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Improvement of LVRT Capability for DFIG based WECS by Optimal Design of FoPID Controller using SLnO + GWO Algorithm

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Abstract: One of the wind energy industry's fastest-growing technologies is the doubly fed induction generator (DFIG). Wind energy resources (WER) must be connected to the network both during and after grid voltage disturbances, according to the most recent grid codes. For improving the low-voltage ride through (LVRT) capability of DFIG without an additional hardware equipment during voltage sag, a control strategy is developed in this research, which is based on fractional order proportional integral derivative (FoPID) controller. A sea Lion adapted grey wolf optimized (SLnO+GWO) hybrid algorithm is employed for optimal selection of controller parameters. Consequently minimizes the variations in active, reactive powers, rotor current harmonics and dc link voltage in DFIG. Furthermore the proposed method is simulated in MATLAB/SIMULNK and has 2.56% THD in rotor current whereas existing methods has more. The performance of chosen method is compared with the methods available in literature RTO, MEHRFA, GSA and is found to be superior.

Keywords: DFIG, FoPID controller, Gravitational search algorithm (GSA), Grey wolf optimization (GWO), Low voltage ride through (LVRT), Modified elephant herding random forest algorithm (MEHRFA), Root tree optimization (RTO), Sea lion optimization (SLnO).

1. Introduction

Doubly fed induction generator (DFIG) oriented wind turbine (WT) systems have raised as a most important technology in WTs industries, revealing that it is a consistent, gainful and efficient solution. The wind energy resources (WER) must be connected to the grid after and during faults in accordance with the most recent grid codes [1-3]. The capacity to ride through low voltage is commonly referred to as LVRT [4, 5]. The DFIG must endure synchronism through faults for certain duration in the form of national grid code is LVRT. Normally, LVRT have two strategies. (a) LVRT for wind farm or PV power plants (b) grid connected micro-grid. DFIG are most famous wind turbine system for the reason of higher energy efficiency, variable speed, cost, etc [6-8]. In addition, DFIG is much susceptible to network interruptions as the DFIG stator is linked to the network in a direct manner. As a result, LVRT capability for DFIG needs further analysis. DFIGs require more complicated start-up process when compared to AC generators, since it produces inadequate AC voltage for supplying the rotor winding. Further, additional difficulty arises from the usual performance of DFIG itself [9]. While supplying the rotor with low size back-to-back converters, the DFIG should be maintained with a rotor speed lesser than ±30% of speed. Hence, it is necessary to utilize an exterior acceleration method to start-up if the rotating speed is nearer to zero [10-12].

Diverse controlling policies are developed in the past twenty years for grid-tied modes of DFIG [13, 14]. Among them, the stator reactive and active

Table 1. Reviews on DFIG models: Conventional Techniques

Author	Implemented methods	Features	Challenges
[24]	Crowbar resistance protection scheme	❖ Improved rotor speed ❖ Reduced time consumption	❖ Detailed economic analysis is not performed. ❖ FACT devices are not integrated.
[25]	RTO model	❖ Enhanced dynamic performance ❖ Minimizes the harmonic currents	❖ Convergence factors are not much concentrated
[26]	Nonlinear control theory	❖ Better handling of unbalanced line faults ❖ Increased internal dynamics	❖ Fluctuations occur due to noise.
[27]	FLC	❖ High stability ❖ Enhanced power quality	❖ Practical implementation is not carried out.
[28]	Crowbar based model	❖ Eliminates the oscillations ❖ Minimal time	❖ Voltage sags may occur.
[29]	Fuzzy controller	❖ Improved robustness ❖ Minimal error	❖ Invariant behaviours occur with variation in rotor speed.
[30]	HSPM model	❖ Ensures better tracking ❖ Reduced mechanical loads	❖ Loss occurs in actual turbines.
[31]	Kalman filter	❖ Minimized transient rotor current ❖ Removes faults	❖ Line to ground issue is not considered.

power oriented controlling techniques were mostly discussed. Numerous random search techniques, AI methods and meta-heuristic techniques such as stochastic Komodo algorithm (SKA) [15], Fixed step average and subtraction based optimizer (FS-ASBO) [16], mixed leader based optimizer for solving optimization problems (MLBO) [17], three influential members based optimizer (TIMBO) [18], random selected leader based optimizer (RSLBO) [19], puzzle optimization algorithm (POA) [20], ring toss game-based optimization algorithm (RTGBO) [21] are deployed to improve the control of DFIG. In addition modified elephant herding random forest algorithm (MEHRFA) [22], particle swarm optimization (PSO), bacterial foraging optimization (BFO), and gravitational search algorithm (GSA) [23] are broadly used to appropriate tuning of diverse controller constraints. Moreover, PID controllers usually exploited in industries to be reliable and efficient, however they require an excellent tuning of their gains so as to discover the fine compromise among speediness and accuracy.

