optimal Transient Search Algorithm-Based PI Controllers for Enhancing Low Voltage Ride-Through Ability of Grid-Linked PMSG-Based Wind Turbine

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Abstract: This paper depicts a new attempt to apply a novel transient search optimization (TSO) algorithm to optimally design the proportional-integral (PI) controllers. Optimal PI controllers are utilized in all converters of a grid-linked permanent magnet synchronous generator (PMSG) powered by a variable-speed wind turbine. The converters of such wind energy systems contain a generator-side converter (GSC) and a grid-side inverter (GSI). Both of these converters are optimally controlled by the proposed TSO-based PI controllers using a vector control scheme. The GSC is responsible for regulating the maximum power point, the reactive generator power, and the generator currents. In addition, the GSI is essentially controlled to control the point of common coupling (PCC) voltage, DC link voltage, and the grid currents. The TSO is applied to minimize the fitness function, which has the sum of these variables' squared error. The optimization problem's constraints include the range of the proportional and integral gains of the PI controllers. All the simulation studies, including the TSO code, are implemented using PSCAD software. This represents a salient and new contribution of this study, where the TSO is coded using Fortran language within PSCAD software. The TSO-PI control scheme's effectiveness is compared with that achieved by using a recent grey wolf optimization (GWO) algorithm-PI control scheme. The validity of the proposed TSO-PI controllers is tested under several network disturbances, such as subjecting the system to balanced and unbalanced faults. With the optimal TSO-PI controller, the low voltage ride-through ability of the grid-linked PMSG can be further improved.

Keywords: frequency converter; PI controllers; transient search optimization; wind energy

1. Introduction

The remarkable development of wind power has become a pressing modern energy subject all over the world. This is due to the need to obtain new electrical power sources, avoid the need for fossil fuels, and the target to obtain clean energy, considering the environmental concerns [1]. Wind power represents the second-largest source after hydropower sources worldwide [2]. The wind power industry is extensively developed, resulting in a bright future of renewable energy sources. Based on the Global Wind Energy Council's statistical analysis and annual report, the last year (2019) was an outstanding year for the wind power industry, where 60.4 GW was globally installed by the end of 2019 [3]. The total cumulative wind power capacity reached 651 GW. An increase in wind power installation by 17% was achieved compared with that obtained in 2018. It is expected that this type of renewable energy source shall increase in the future and will rigorously contribute to the

electricity market [4]. It can be noted from this numerical analysis that a high level of wind power is penetrated in electric power networks [5]. Therefore, several problems have arisen, and these issues should be studied, investigated, and solved to obtain an efficient operation of wind energy conversion systems [6]. In fact, most of these problems come from the sophisticated and intermittent nature of wind power, which is based on the cube of wind speed [7]. One of the main problems that this wind power system faces is enhancing the low voltage ride through (LVRT) of the grid-connected wind energy systems [8]. Power grids have recently imposed grid codes on wind power systems to remain connected and support the power grid during grid faults [9]. This generally enhances the power grids' stability and reliability. Therefore, wind power plants should satisfy the LVRT requirements [10]. This study focuses on strengthening the LVRT of grid-linked variable-speed wind turbine (VSWT) that drives a permanent magnet synchronous generator (PMSG).

The variable-speed wind turbines are the most commonly used in the wind power industry. These turbines have higher capture power, better control of maximum power point, higher efficiency, and lower mechanical stress than fixed-speed wind turbines [11]. Several generators have been implemented in this technology like doubly-fed induction generator (DFIG) [12], PMSG [13–15], and switched reluctance generator [16]. PMSGs possess many magnetic poles with large air gaps. Hence, the PMSG can rotate at lower speed compacting with the wind turbine without needing a gearbox. This technology reduces system costs and losses [17].

