

## Optimal Controller Design of Crowbar System for DFIG-based WT: Applications of Gravitational Search Algorithm

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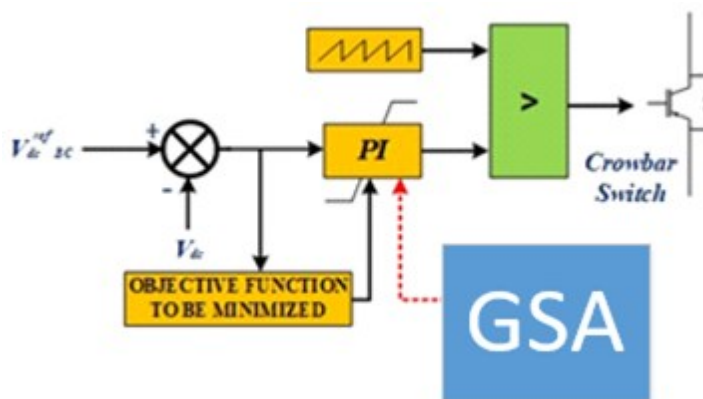
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### ABSTRACT



The optimal output and efficacy of a doubly fed induction wind generator (DFIG) are dependent on a multitude of uncontrollable components, necessitating the use of an adequate control system. The crowbar system is essential to the system during abnormal events; thus, it requires appropriate control algorithms and enough control settings. This work suggests the gravitational search algorithm (GSA) to construct the crowbar controller. A synopsis of wind energy and a conversation about the pertinent DFIG component and its methodology. The outcomes acquired with the suggested optimized crowbar system are contrasted with those obtained with a traditional crowbar and without protection. The outcomes confirmed the higher performance of the suggested strategy. The DFIG system responds marginally improved to active and reactive (P&Q) power, DC-Link voltage (DCLV), and machine rotation when a GSA-based PI controller is used. Finally, it can be said that by maintaining the DCLV below the allowable value, which permits the high penetration possibilities of wind energy, the suggested technique assures fault ride-through capacity (FRTC).

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## 1. INTRODUCTION

Enterprises, governments, and research centers around the world are all interested in electrical energy, and there is a continuous discussion about which developed and developing nations should prioritize various forms of generating. The energy revolution that seeks to eradicate climate change has been the most essential applied development to ensure sustainable progress [1]-[3]. As fossil fuels continue to exhaust and worries about greenhouse gas emissions are on the rise, renewable energy technologies (RETs) exhibit an unparalleled growth. Leading this revolution are wind systems, which have been found to be low-cost, easy to implement, and highly scalable for various applications [4]-[7]. A few drawbacks of such technologies include variability of performance, integration into existing systems and maximizing the generation of power. Globally, energy source use is changing. IRENA reports that international renewable energy capacity expanded 80% from 2010 to 2020, mostly owing to solar and wind energy [8]-[10]. This quick increase revealed various constraints, including weather dependence, electric grid 'ramp' instabilities, and low energy user facilities. All of the above issues can be overcome using hybrid RETs that integrate multiple RETs with high-performance energy storage [11]-[13]. The global transition to RETs has varying implications across regions. Germany and Spain, for example, have achieved over 40% penetration of renewables through feed-in tariffs and other measures. That during the next 20 years, wind power will account for more than 20% of global energy production [14]-[16].

Nevertheless, the biggest barriers to the widespread implementation of wind energy (WE) production are the particular conditions required in its manufacturing, namely the advanced and costly methods necessary to create WE and the huge surfaces demanded [17]-[20]. A WE are accessible all year round, in contrast to SE, which is only accessible for certain parts of the year. Numerous companies sell a range of WE model providing modest prices and differing degrees of efficacy. On the other hand, there are complex WE with complex gearshifts that show the constant efforts required to attain perfections in energy gathering efficacy [12],[21][22].

To increase the FRTC, a number of strategies using a range of scientific methods have been proposed in this area [23][24]. They fall into two primary groups: (1) passive (PMs) and (2) active (AMs) approaches, both of which are thoroughly discussed in [25]. Instead of using costly tools of DFIG that was proposed in [26], appropriate converter governs were utilized in AMs to strengthen the FRTC in conjunction with a conventional crowbar circuit. One of PM's disadvantages is that installing more instruments raises expenses. A modified GSC control strategy was used to provide FRTC [27]. Similarly, it has been demonstrated that utilizing only traditional vector control techniques for converter regulation is more effective in meeting the grid code requirements [28]. Although these control techniques are simple, they cannot sustain the FRTC at large voltage sags (VDs) [29]. With the help of clever controllers, regulators were developed to ensure the FRTC during VDs [30], and they outperformed the PI controllers of the past. A linear controller was created to manage the after-fault situation [31]. Nevertheless, due to their numerical and theoretical difficulty, these methods are very challenging to implement in a DFIG system built on two series converters. Improved crowbar systems continue to be the dominant method because of its controllability and convenience of use [32][33]. Therefore, the goal of this effort is to cooperate with the GSA to design a crowbar system. To further demonstrate the efficacy of the suggested approach, three scenarios in four examples are examined.

## 2. METHODS

DFIGs have extra capabilities that allow them to function at speeds that are somewhat faster or slower than their inherent synchronous pace. This is advantageous for large DFIGs since wind speed may vary fast. The blades of a WT want to accelerate when hit by a gust, but because synchronous generators are synced to the speed of the power grid, they are unable to do so. The hub, gearbox, and generator all experience significant stresses when the electrical grid pushes back. The mechanism is harmed and worn down as a result. The strains are reduced and the wind gust's energy is transferred to usable electricity if the turbine is permitted to accelerate right away after being impacted by a gust [34]-[36].