This research work proposes an optimal design of FoPID controller based on SLnO+GWO algorithm to enhance LVRT capability during voltage sag without need of auxiliary hardware consequently for minimizing the variations in active and reactive powers, rotor current harmonics and to stabilize the DC link voltage of DFIG.

The paper is organized as follows: literature is presented in section 2. Modelling of DFIG based wind turbine described in section 3 and section 4 presents optimal design of FoPID controller with SLnO+GWO algorithm. Results & discussions are presented in section 5 and conclusion are provided in section 6.

2. Literature review

2.1 Review

Table 1 shows the reviews on conventional DFIG systems. At first, crowbar resistance protection scheme was introduced in [24] that offers high rotor speed and it also offers reduced time consumption. However, detailed economic analysis is not performed. RTO model was exploited in [25] that offers minimal harmonic currents with enhanced dynamic performance, but it has to analyse more on convergence factors. Nonlinear control theory was used in [26] that provide better handling of unbalanced line faults and it also offers high internal dynamics. However, fluctuations occur due to noise. In addition, FLC was implemented in [27] that attain high stability along with enhanced power quality; nevertheless, practical implementation is not carried out. Crowbar based model presented in [28] eliminates the oscillations and it consumed minimal time; however voltage sags may occur. Moreover, fuzzy controller was implemented in [29] that provide high robustness along with minimal error. Nevertheless, invariant behaviours occur with variation in rotor speed. In addition, HSPM model was suggested in [30] which offer better tracking with reduced mechanical loads. However, loss occurs in actual turbines. Kalman filter was introduced in [31] which minimize the transient rotor current and removes faults, however, Line to ground issue is not considered.

To counter the challenges listed in literature a SLnO+GWO algorithm is proposed to enhance LVRT capability during voltage sag without need of auxiliary hardware.

3. Proposed DFIG based wind turbine modelling

The generator dynamic model is modelled in Eq. (1) and Eq. (2), by deploying the park transformation [32-34].

$$\left.\begin{aligned} V_{sd} &= i_{sd}R_s + \frac{d}{dt}\varphi_{sd} - \varphi_{sq}\omega_s \\ V_{sq} &= i_{sq}R_s + \frac{d}{dt}\varphi_{sq} - \varphi_{sd}\omega_s \\ V_{rd} &= i_{rd}R_r + \frac{d}{dt}\varphi_{rd} - (\omega_s - \omega)\varphi_{rq} \\ V_{rq} &= i_{rq}R_r + \frac{d}{dt}\varphi_{rq} - (\omega_s - \omega)\varphi_{rd} \end{aligned}\right\} \quad (1)$$

The rotor and stator fluxes are formulated as per Eq. (2) [35, 36].

$$\left.\begin{aligned} \varphi_{sd} &= i_{sd}L_s + Ni_{rd} \\ \varphi_{sq} &= i_{sq}L_s + Ni_{rq} \\ \varphi_{rd} &= i_{rd}L_r + Ni_{sd} \\ \varphi_{rq} &= i_{rq}L_r + Ni_{sq} \end{aligned}\right\} \quad (2)$$

The EM torque, T_e is modelled as shown in Eq. (3). The mechanical modelling of DFIG is shown in Eq. (4).

$$T_e = \rho\, N(i_{rd}i_{sq} - i_{rq}i_{sd}) \quad (3)$$

$$T_e - T_r = I\,\frac{d\Omega}{dt} + F\Omega \quad (4)$$

The proposed method specifications are represented in Table 2.