The VSWT-PMSG system is directly coupled with the main grid via a generator-side converter (GSC), a DC link capacitor, and a grid-side inverter (GSI) [18]. In general, the cascaded control scheme is utilized in controlling both converters. The cascaded control system controls the generator's real and reactive power and the generator currents through the GSC. Moreover, the vector control can control the point of common coupling (PCC) voltage, the DC link voltage, and the grid currents through the GSI. Several control strategies have been used to control VSWT-PMSG systems. In [19], a linear quadratic regulator controller is introduced to obtain high performance of the VSWT-PMSG. However, many mathematical calculations are needed to simplify the quadratic regulator. In addition, the fuzzy logic controllers are presented to achieve better performance of such systems by using the Sugeno fuzzy system [20]. Although the fuzzy logic controllers can efficiently deal with the system nonlinearity and do not need the system's mathematical model, they depend mainly on the designer experience. Additionally, optimal fuzzy logic controllers are very complex, where they involve many design variables to be fine-tuned. In [21], an adaptive neuro-fuzzy inference system is proposed to improve the system performance with the cooperation with genetic algorithms. However, this type of controllers is very complex and has several mathematical procedures. In the wind power industry, the proportional-integral (PI) controller is still the most capable of doing the control task, where it possesses a large stability margin. However, the PI controller suffers from its high sensitivity to the system parameters variation nonlinearity of the system under study. In these heavy nonlinear systems, like the wind energy conversion system, it is not easy to represent the system by transfer functions or state-space models mathematically. Therefore, many optimization methods and algorithms have been applied to design the PI controllers in such systems, such as genetic algorithm [22], the Taguchi method [23], water cycle algorithm [24], grey wolf optimizer [25], enhanced whale optimization algorithm [26], symbiotic optimization [27], enhanced salp swarm optimization algorithm [28], and hybrid cuckoo search and grey wolf optimization algorithm [29]. The tremendous revolution of meta-heuristics and soft computing algorithms represents the authors' principal motivation to apply a novel transient search optimization algorithm (TSO) to design all PI controllers of the fully developed VSWT-PMSG system. In today's world, meta-heuristic algorithms and their emerging strategies are highly welcomed as they are expected to obtain better results. However, no algorithm can solve all engineering problems; it can solve one and fails with another application (this is on the basis of the no-free-lunch theorem).

The TSO is a novel meta-heuristic-based algorithm. It was introduced by the same authors of this study in 2020 [30]. The proposed algorithm is motivated by switching electric circuits, including

inductors and capacitors. The TSO has been successfully applied to twenty-three optimization problems, and its results have proven its high performance over other conventional and meta-heuristic algorithms. Many performance tests have been carried out for this issue like non-parametric sign test and p-value test. Furthermore, the TSO has been used to optimally design engineering applications like coil spring, welded beam, and pressure vessel. Recently, it was applied to determine the electrical parameters of the photovoltaic model [31].

In this paper, a new attempt in the application of the TSO algorithm is proposed to fully design the PI controllers of the GSC and GSI of grid-linked VSWT-PMSG systems. The GSC is optimally controlled by the TSO-PI controllers to efficiently control the maximum power point, the reactive generator power, and the generator currents. In addition, the GSI is optimally controlled by the TSO-PI controllers to control the PCC voltage, DC link voltage, and the grid currents. All these control strategies are built using cascaded or vector control schemes to produce the firing pulses of the converters' electronic switches. The TSO is applied to minimize the fitness function, which has the sum of these variables' squared error. The optimization problem's constraints include the range of the proportional and integral gains of the PI controllers. All the simulation studies, including the TSO code, are implemented using PSCAD software [32]. This represents a salient and new contribution of this study, where the TSO is coded using Fortran language within PSCAD software. The TSO-PI control scheme's effectiveness is compared with that achieved by using a recent grey wolf optimization (GWO) algorithm-PI control scheme. The proposed TSO-PI controllers' validity is tested under several network disturbances, such as subjecting the system to symmetrical and unsymmetrical faults. With the optimal TSO-PI controller, the LVRT ability of the grid-linked VSWT-PMSG can be further improved.

The paper's detailed structure is as follows: Section 2 points out the power system model components in detail. In Section 3, the frequency converter, GSC, and GSI models are presented. Section 4 presents the optimization methodology of using TSO algorithm. Section 5 demonstrates the optimization and simulation results under various network disturbances with many analyses. Lastly, a conclusion of this paper is formed in Section 6.

2. Power System Modeling

In this study, the wind power harvesting, conversion, and supply to the electrical grid are modeled as depicted in Figure 1. This model consists of a three-bladed horizontal-axis wind turbine (WT), which harvests the kinetic energy of wind and converts it into mechanical power. Then, the WT is interconnected directly (without gearbox) to the shaft of the PMSG, which will convert the mechanical power to electrical power. However, the rotor side's rotation speed is deficient, so the frequency converter links the generator and the grid sides. The GSC converts the AC power into DC power, where the DC link capacitor (C_{dc}) and a chopper resistor (R_{ch}) exists. The GSI converts the DC power to AC power, which is delivered to the electrical grid through inductance filter (L_f), a step-up transformer, and double-circuit overhead transmission lines (TLs). The control system synchronizes the rectifier and the inverter with the voltage and frequency on each side. The data of the power system are listed in the Appendix A.