Accepting the frequency that the generator produces, converting it to DC, and then using an inverter to convert it back to AC at the required output frequency is one method for allowing the speed of a WT to vary. This is typical of WTs used on farms and small homes. However, the size and cost of the inverters are needed for megawatt-scale WTs. DFIGs are one approach to this issue. Two stationary and one rotating three-phase windings are independently linked to the generator outside the equipment in place of the typical field winding fed with the DC and winding with the armature where the produced power exits. Hence, "doubly fed". Three-phase AC power is generated at the appropriate grid frequency by one winding, which is directly coupled to the output. The other winding, which is typically Known as the field, although in this instance, both might be outputs, is linked to 3-phase AC electricity with variable frequency. To account for fluctuation in the speed WT this i/p power is phased and frequency-adjusted. A converter from AC /DC /AC is needed for frequency change and phase. This is often built using extremely massive IGBT semiconductors. Because it is

bidirectional, the converter may transmit power in either way. Both the output winding and this winding are capable of supplying power can be seen in Figure 1 [37]-[39].

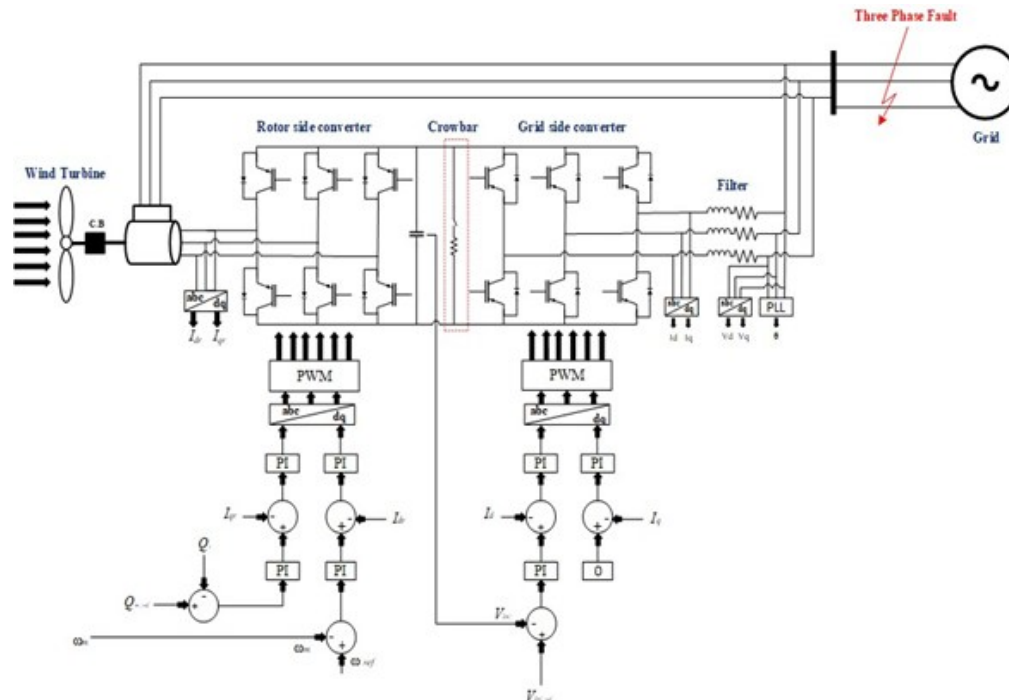


Figure 1. Addressed system

### 2.1. Power Conversion of DFIG

The rotor windings (RW) have been wired to a power converter, while stator winding (SW) is linked to the grid directly. To produce the stator magnetic field, the grid energizes the SWs. Create the rotor field magnetic, the converter energizes the RWs. The interaction of the stator magnetic fields with the rotor magnetic field produces torque. The two magnetic fields' combined strength and their relative angular displacement determine how much torque is produced. Because the stator is directly related to the grid, its field depends on the grid voltage, and its rotation depends on grid freq. & relates to the synchronous speed. Since the stator flux may be taken into consideration as constant. In steady state operation grid voltage can be considered to be relatively constant, which means the power converter directly manages the rotor flux will rotate. As a result, altering the rotor current's size and angle concerning the stator flux will directly affect how much torque is produced in the DFIG. The applied stator voltage in which magnitude of grid voltage and phase and managing the rotor current such that perpendicular to the stator flux and large enough to provide the necessary torque it is possible to calculate the angular position and stator flux [40]-[42].

### 2.2. Operation and control of RSC

Direct control of the rotor current is used to regulate the output torque. The RSC accomplishes this by supplying the rotor windings with a voltage that matches the desired current. The torque, P controllers on the RSC can be used to regulate the DFIG's output P. The torque, speed, or power is often controlled to their reference value using a PI controller. Regardless of the controller employed, its output is the desired rotor current necessary to provide the desired values. The controller output is the rotor voltage reference and the inner control loop of PI is used to bring the error of rotor current from a reference value. The rotor current can also be utilized to regulate the DFIG's ability to produce Q [43]-[45].

### 2.3. Operation and control of GSC

The DCLV is controlled by the GSC to keep it with accepted limit, GSC on the outer loop controls it. The GSC current is managed by a PI inner control loop. It is typical for the GSC to maximize the output P and set  $Q_{GSC} = 0$ . Due to the GSC's direct grid connection, it is required to provide power at a constant frequency that matches the grid frequency [46][47].