Table 2. DFIG based WT parameters

Symbol	Parameter	Value
P_r	Rated Power	9 MW
V_r	Rated Voltage	575 V
f	Grid frequency	60 Hz
R_s	Stator Resistance	0.023 p.u.
R_r	Rotor resistance	0.016 p.u.
L_s	Stator inductance	0.18 p.u.
L_r	Rotor inductance	0.16 p.u.
N	Mutual inductance	2.9 p.u.
I	Inertia	0.685 p.u.
V_{dc}	Nominal DC voltage	1150 V

4. Optimized FoPID controller using SLnO+GWO algorithm

4.1 Optimized FoPID control

The proposed FoPID controller for DFIG is shown in Fig. 1. Numerous methods have been developed for adjusting the gain parameters of the FoPID controller in order to resolve the system's issues. Proposed SLnO+GWO algorithm used to optimize the FoPID controller parameters. Eq. (5) demonstrates the formulation of the basic operator ${}_aW_t^{\alpha}$, here $\alpha\epsilon\Re$ point outs the order of operation [37].

$${}_aW_t^{\alpha} = \begin{cases} \frac{d^{\alpha}}{dt^{\alpha}}\,, & \alpha > 0 \\ 1, & \alpha = 0 \\ \int_a^t (d\tau)^{-\alpha}, & \alpha < 0 \end{cases} \quad (5)$$

Eq. (6) shows RL description that deploys the Gamma function $\Gamma(.)$, in which n refer to 1st integer that was larger than operation order α. Furthermore, the RL description for FoPID is specified in Eq. (7).

$${}_aW_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)}\frac{d^n}{dt^n}\int_a^t \frac{f(\tau)}{(t-\tau)^{\alpha-n+1}}d\tau \quad (6)$$

$${}_aW_t^{\alpha} f(t) = \frac{1}{\Gamma(\alpha)}\int_a^t (t-\tau)^{\alpha-1} f(\tau)d\tau \quad (7)$$

The Laplace transformation of Eq. (6) is specified in Eq. (8), here $\ell\{.\}$ stand for the Laplace operator.

$$\int_0^{\infty} {}_0W_t^{\alpha} f(t)\, e^{-St}dt = S^{\alpha}\ell\{f(t)\} - \sum_{K=o}^{n-1} S^K\, {}_0W_t^{\alpha-K-1} f(t)|_{\,t=0} \quad (8)$$

The transfer function of FoPID $Y(s)$ is indicated by Eq. (9), here K_p, K_i, & K_d denotes proportional, integral and derivative gain correspondingly. In addition, λ and μ point out the fractional integrator and differentiator orders correspondingly.

$$Y(s) = K_p + \frac{K_i}{S^{\lambda}} + K_d S^{\mu} \quad (9)$$

4.2 Objective function and solution encoding

This work intends to make specific enhancements in FoPID controller design for enhancing LVRT capability in DFIG, consequently to minimize

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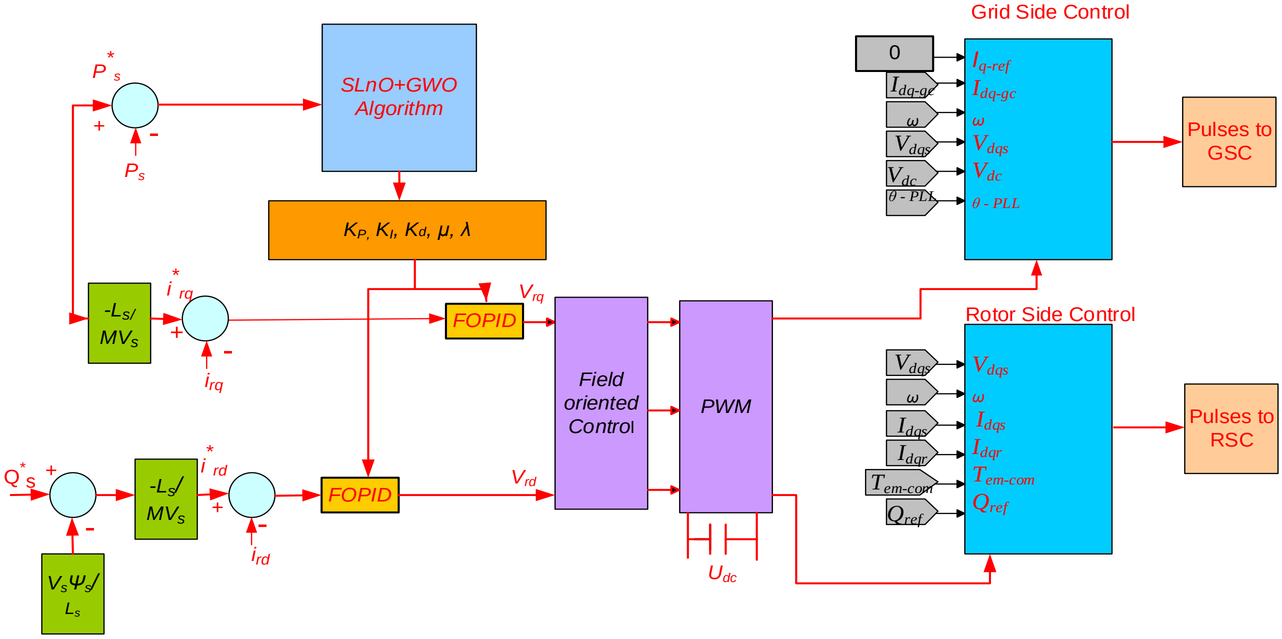