2.1. Horizontal-Axis WT Modeling

A horizontal-axis three-bladed wind turbine is the most widespread type of wind turbine, where the generator is placed on the top of the tower. The airflow is with density $\rho_a = 1.225 \text{ kg/m}^3$. v_a is the velocity and the blades have radius (R_b). The kinetic power (P_k) is converted into rotating power (P_r) with efficacy called power coefficient (C_p) as in Equation (1). However, the efficacy of WT is limited by the Betz constant (0.593) [33].

$$C_p = \frac{P_r}{P_k} \quad (1)$$

$$P_k = 0.5\rho_a(\pi R_b^2)v_a^3 \quad (2)$$

$$P_r = T_r \omega_r \quad (3)$$

where T_r is the rotor torque, and ω_r is the rotor speed. C_p is expressed in Equation (4), where its variables are the tip-speed ratio (TSR λ) and pitch angle (β) of three-blades. C_p is plotted against λ at different values of β , as depicted in Figure 2, where the peak value of C_p occurs at $\beta = 0$. Additionally, the rotor power and maximum power (P_{max}) are expressed in Equations (7) and (8). Figure 3 shows the rotor power variations and the locus of maximum power versus the rotor speed at different wind speed values [34].

$$C_p(\lambda, \beta) = 0.5176(116\gamma - 0.4\beta - 5)e^{-21\gamma} + 0.0068\lambda \quad (4)$$

$$\gamma = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^3} \quad (5)$$

$$\lambda = \frac{\omega_r \times R_b}{v_a} \quad (6)$$

$$P_r = 0.5\rho_a(\pi R_b^2)C_p(\lambda, \beta)v_a^3 \quad (7)$$

$$P_{max} = 0.5\rho_{air}A_b C_{pmax} \left(\frac{\omega_m R}{\lambda_{max}}\right)^3 \quad (8)$$

Figure 1. Grid-linked permanent magnet synchronous generator (PMSG) driven by variable-speed wind turbine (VSWT).

Figure 2. The variations of power coefficient (C_p) versus tip-speed ratio (λ) at different values of pitch angle (β).

Figure 3. Per unit rotor power variations versus rotor speed at different wind speeds.

2.2. Gearless Shaft Modeling

The shaft of PMSG is interconnected to the wind turbine's shaft without a gearbox, so the rotor speed is low, resulting in a low frequency in the electrical side of PMSG. Therefore, the frequency converter is applied to convert the low frequency to the grid frequency. On the other hand, the frequency converter reduces the grid stresses to the PMSG. A single shaft model can then be used to model the shafts of wind turbines and PMSG, as in Equation (9) [35].

$$j_s \frac{d\omega_r}{dt} + D_s \omega_r = T_r - T_g \quad (9)$$

where D_s is the shaft damping, j_s is the shaft inertia, and T_g is the generated torque by the PMSG.

2.3. Generator-Side Modeling

The generator converts the rotational power to electrical power, where the input of the generator model is ω_r , and its outputs are the stator voltages, as in Equation (10). The generator voltages (v_d, v_q), currents (i_d, i_q), and inductances (L_d, L_q) are expressed in the direct and quadrature axis (d - q axis) [36].

$$\begin{pmatrix} v_d \\ v_q \end{pmatrix} = -R_s \begin{pmatrix} i_d \\ i_q \end{pmatrix} - \frac{d}{dt} \begin{pmatrix} L_d i_d \\ L_q i_q \end{pmatrix} + \omega_g \begin{pmatrix} L_q i_q \\ -L_d i_d + \psi_f \end{pmatrix} \quad (10)$$

where R_s is the stator resistor, ω_g is the electric generator speed, and the ψ_f is the rotor flux linked the stator.