## 2.4. Mathematical Modelling

Figure 2(a) and Figure 2(b), shows the DFIG modes (super-synchronous ( $s$  is -tve), (b) sub-synchronous ( $s$  is +tve)). The DFIG model is presented in Eqs. (1) to Eqs. 21 and fully detailed in [48]-[51]. Figure 3 represents the DFIG circuit.

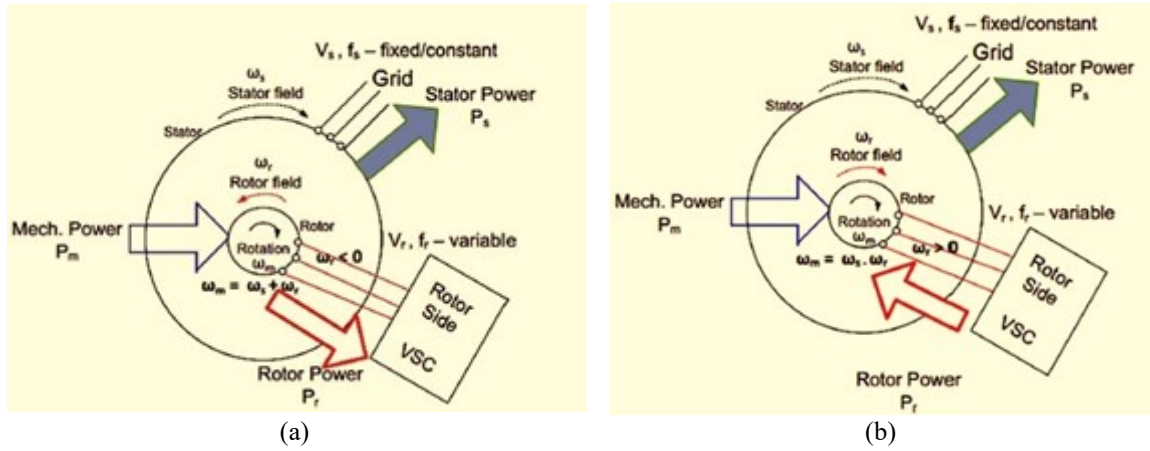


Figure 2. DFIG Modes: (a) super-synchronous, (b) sub-synchronous

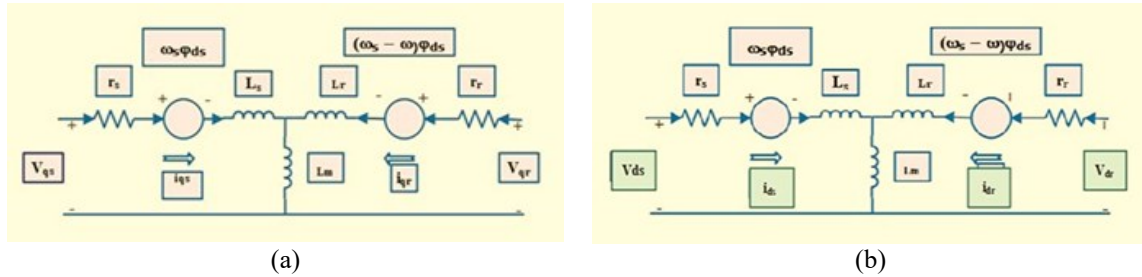


Figure 3. (a) d-q frame depicts both the d-q-axis comparable circuit, and (b) control system schematic diagram

$$v_{qs} = r_s i_{qs} + \frac{\omega}{\omega_b} \psi_{ds} + \frac{p}{\omega_b} \psi_{qs} \quad (1)$$

$$v_{ds} = r_s i_{ds} + \frac{\omega}{\omega_b} \psi_{qs} + \frac{p}{\omega_b} \psi_{ds} \quad (2)$$

$$v_{0s} = r_s i_{0s} + \frac{p}{\omega_b} \psi_{qs} \quad (3)$$

$$v'_{qr} = r'_r i'_{qr} + \left( \frac{\omega - \omega_r}{\omega} \right) \psi'_{qr} + \frac{p}{\omega_b} \psi_{qr} \quad (4)$$

$$v'_{dr} = r'_r i'_{dr} + \left( \frac{\omega - \omega_r}{\omega} \right) \psi'_{dr} + \frac{p}{\omega_b} \psi_{dr} \quad (5)$$