Figure. 1 Proposed FoPID controller for DFIG

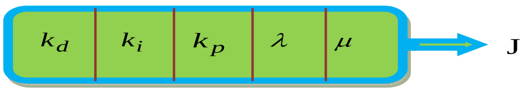

Figure. 2 Solution encoding

harmonics and for mitigating the variations in DC-link voltage during abnormal conditions of grid-voltage. Therefore, the dynamic performance of DFIG is enhanced by its improved LVRT capability. With regard to LVRT conditions, the WT equipped with DFIG should satisfy the conditions (C_1 and C_2) given in Eq. (12) and Eq. (13). In Eq. (12) and Eq. (13), the acceptable range of voltage deviations in DC-link is limited to ±15% of its rated value [38 - 40].

$$V_{max} = |V_{dc-max} - V_{dc-ref}| \quad (10)$$

$$V_{min} = |V_{dc-min} - V_{dc-ref}| \quad (11)$$

$$C_1 = |V_{dc-max} \leq 1.15 \times V_{dc-ref}| \quad (12)$$

$$C_2 = |V_{dc-min} \geq 0.85 \times V_{dc-ref}| \quad (13)$$

The fitness function taken into consideration is Integral time absolute error.

$$ITAE = \int_0^t t\,(|\Delta P| + |\Delta Q| + |\Delta I|)dt \quad (14)$$

Where $\Delta P = P_{ref} - P_{actual}$, $\Delta Q = Q_{ref} - Q_{actual}$ *and* $\Delta I = I_{ref} - I_{actual}$ are the error values between actual & set values of stator active power, reactive power and rotor current respectively.

To attain an optimal control, the FoPID parameters are tuned by means of a new SLnO+GWO algorithm. The solution given to the implemented scheme is illustrated by Fig. 2, in which K_d, K_i, K_p, λ and μ are the gain parameters FoPID controller.

4.3 Proposed algorithm

The proposed work hybridises the concepts of SLnO [41] algorithm and GWO algorithm [42] by considering the enhanced qualities into account like good stability, flexibility and speed of convergence. The proposed method SLnO+GWO algorithm enhances the tuning process more precise, which helps in attaining better performance of controller. According to [43], hybrid evolutionary algorithms carry the potential for addressing various search issues.

In general there are four types of wolves α, β, γ and ω in which the first three are the most significant wolves in terms of the hunting process. where α is the leader and in-charge of making judgments on hunting procedures, sleeping locations, and waking times, among other, while the 2nd and 3rd levels β and γ assist α in making decisions. As a result, the wolf's last level ω is focused on feeding.

Encircling behaviour is modelled in Eq. (15) and Eq. (16), Where D_p is the prey distance vector, D is the wolves distance vector, and it is the current iteration.

Modelling for G and U shown in Eq. (17), Eq. (18).

Here b is a constant decreased from 2 to 0 for next iterations. Here, r_{a1} and r_{a2} points out the random

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vectors amongst [0, 1] and it_{max} point out the maximum iterations.

$$Z = \left|F.\ J_p\,(it) - J(it)\right| \quad (15)$$

$$J(it+1) = J_p(it) - G.Z \quad (16)$$

$$G = 2\hat{b}\ .ra_1 - \hat{b} \quad (17)$$

$$U = 2\ ra_2 \quad (18)$$

The mathematical modelling for wolves hunting behaviour is specified in Eq. (19) to Eq. (23), Eq. (24) represents modelling equation for update position.

$$Z_\alpha = \left|U_1\,J_\alpha - J\right| \quad (19)$$

$$Z_\beta = \left|U_2\,J_\beta - J\right| \quad (20)$$

$$Z_\gamma = \left|U_3\,J_\gamma - J\right| \quad (21)$$

$$J_1 = J_\alpha - G_1.(Z_\alpha) \quad (22)$$

$$J_2 = J_\beta - G_2.(Z_\beta) \quad (23)$$

The proposed evaluation takes place while computing the J_3 and is evaluated based on 3rd grey wolve. However, as per the proposed model, the computation of J_3 takes place based on the update equation of attacking phase in SLnO algorithm as given by Eq. (24), where $\vec{M}(it) - \vec{J}(it)$represents the position vector between sea lion and target prey, l points out the random value between [-1, 1]**.**

$$J_3 = \left|\vec{M}(it) - \vec{J}(it).Cos(2\pi l)\right| + \vec{M}(it) \quad (24)$$

$$J(it+1) = \frac{J_1 + J_2 + J_3}{3} \quad (25)$$

The Algorithm for proposed SLnO+GWO scheme is Algorithm 1.