2.4. Grid Side Modeling

In this study, the grid is an extensive power system, which can be modeled by inductance in series with a controlled voltage source. The equivalent inductance (L_g) represents the inductances of the filter, transformer, and TLLs. The terminal voltages at the GSI (v_{id}, v_{iq}) are expressed in terms of the grid currents (i_{gd}, i_{gq}) and grid voltages (v_{gd}, v_{gq}) that are measured at the point of common coupling (PCC), as in Equation (11).

$$\begin{pmatrix} v_{id} \\ v_{iq} \end{pmatrix} = \begin{pmatrix} v_{gd} \\ v_{gq} \end{pmatrix} + L_g \frac{d}{dt} \begin{pmatrix} i_{gd} \\ i_{gq} \end{pmatrix} \quad (11)$$

3. Frequency Converter Modeling

The frequencies in the generator and grid sides are not synchronized, so the frequency converter is utilized in this study. The frequency converter is constructed from two voltage source converters connected in a back-to-back manner. These converters are based on the insulated gates bipolar transistors (IGBTs) paralleled with diodes. The converter at the generator side, called the GSC, converts the generated AC power to DC power. However, the converter at the grid side, which is called GSI, converts the DC power to AC power that is synchronized with the grid frequency. The IGBTs are switched on and off using pulse width modulation (PWM) signals produced by cascaded control systems of GSC and GSI. The control system consists of four proportional-integral (PI) controllers at each side, so eight PI controllers are used in total. Each PI controller has two parameters (proportional gain (k_p) and integral time constant (T_i)).

3.1. GSC Control Modeling

The GSC vector control objectives are to obtain i) maximum power point tracking (MPPT) and ii) unity power factor at the generator side. Since T_g is proportional to the i_q , as in Equation (12), then the vector control of GSC is a field-oriented control, and the generated real power (P_g) is proportionate with i_q , as in Equation (13) [33,36].

$$T_g = \frac{3}{2} \left(\frac{p}{2} \right) (\lambda_r i_q - (L_d - L_q) i_d i_q) \quad (12)$$

where $L_d \approx L_q$, then

$$P_g = \omega_g T_g = \frac{3}{2} \left(\frac{p}{2} \right) (\lambda_r i_q) \omega_g \quad (13)$$

So, PI1 regulates the P_g with respect to P_{max} to generate the reference i_q^* , as in Equation (14), while PI2 regulates the reactive power (Q_g) of generator with respect to the reference Q_{ref} to generate the reference i_d^* , as in Equation (15). Consequently, PI3 and PI4 regulate the currents i_q , i_d with respect to i_q^* , i_d^* to generate the references v_q^* and v_d^* , as in Equations (16) and (17). The reference voltage is then transformed using dq - abc transformer, which is synchronized using the phase angle (θ) of PMSG by measuring ω_r . So, the cascaded control system of the GSC is depicted in Figure 4.

$$i_q^* = k_{p1} \left(1 + \frac{1}{sT_{i1}} \right) (P_{max} - P_g) \quad (14)$$

$$i_d^* = k_{p2} \left(1 + \frac{1}{sT_{i2}} \right) (Q_{ref} - Q_g) \quad (15)$$

$$v_q^* = k_{p3} \left(1 + \frac{1}{sT_{i3}} \right) (i_q^* - i_q) \quad (16)$$

$$v_d^* = k_{p4} \left(1 + \frac{1}{sT_{i4}} \right) (i_d^* - i_d) \quad (17)$$

Figure 4. Control system of generator-side converter (GSC).

3.2. GSI Control Modeling

The objectives of the control system of the GSI are: i) low voltage ride-through capability enhancement during short circuits by producing reactive power to support stability restoration of the grid, and ii) regulating the DC link voltage to deliver smooth power to the grid. Hence, the DC link voltage (V_{dc}) is proportionate to the i_{gd} , as in Equation (18), PI5 regulates the V_{dc} with respect to the reference V_{dc}^* to generate the reference i_{gd}^* , as in Equation (19). Furthermore, PI6 regulates the PCC voltage V_{rms} relative to the reference voltage V_{rms}^* to create the reference i_{gq}^* , as in Equation (20). Consequently, PI7 and PI8 regulate the currents i_{gd} , i_{gq} relative to i_{gd}^* , i_{gq}^* to generate the references v_{id}^* and v_{iq}^* , as in Equations (21) and (22), as shown in Figure 5a. Then, the reference voltages are transformed to abc form using dq - abc transformer. The phase-locked loop (PLL) is utilized to produce the phase angle (θ_g) of the grid for phase synchronization. PLL is based on the dq -frame, where the q-axis voltage is regulated with zero reference, as shown in Figure 5b. In addition, the angular frequency of grid is $\omega_s = 2\pi \times 60 = 377$ rad/s.