$$v'_{0r} = r'_r i'_{0r} + \frac{p}{\omega_b} \psi'_{0r} \quad (6)$$

$$\psi_{qs} = X_{Is} i_{qs} + X_M (i_{qs} + i'_{qr}) \quad (7)$$

$$\psi_{ds} = X_{Is} i_{ds} + X_M (i_{ds} + i'_{dr}) \quad (8)$$

$$\psi'_{0s} = X'_{Is} i_{0s} \quad (9)$$

$$\psi'_{qr} = X'_{lr} i'_{qr} + X_M(i_{qs} + i'_{qr}) \quad (10)$$

$$\psi'_{dr} = X'_{ls} i'_{dr} + X_M(i_{ds} + i'_{dr}) \quad (11)$$

$$\psi'_{0r} = X'_{ls} i'_{0r} \quad (12)$$

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{0s} \\ v'_{qr} \\ v'_{dr} \\ v'_{0r} \end{bmatrix} = \begin{bmatrix} r_s + \frac{p}{\omega_b} X_{ss} & \frac{\omega}{\omega_b} X_{ss} & 0 & \frac{p}{\omega_b} X_m & \frac{\omega}{\omega_b} X_m & 0 \\ \frac{\omega}{\omega_b} X_{ss} & r_s + \frac{p}{\omega_b} X_{ss} & 0 & \frac{\omega}{\omega_b} X_m & \frac{p}{\omega_b} X_m & 0 \\ 0 & 0 & r_s + \frac{p}{\omega_b} X_{ls} & 0 & 0 & 0 \\ \frac{p}{\omega_b} X_m & (\frac{\omega - \omega_r}{\omega_b}) X_m & 0 & r'_r + \frac{p}{\omega_b} X'_{rr} & (\frac{\omega - \omega_r}{\omega_b}) X'_{rr} & 0 \\ -(\frac{\omega - \omega_r}{\omega_b}) X_m & \frac{p}{\omega_b} X_m & 0 & -(\frac{\omega - \omega_r}{\omega_b}) X'_{rr} & r'_r + \frac{p}{\omega_b} X'_{rr} & 0 \\ 0 & 0 & 0 & 0 & 0 & r_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \\ i'_{qr} \\ i'_{dr} \\ i'_{0r} \end{bmatrix} \quad (13)$$

$$X_{ss} = X_{ls} + X_M \quad (14)$$

$$X'_{rr} = X'_{lr} + X_M \quad (15)$$

$$\psi_{qm} = L_m(i_{qs} + i'_{qr}) \quad (16)$$

$$\psi_{dm} = L_m(i_{ds} + i'_{dr}) \quad (17)$$

$$T_e = \frac{3}{2} \left( \frac{p}{2} \right) (\psi_{qm} i_{dr} - \psi_{dm} i_{qr}) \quad (18)$$

$$P_s = (v_{ds} i_{ds} + v_{ds} i_{ds}) \quad (19)$$

$$Q_s = (v_{qs} i_{ds} - v_{ds} i_{qs}) \quad (20)$$

$$T_s = \psi_{dr} i_{qs} - \psi_{qr} i_{ds} \quad (21)$$

## 2.5. Investigated optimizer

The mathematical model of the GSA is fully described and discussed in [52][53]. The GSA flowchart is presented in Figure 4.

$$F_G = \frac{Gm_1m_2}{r^2} \quad (22)$$

$$a = \frac{F}{M} \quad (23)$$

$$G(t) = G(t_0) \times \left( \frac{t_0}{t} \right)^\beta, \beta < 1 \quad (24)$$

$$F_{ij} = G \frac{M_{aj} \times M_{pi}}{R^2} \quad (25)$$

$$a_i = \frac{F_{ij}}{M_{ii}} \quad (26)$$

$$X_i = (X_i^1, \dots, X_i^d, \dots, X_i^n) \quad (27)$$

$$F_{ij}^d(t) = G(t) \frac{M_{pi(t)} \times M_{aj(t)}}{R_{ij}(t) + \varepsilon} (x_j^d(t) - x_i^d(t)) \quad (28)$$

$$R_{ij}(t) = \|X_i(t), X_j(t)\|_2 \quad (29)$$

$$F_i^d(t) = \sum_{j=1, j \neq i}^N rand_j F_{ij}^d(t) \quad (30)$$

$$a_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)} \quad (31)$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad (32)$$

$$v_i^d(t+1) = rand_i \times v_i^d(t) + a_i^d(t) \quad (33)$$

$$G(t) = g(G_0, t) \quad (34)$$

$$M_{ai} = M_{pi} = M_{ii} = M_i, \text{ and, } i = 1, 2, \dots, N \quad (35)$$

$$m_i(t) = \frac{[fit_i(t) - worst(t)]}{[best(t) - worst(t)]} \quad (36)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^N m_j(t)} \quad (37)$$

$$best(t) = \min_{j \in \{1, \dots, N\}} fit_j(t) \quad (38)$$

$$worst(t) = \max_{j \in \{1, \dots, N\}} fit_j(t) \quad (39)$$

$$F_i^d(t) = \sum_{j \in Kbest, j \neq i} rand_j F_{ij}^d(t) \quad (40)$$

Grid faults have a negative impact on DFIGs' responsiveness. These problems result in amplified DFIG (speeds, DCLV, and currents), torque fluctuations, and a decrease the P [54]-[56]. The DFIG's RSC is safeguarded by a crowbar, which also enhances the responsiveness of the system under grid failures. By using a crowbar, DFIG can sustain energy even in the event of a grid failure and weather the fault. For DFIG, the values of  $K_i$  and  $K_p$  are 0.05328. The controller's inputs are the values that are being watched and pointed to, and its output decides how to run the system while accounting for the sawtooth signal. Figure 5 shows the suggested crowbar control technique. The crowbar action can often be represented as in (41). The parameters for each of the subsequent equations are explained in detail [57]-[59].

$$V_C = F_S R_C I_C \quad (41)$$

$$T_r^{SC} = \left( \frac{L_r^{SC}}{R_r + R_{tc}} \right) \quad (42)$$

$$I_r^{max} = \left( \frac{V_r^{max}}{\sqrt{(X_r^{SC})^2 + (R_{tc})^2}} \right) \quad (43)$$

$$R_{tc} < \left( \frac{\sqrt{2} X_{rs}^{sc} V_r^{max}}{\sqrt{3.2 (V_s)^2 + 2 (V_r^{max})^2}} \right) \quad (44)$$



$$V_r = k m V_{DC}, \text{ and } k = \left( \frac{1}{\sqrt{3}} \right) \frac{V_{DC}^b}{V_r^b} \quad (45)$$

$$V_r^{max} = IR_{DC} - V_{DC} = 0 \quad (46)$$

The choosen objective function using the GSA is defined as follows :

$$OF = \int_0^T t |V_{dc(ref)} - V_{dc(act)} + P_{ref} - P_{act} + Q_{ref} - Q_{act}| dt \quad (47)$$