5. Results and discussion

The proposed method was simulated in MATLAB/SIMULINK and the results were accomplished when the voltage sag of 0.5pu is created from time t=0.03s-0.13s. Analysis on various parameters was carried out and the proposed approach superiority was proved over the method available in literature RTO+PI [25].

Algorithm 1: Algorithm for proposed method

Initialization
Compute the fitness of all search agents
Assign J_α as best search agents
Assign J_β as 2nd best search agents
Assign J_γ as 3rd best search agents
While ($it < it_{max}$)
    For every wolf
        Determine J_3 based on the update equation of attacking phase in SLnO algorithm as per Eq. (24)
        Update position as in Eq. (25)
    End for
    Update $\hat{b}$, G and U
    Compute the fitness of all search agents
    Update J_α, J_β and J_γ
    $it = it + 1$
End while
Return J_α

Fig. 3 describes the dc link voltage waveforms using SLnO+GWO + FoPID controller over existing method with respect to time. As per the LVRT condition, the acceptable deviations in dc-link voltage should be restricted to ±15% of $V_{dc\text{-}ref}$. Here, the value of $V_{dc\text{-}ref}$ is set at 1150 Volts. When the voltage sag of 0.5pu is created from time t=0.03s-0.13s the existing method produces large variations in dc link voltage, whereas the proposed method has less variations. On analysing the Fig. 3 Proposed model has accomplished the LVRT conditions in an efficient way. Thus, the enhancement of adopted SLnO+GWO algorithm + FoPID model is proved.

The analysis on rotor current for proposed method over existing approach with respect to time is revealed in Fig. 4. On examining the graph, the rotor current attained using the adopted model shows minimal oscillations whereas the existing method has more oscillations. Moreover, the maximal acceptable rotor current is effectively regulated within ±1.5 pu using the SLnO + GWO algorithm + FoPID controller. As a result, there are no possibilities of over currents in rotor winding of DFIG during the grid voltage sag.

The analysis on stator active power attained by the adopted SLnO + GWO algorithm + FoPID model over existing model with respect to time is revealed in Fig. 5. At time t=0.03s a voltage sag of 0.5pu is created due to which stator active power produced by DFIG is decreased and the system is recovered after time t=0.13s. Thus, the enhancement of LVRT capability using adopted model is proved. Fig. 6 illustrates reactive power waveform.

Fig. 7 illustrates the analysis on stator current for proposed SLnO + GWO algorithm + FoPID