$$P_{grid} = V_{dc} \times I_{dc} = \frac{3}{2} v_{gd} \times i_{gd} \quad (18)$$

$$i_{gd}^* = k_{p5} \left(1 + \frac{1}{sT_{i5}}\right) (V_{dc}^* - V_{dc}) \quad (19)$$

$$i_{gq}^* = k_{p6} \left(1 + \frac{1}{sT_{i6}}\right) (V_{rms}^* - V_{rms}) \quad (20)$$

$$v_{id}^* = k_{p7} \left(1 + \frac{1}{sT_{i7}}\right) (i_{gd} - i_{gd}^*) \quad (21)$$

$$v_{iq}^* = k_{p8} \left(1 + \frac{1}{sT_{i8}}\right) (i_{gq} - i_{gq}^*) \quad (22)$$

Figure 5. Control system of grid-side inverter (GSI), (a) vector control of voltage and (b) phase angle control by phase-locked loop (PLL).

4. Optimization Methodology

This study's main objective is to improve the low voltage ride-through ability of the grid-linked PMSG-based WT. This objective can be achieved by designing optimal PI controllers that exist in the control system. However, as shown in Figure 1, the power system is a big nonlinear dynamic system, which cannot be represented by a transfer function. Therefore, the objective function is considered the sum of the integral of PI controllers' squared errors (Equation (23)). The stochastic optimization algorithms are applied to design PI controllers' optimal parameters (k_p and T_i) by executing the modeled power system using PSCAD/EMTDC software, as depicted in the flowchart in Figure 6. The power system model's simulation time is 10 s, and a balanced fault is applied at $t = 5$ s, with a duration of 0.15 s. In this study, the TSO and GWO algorithms are utilized in minimizing the objective function.

$$ISE(x_1, x_2, \dots, x_{16}) = \int_0^{10} [(P_{\max} - P_g)^2 + (Q_{ref} - Q_g)^2 + (V_{dc}^* - V_{dc})^2 + (V_{rms}^* - V_{rms})^2 + (i_q^* - i_q)^2 + (i_d^* - i_d)^2 + (i_{gd}^* - i_{gd})^2 + (i_{gq}^* - i_{gq})^2] dt \quad (23)$$

where $x_1, x_2, \dots, x_{16} = \{k_{p1}, k_{p2}, \dots, k_{p8}, T_{i1}, T_{i2}, \dots, T_{i8}\}$, where $0.01 \leq k_p \leq 10$ and $0.001 \leq T_i \leq 1$.

Figure 6. Flowchart of optimization.

4.1. Transient Search Optimization (TSO)

The TSO algorithm is inspired by the transient response of switched electrical circuits that consists of one and two energy storage elements (inductors (L) and capacitors (C)) besides resistors (R), as depicted in Figure 7. The exploration of the TSO algorithm imitates the underdamped transient response of RLC circuits. However, the exploitation of TSO imitates the exponential decay of the transient response of RC circuits. So, the voltage responses across the capacitors in RC and RLC circuits are expressed in Equations (24) and (25).

$$v_1(t) = v_1(\infty) + (v_1(0) - v_1(\infty))e^{\frac{-t}{R_1C_1}} \quad (24)$$

$$v_2(t) = e^{\frac{-R_2t}{2L}} (B_1 \cos(2\pi f_d t) + B_2 \sin(2\pi f_d t)) + v_2(\infty) \text{ if } (R_2/2L)^2 < 1/LC_2 \quad (25)$$

where f_d is the damping frequency, and B_1 and B_2 are constant numbers.

Figure 7. The electrical circuit including (a) one-storage element and (b) two-storage element.