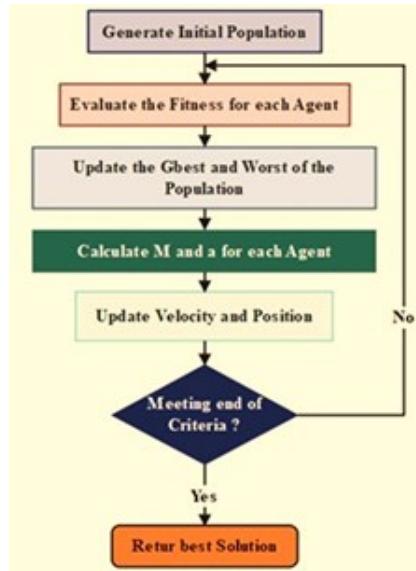


Figure 4. The GSA flowchart

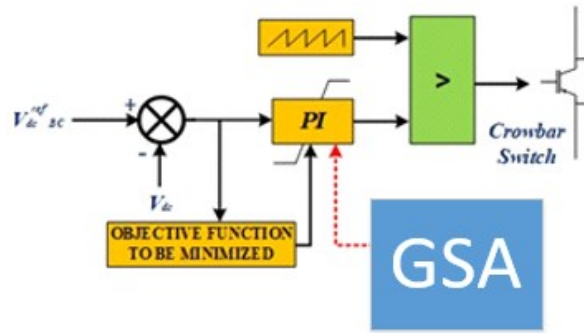


Figure 5. Proposed strategy

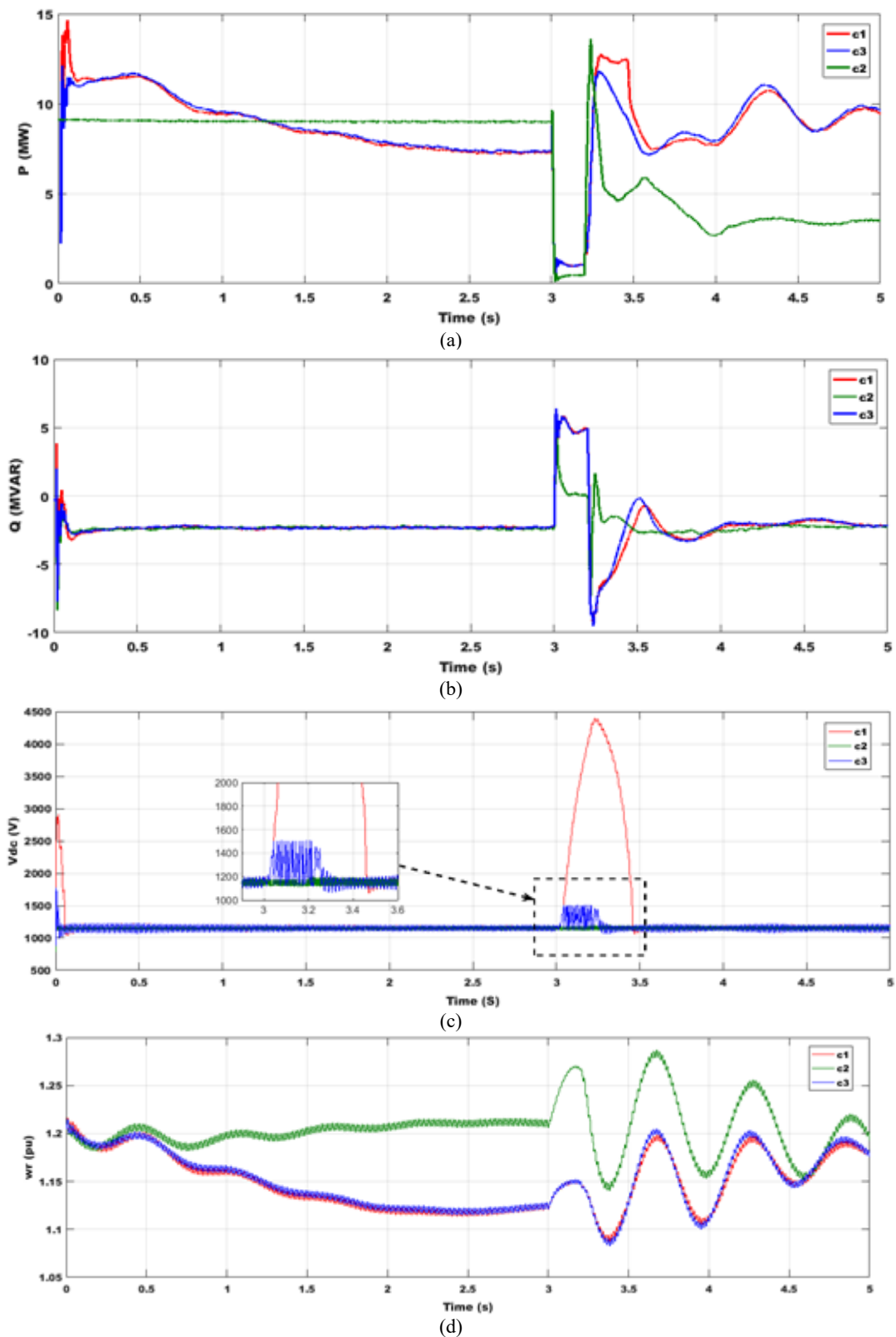
### 3. RESULT AND DISCUSSION

In order to demonstrate the function of the GSA approach, this study discusses the recital enhancement of DFIG under various scenarios. Three scenarios have been used to test different fault conditions (0.0 V, 0.3 V, 0.5 V, and 0.7 V) in order to demonstrate the influence of GSA. The scenarios are (C1) unprotected, (C2) with a traditional crowbar, and (C3) with an improved crowbar. To demonstrate how the suggested technique affects DFIG performance, all of (P, V<sub>DC</sub>, Q, ω<sub>r</sub>) are examined. To verify the effectiveness of the recommended approach, the analyzed DFIG is simulated using MATLAB/Simulink. The PCC is a crucial location to evaluate FRTC. The parameters of the system are mentioned in [60].