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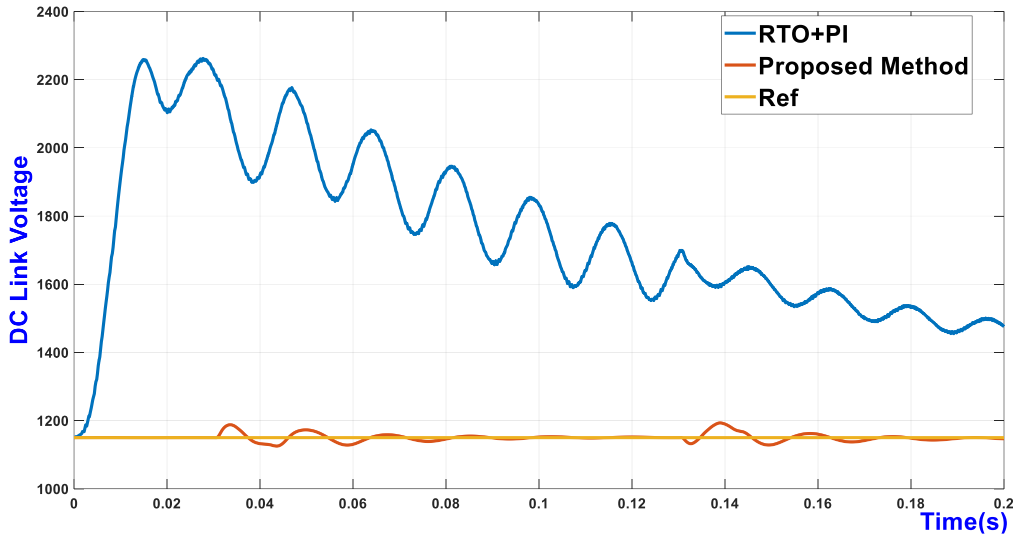
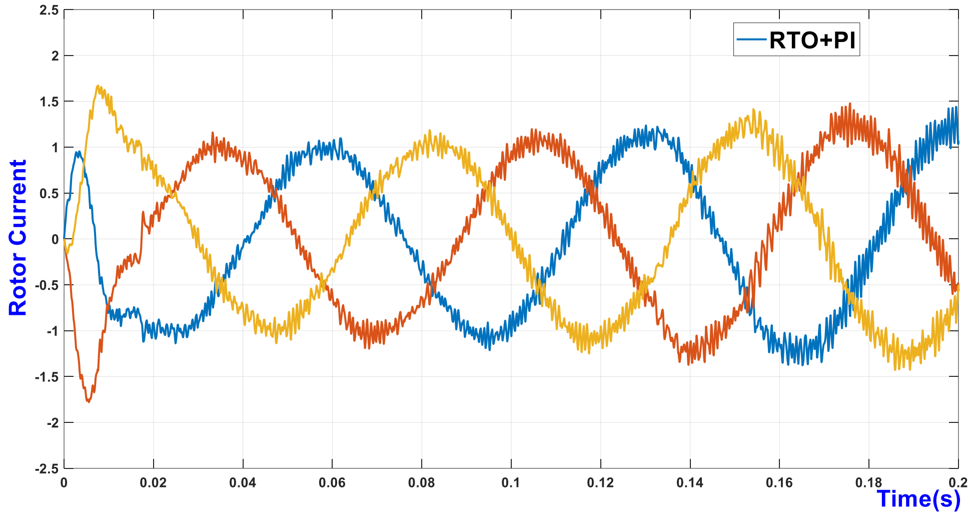
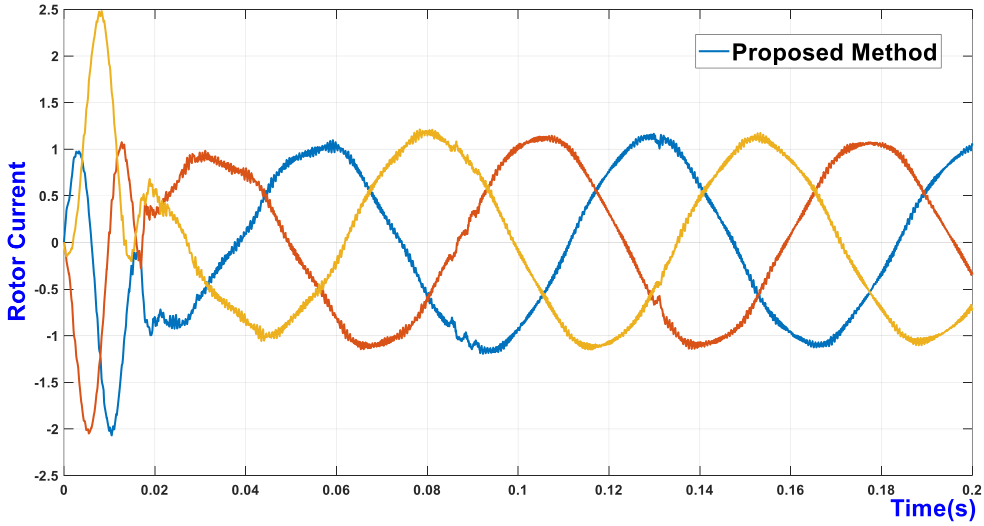


Figure. 3 DC link voltage waveform for RTO+PI and proposed method when voltage sag of 0.5pu is created from time t=0.03s-0.13s.



(a)



(b)

Figure. 4 Rotor Current waveform attained by: (a) RTO+PI and (b) Proposed method with respect to time when voltage sag of 0.5pu is created from time t=0.03s-0.13s.