Therefore, the main frame of the Equations (24) and (25) is exploited to mode the TSO algorithm mathematically, as in Equation (26). However, the resistors, capacitors and inductor (R_1 , R_2 , C_1 , C_2 , and L) in Equations (24) and (25) are replaced with random numbers, such as (W and A), that are suitable for metaheuristic algorithms. The variables of TSO algorithm are the search agent X_{l+1} and X_l , which are equivalent to the variables $v(t)$ and $v(0)$ in Equations (24) and (25). Additionally, the variable X^* is the best agent, which is equivalent to the $v(\infty)$. In addition, $B_1 = B_2 = |X_l - W.X_l^*|$, where W is expressed as $W = k \times r_2 \times a + 1$, k is a real number, $a = 2 - 2 \times l/L_{max}$, L_{max} is the total number of iterations, and r_2 is a random number between 0 and 1. The exploration and exploitation of TSO are balanced by using a random number r_1 .

$$X_{l+1} = \begin{cases} X_l^* + (X_l - W.X_l^*)e^{-A} & r_1 < 0.5 \\ X_l^* + e^{-A}[\cos(2\pi A) + \sin(2\pi A)]|X_l - W.X_l^*| & r_1 \geq 0.5 \end{cases} \quad (26)$$

where, $A = 2 \times a \times r_3 - a$, and r_3 are real random numbers between 0 and 1. The pseudo-code of the TSO algorithm is illustrated in Algorithm 1.

Algorithm 1 Transient search optimization (TSO)

Input the random initial values of search agents $X_l = \{k_{p1}, k_{p2}, \dots, k_{p8}, T_{i1}, T_{i2}, \dots, T_{i8}\}$ between $0.01 \leq k_p \leq 10$ and $0.001 \leq T_i \leq 1$

Calculate the $ISE(X_l)$

while $l < L_{max}$

Modify A and W

do all search agents X_l

Update the search agents by Equation (26)

end do

Compute the $ISE(X_{l+1})$

Compare the $ISE(X_l)$ with $ISE(X_{l+1})$ and find the new best search agents X^*

$l = l + 1$

end while

return the best search agents X^*

4.2. Grey Wolf Optimizer (GWO)

The GWO is inspired by the leader and followers' behavior in the group of the grey wolves [37]. There are main leaders (called α) and secondary leaders (called β), and followers (called δ). Grey wolves start the hunting procedure searching for the food, then surround the prey, and then attack the target. So, the mathematical expression of surrounding the food is:

$$D = |C.X^* - X_l| \quad (27)$$

$$X_{l+1} = X^* - A.D \quad (28)$$

where X is the grey wolf position, X^* is the food position, $a = 2 - 2l/L_{max}$, $A = 2ar_1 - a$, $C = 2r_2$, r_1 , and r_2 are real numbers that are randomly distributed between 0 and 1.

The variables of the GWO algorithm are the search agent X_l and X_{l+1} and the best position X_α , however, the constants are a , C and A . The leaders' X_α start attacking the prey and are supported by the secondary leaders' X_β and the followers' X_δ , where the attacking process is modeled (Equations (29)–(31)). The pseudo-code of the GWO algorithm is explained in Algorithm 2.

$$D_\alpha = |C_1 \cdot X_{\alpha l} - X_l|, D_\beta = |C_2 \cdot X_{\beta l} - X_l|, D_\delta = |C_3 \cdot X_{\delta l} - X_l| \quad (29)$$

$$X_1 = X_{\alpha l} - A_1 \cdot D_\alpha, X_2 = X_{\beta l} - A_2 \cdot D_\beta, X_3 = X_{\delta l} - A_3 \cdot D_\delta \quad (30)$$

$$X_{l+1} = \frac{X_1 + X_2 + X_3}{3} \quad (31)$$

Algorithm 2 Grey wolf optimizer (GWO)

Input the random initial values of search agents $X_l = \{k_{p1}, k_{p2}, \dots, k_{p8}, T_{i1}, T_{i2}, \dots, T_{i8}\}$ between $0.01 \leq k_p \leq 10$ and $0.001 \leq T_i \leq 1$

Compute the ISE(X_l)

while $l < L_{max}$

Modify a , A , and C

for All search agents

Update the search agent (X_{l+1}) by Equation (31)

end for

Compute the ISE(X_{l+1})

Compare ISE(X_{l+1}) with ISE(X_l) and update X_α , X_β , and X_δ

$l = l + 1$

end while

Output best search agent X_α

5. Results and Discussion

5.1. Optimization Results

The TSO and GWO are applied to find the PI controllers' optimal variables by minimizing the objective function in Equation (23). These algorithms are coded using FORTRAN and implemented in PSCAD to design the optimal PI controllers. The parameters of TSO and GWO are set as shown in Table 1, where the number of optimization iterations is 1000 for each algorithm and the simulation time of each iteration is 10 s. Additionally, the balanced fault is considered during optimization to emphasize enhancing the low voltage ride-through (LVRT) ability of grid-linked PMSG-based WT. Hence, Figure 8 illustrates the convergence curves of the integral squared-error (ISE) minimization by using TSO and GWO, where the TSO algorithm has achieved a lower ISE value (0.25953) than the ISE value (0.27269) of the GWO algorithm. In addition, Tables 2 and 3 show the optimal 16 variables of eight PI controllers that are optimally based on TSO and GWO.