#### 3.1. Case 1: 100% Voltage Dip (VD)

As shown in Figure 6, a fault time of 200 ms is used to assess the effectiveness of the suggested strategy under a 100% VD. Part (a) shows that P declines with a fault, while parts (b), (c), and (d) show that Q, V<sub>DC</sub>, and ω<sub>r</sub> rise. To maintain V<sub>DC</sub> as shown in part (c), the crowbar is within the designated range. Overshoot of P

and oscillations in  $\omega_r$  are muffled. Nevertheless, spite of significant malfunctions, the DFIG manages to function as intended, according to the outcomes. Table 1 summarizes and lists all of the DFIG's fluctuations and alterations for the instances that are being studied.



**Figure 6.** System outcomes under case 1



### 3.2. Case 2: 70% VD

The suggested method is tested with a fault period of 200 ms under a 70% VD as depicted in Figure 7. In part (a), P falls at fault, whereas parts (b), (c), and (d) show a rise in Q,  $V_{DC}$ , and  $\omega_r$ . Part (c) shows the crowbar in order to maintain  $V_{DC}$  within the designated range. There is a muffled overrun of P and swings in  $\omega_r$ . The findings seen demonstrate that despite significant failures, the DFIG maintains to function as intended. A summary and list of DFIG's fluctuations and changes for the cases under investigation may be seen in Table 1.