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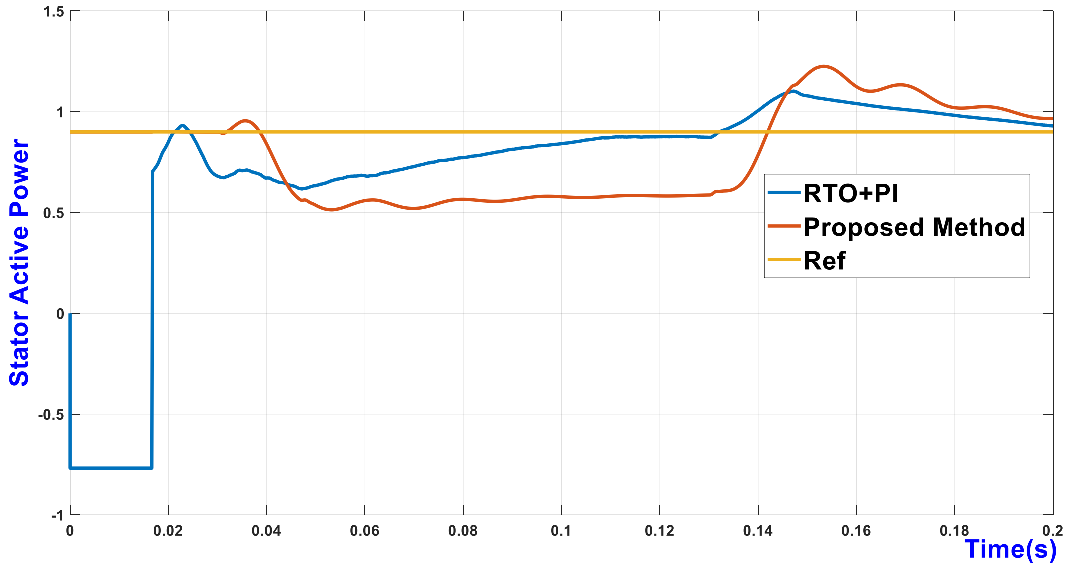


Figure. 5 Stator active power waveform attained by RTO+PI and proposed method with respect to time when voltage sag of 0.5pu is created from time t=0.03s-0.13s.

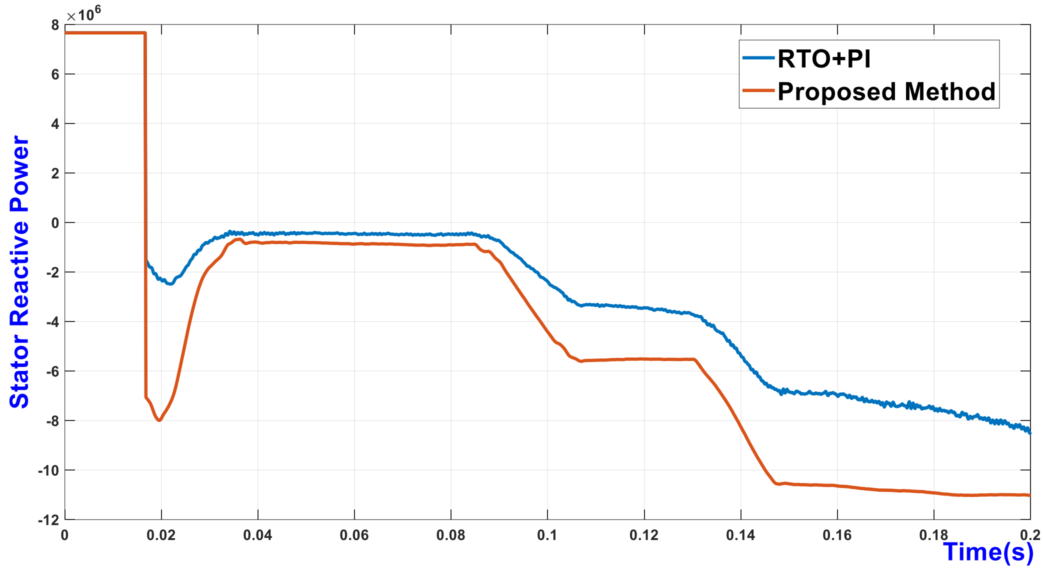
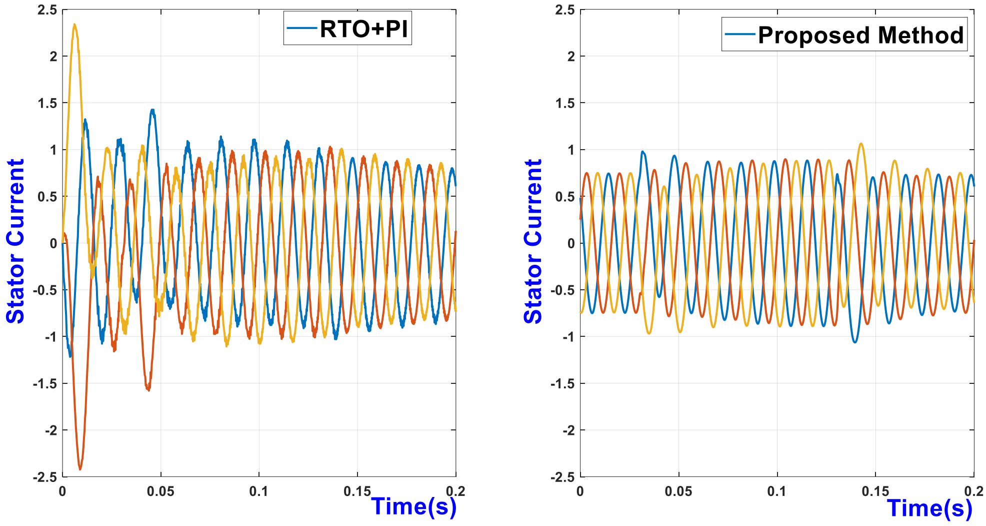