Table 1. Parameters settings of transient search optimization (TSO) and grey wolf optimization (GWO).

Algorithm	Parameters of Algorithms
TSO	$L_{max} = 1000, k = 1, a \in [2, 0]$, dimensions = 16, no. of population = 10
GWO	$L_{max} = 1000, a \in [2, 0]$, dimensions = 16, no. of population = 10

Table 2. Optimal variables of the proportional-integral (PI) controllers of GSC control.

	PI1		PI2		PI3		PI4	
	k_p	T_i	k_p	T_i	k_p	T_i	k_p	T_i
TSO	2.014644	0.017984	1.011208	0.017122	5.038511	0.998511	1.012340	0.020618
GWO	2.028126	0.020285	1.109651	0.214817	1.624001	0.416161	0.667845	0.186149

Figure 8. Convergence of best values of ISE function.

Table 3. Optimal variables of PI controllers of GSI control.

	PI5		PI6		PI7		PI8	
	k_p	T_i	k_p	T_i	k_p	T_i	k_p	T_i
TSO	3.312642	0.064859863	1.032979	0.862991	6.006839	0.001015	3.755012	0.008518
GWO	1.188707	0.993525	0.065729	0.877969	3.181436	0.140109	2.468010	0.001349

5.2. Simulation Results

In this section, the LVRT ability of the optimal TSO–PI and GWO–PI controllers is tested under balanced and unbalanced short circuits. These abnormal conditions are simulated and applied to the power system model in PSCAD/EMTDC, where the time step is 20 μ s.

Case 1, balanced short circuits: This means that TL’s three-phase lines are short-circuited together with ground, which is called three-phase to ground fault (3PGF). This fault occurs at the PCC bus bar at the end of one circuit of the double-circuit TLs, as depicted in Figure 1. The power system model is operating under steady state before the fault occurs at $t = 0$ s, the circuit breakers (CBs) trip the short-circuited TL after 0.15 s.

Firstly, a temporary balanced short circuit is assumed (e.g., flashover, arc, . . . , etc.), so the CBs are assumed to reclose at $t = 1$ s, as depicted in Figure 9. The transient response of V_{rms} at the PCC bus bar is depicted in Figure 9a, which changes from 1 (pu) at steady state to 0 during the effect of the 3PGF, then returns to the steady-state value once a fault is cleared. During CBs reclosing, the voltage recovery is combined with adverse overshoot and oscillates around the steady-state value until it reaches this value. Therefore, the TSO–PI controllers have attained a lower overshoot than that of the GWO–PI controllers; however, they have the same steady-state error. Figure 9b depicts the real power response during 3PGF, which decreases to 0 during fault at PCC, then recovers to the steady state after fault clearance. Figure 9b shows that the TSO–PI recovers the power faster than the GWO–PI.

Furthermore, the DC link voltage increases during fault due to the excessive power in the DC link, so an adverse overvoltage occurs across the DC capacitors and can be damaged. These capacitors are protected using chopper circuits, as in Figure 1. Additionally, the control system regulates the DC voltage across the capacitors. Figure 9c illustrates that the TSO–PI controller has attained an overvoltage at DC link lower than that of the GWO–PI controller. Moreover, the reactive power at PCC is near the zero value at steady state for a unity power factor correction. Then, after fault clearance, the GSI supports the grid with reactive power to restore the grid stability. Figure 9d shows that reactive power supplied by the TSO–PI controllers is lower than that supplied by the GWO–PI controllers.

Secondly, a permanent balanced short circuit is assumed, so the CBs fail to reclose at $t = 1$ s, as depicted in Figure 10, then the short-circuited TLs are tripped permanently for maintenance. Figure 10a shows the response of the V_{rms} measured at PCC during permanent fault and failure of CBs to reclose the tripped TL. The overshoot of TSO–PI controllers is lower than that of GWO–PI during voltage recovery in the first and the second operations of CBs. Moreover, Figure 10b demonstrates the

response of real power at PCC during both operations of CBs, where the power response of GWO-PI is much slower in the second act of CBs than the first operation of CBs. However, TSO-PI controllers have attained a fast power response during both operations of CBs. In addition, Figure 10c reveals that the overvoltage and oscillations of DC voltage for TSO-PI are lower than that of GWO-PI. Finally, the reactive power supply during voltage recovery by GWO-PI is higher than that of TSO-PI, as depicted in Figure 10d.