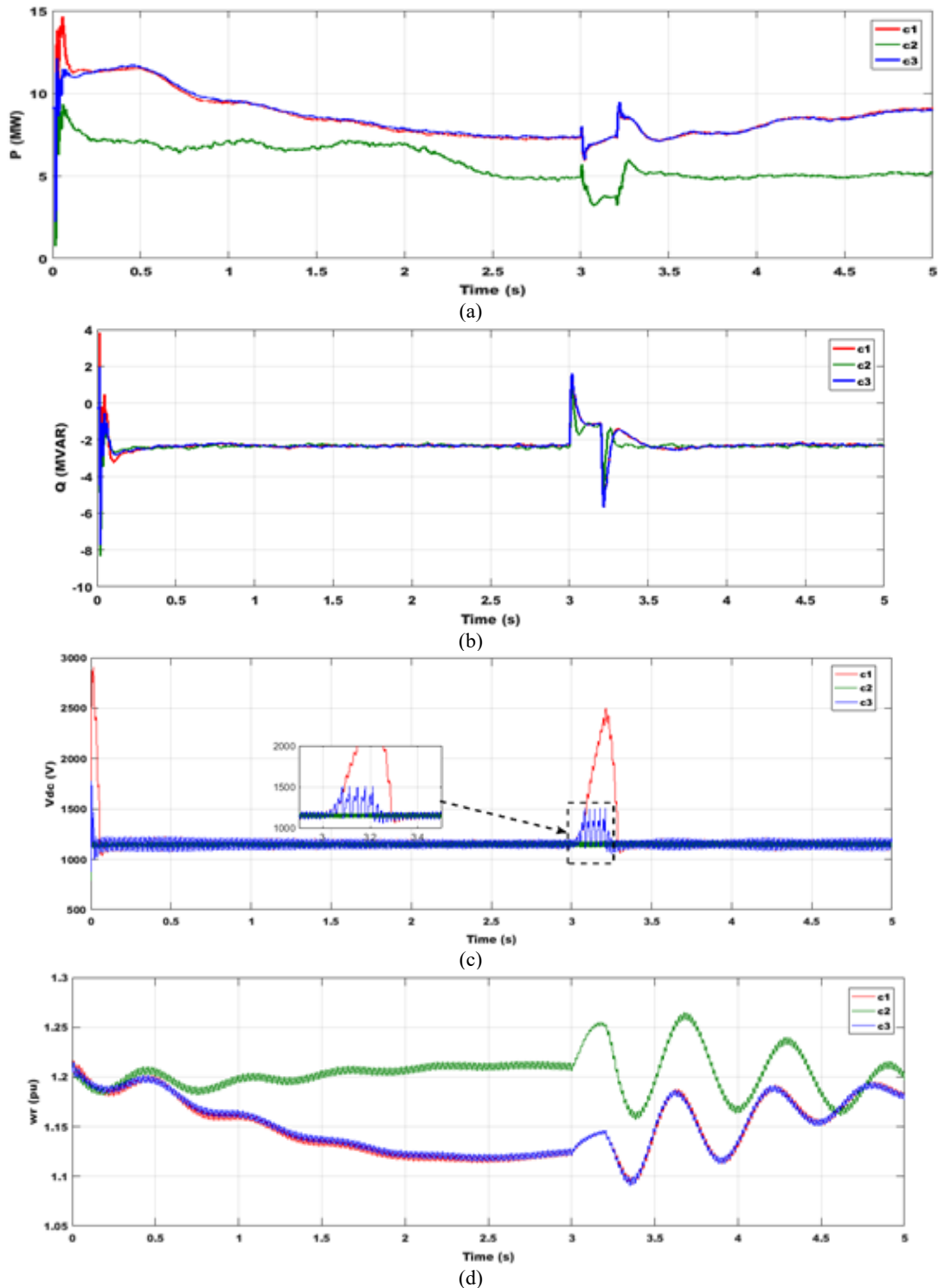


Figure 7. System outcomes under case 2

### 3.3. Case 3: 50% VD

For the evaluation of the suggested plan, the failure interval is 200 ms at a 50% VD as in Figure 8. Part (a) shows that  $P$  declines during a fault, while parts (b), (c), and (d) show that  $Q$ ,  $V_{DC}$ , and  $\omega_r$  rise. As shown in part (c), the crowbar was employed to maintain  $V_{DC}$  within the designated range. The overshoot of  $P$  and vibrations in  $\omega_r$  are muffled. The DFIG remains to function as intended, according to the actual simulation outcomes. Table 1 summarizes and lists the variances for the instances that are being studied.

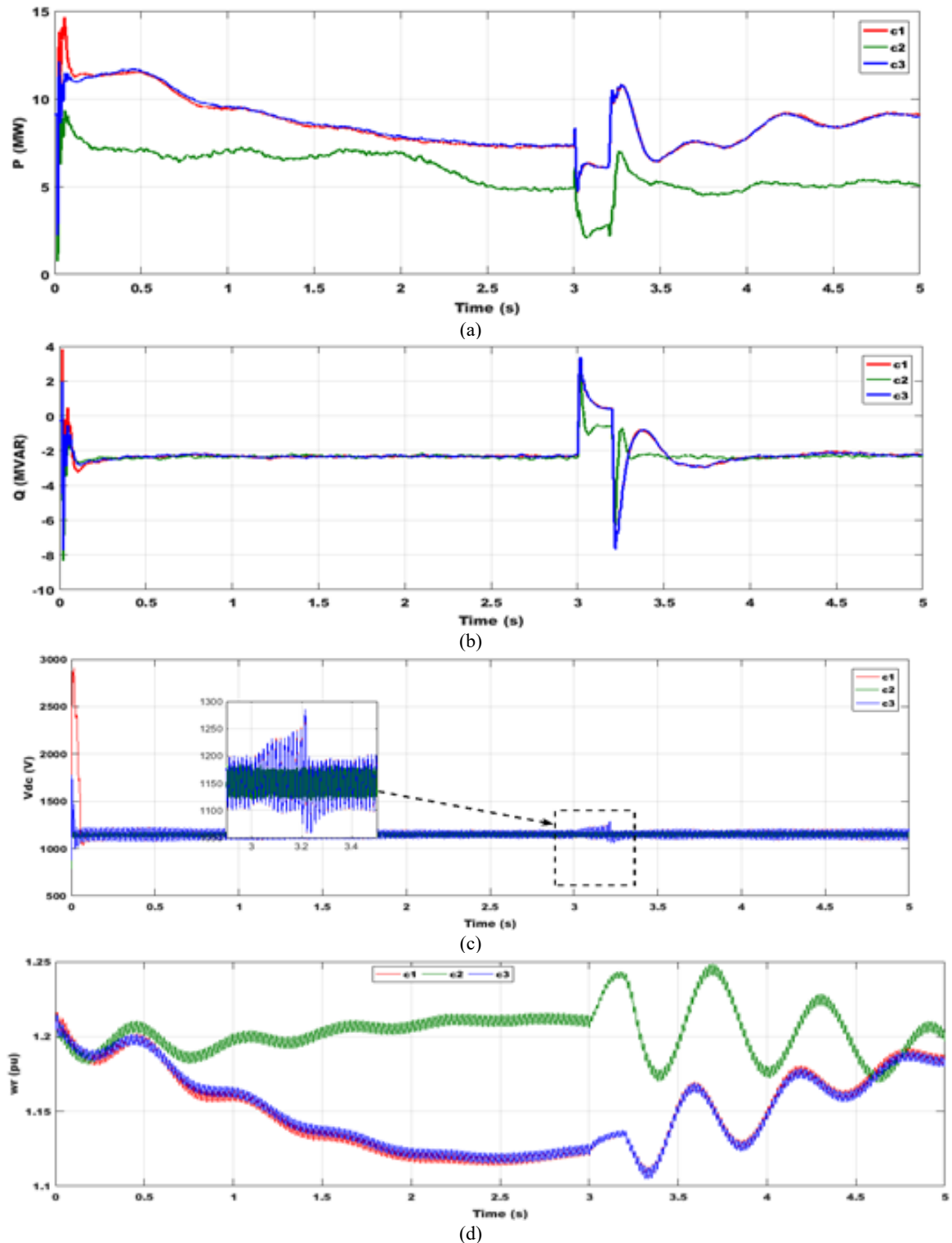


Figure 8. System outcomes under case 3

### 3.4. Case 4: 30% VD

To verify the suggested arrangement, a 30% VD interval of 200 ms is used as in Figure 9. Part (a) shows that  $P$  declines at a malfunction, while parts (b), (c), and (d) show that  $Q$ ,  $V_{DC}$ , and  $\omega_r$  rise, respectively. As shown in part (c), the crowbar is used to maintain the  $V_{DC}$  at the acceptable values. When any changes in  $\omega_r$  and  $P$  overshoot were suppressed, the proposed technique performs well. when the FRTC has been attained and a problem has been fixed before  $Q$  is pumped. Even in the face of significant errors, the DFIG maintains to function as intended, according to the reported simulated outcomes. Table 1 summarizes and lists the outcomes.

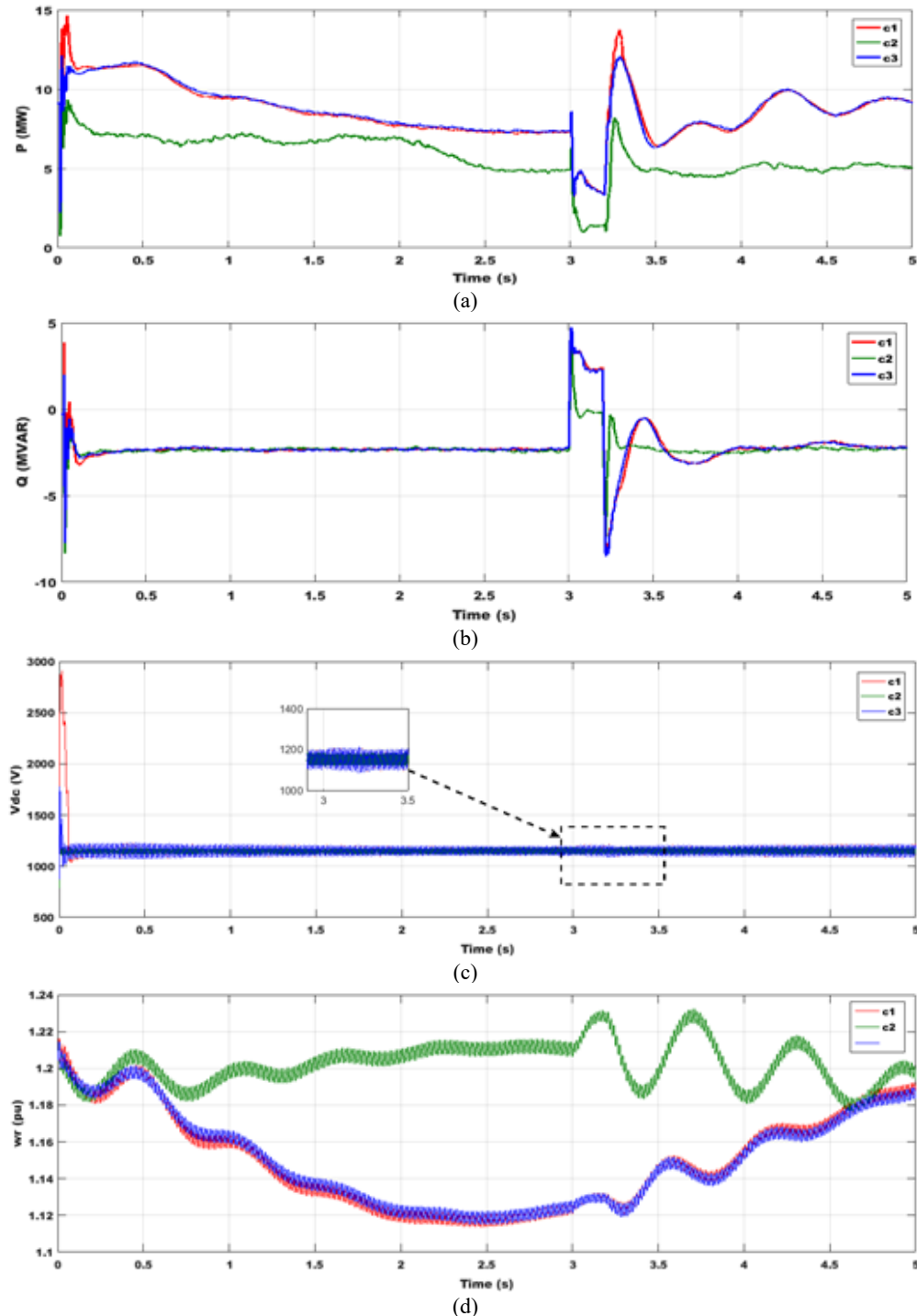


Figure 9. System outcomes under case 4

**Table 1.** Performance of DFIG under investigated scenarios

Parameters	100% VD			70% VD			50% VD			30% VD		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
p	0.5	0.2	0.5	3.5	2	3.5	4.8	3.5	4.8	6	4.1	6
Q	6.1	5	6.1	5	4	5	3.5	3	3.5	1.5	1	1.5
$V_{DC}$	4490	1200	1500	2500	1190	1500	1200	1175	1200	1200	1175	1200
$\omega_r$	1.15	1.27	1.15	1.148	1.25	1.148	1.14	1.24	1.14	1.13	1.23	1.13

#### 4. CONCLUSIONS

The idea presented in this paper concerns the DCLV control of a DFIG, where power converters are costly. It was focused on crowbar control which permits to mitigation of overvoltage at the DCL which could be produced under faults. As given in the introduction section, the structure of the proposed strategy allows us to overcome the weak points of recent methods described previously. This is for the reason that it ensures robustness under the presence of faults as demonstrated through the obtained outcomes. The GSA proves its role in helping the crowbar to operate efficiently. The developed method is based on simple formulas and it was insensitive to sensors' noises and offsets. Utilizing optimization based on the GSA, the PI controller for a DFIG was optimized. It was discovered that the controller parameters produced using GSA have smaller overshoot, settling time, and rising time. In addition to improving system responses, the GSA-based controller significantly supports the wind system to achieve FRTC.

#### DECLARATION

##### Author Contribution

All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

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This research received no external funding.

##### Conflicts of Interest

The authors declare no conflict of interest.

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