Case 2, unbalanced short circuits: single-phase to ground fault (1PGF) and phase to phase fault (PPF) are considered unbalanced short circuits in the TLs of the power system. Temporary unbalanced short circuits are applied at $t = 0$, and then the CBs isolate the short-circuited TL at $t = 0.15$ s; finally, the CBs are assumed to reclose the tripped TL at $t = 1$ s. Firstly, the PCC voltage responses, real power, DC voltage, and reactive power are measured during the applied 1PGF at the end of one TL, as shown in Figure 11. So, the response of V_{rms} of TSO-PI is slightly lower than that of the GWO-PI, as displayed in Figure 11a. However, the overshoot of real power of GWO-PI is much higher than that of the TSO-PI, as depicted in Figure 11b. Furthermore, the DC voltage response of the GWO-PI is higher than that of the TSO-PI, as depicted in Figure 11c. In addition, the reactive power supply using GWO-PI after fault clearing is much higher than that of the TSO-PI, as depicted in Figure 11d. Secondly, a temporary PPF is applied, and the response of TSO-PI is compared with the response of GWO-PI, as depicted in Figure 12. The V_{rms} response using TSO-PI has a lower rise time than that of the GWO-PI, as shown in Figure 12a. However, the real power response of the TSO-PI is faster than that of the GWO-PI, as depicted in Figure 12b. Additionally, the DC voltage response of the TSO-PI has better damped response, as illustrated in Figure 12c. finally, the reactive response of the TSO-PI is nearly similar to that of the GWO-PI, as depicted in Figure 12d.

Figure 9. Cont.

Figure 9. Point of common coupling (PCC) measurements during temporary three-phase to ground fault (3PGF), (a) V_{rms} , (b) P_{grid} , and (c) V_{DC} , and (d) Q_{grid} .

Figure 10. Cont.

Figure 10. PCC measurements during permanent 3PGF, (a) V_{rms} , (b) P_{grid} , and (c) V_{DC} , and (d) Q_{grid} .

(a)

(b)

(c)

Figure 11. Cont.

Figure 11. PCC measurements during temporary single-phase to ground fault (1PGF), (a) V_{rms} , (b) P_{grid} , and (c) V_{DC} , and (d) Q_{grid} .

Figure 12. Cont.

Figure 12. PCC measurements during temporary phase to phase fault (PPF), (a) V_{rms} , (b) P_{grid} , and (c) V_{DC} , and (d) Q_{grid} .

6. Conclusions

This paper has proposed a novel application of the TSO algorithm to optimally fine-tune all PI controller gains of the frequency converters of a PMSG-based VSWT. The main purpose of this study is to achieve LVRT capability enhancement of such systems. The TSO is extensively applied to the fitness function, which possesses the sum of the system variables' squared error. The optimization problem constraints have taken into account all ranges of the controllers' parameters. The simulation results have proven the high performance and superiority of the proposed TSO-PI controllers to the GWO-PI controllers under balanced and unbalanced network fault conditions. The results using TSO-PI controllers have given an improvement of more than 5% of some quantities of the system under study. The proposed controller's high performance comes from the proper design of the TSO during the design procedure, which relies on the designer experience. These good and salient achievements shall encourage researchers to use the TSO-PI controllers to enhance several systems' responses, including renewable energy systems, microgrids, and smart grid systems.

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Appendix A

The data of the power system under study are listed in Table A1.

Table A1. Data of grid-linked PMSG-based WT.

WT			
Diameter	92 m		
PMSG ratings			
Power	5 MVA	Rotor poles	150
Voltage (line to line)	690 V	Inertia time	3 s
Frequency	30 Hz	resistor	0.01 pu
X_d	0.28 pu	X_q	0.28 pu
Magnetic flux	1.04 pu		
Filter			
Inductor	0.2 mH		
Transformer			
Low voltage	0.69 kV	High voltage	33 kV
Reactance	0.08 pu	Frequency	60 Hz

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