Figure. 6 Stator reactive power waveform attained by RTO+PI and proposed method with respect to time when voltage sag of 0.5pu is created from time t=0.03s-0.13s

model over existing model with respect to time. From the outcomes, the proposed method is found to have satisfied the LVRT criteria, i.e. the stator current lies within ±1.5 p.u, whereas, the conventional scheme have exceeded ±1.5 p.u and violated the required LVRT criteria. In addition, the oscillations of stator current attained using proposed model is minimal when compared to the existing approach.

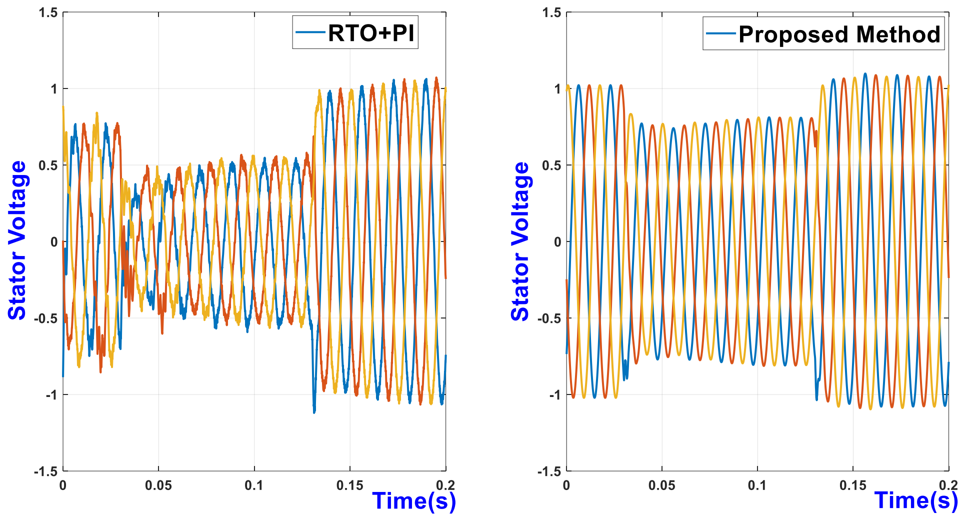
The analysis on stator voltage for the proposed scheme SLnO + GWO algorithm + FoPID as well as the RTO+PI scheme is revealed in Fig. 8. On observing the outcomes, the proposed scheme lies within 1pu and shows minimal oscillations. On the other hand, the compared model has shown higher oscillations than the presented model. Fig. 9 illustrates stator voltage waveform of DFIG under voltage sag of 0.5pu. On observing the outcomes during voltage sag the DFIG was effectively enhanced the LVRT capability as compared to RTO+PI.

Fig. 10 presents the THD spectrum for the proposed method & RTO+PI controller. For improved controller performance, the suggested scheme's THD should be kept to a minimum. Thus, minimal THD refers to minimal oscillation of the signal. Analysis of the results revealed in Table 3 the proposed method had a minimum THD value of 2.56% and confirming its superiority in terms of THD.



(a) (b)

Figure. 7 Stator current waveform for: (a) RTO+ PI and (b) proposed method with respect to time when voltage sag of 0.5pu is created from time t=0.03s-0.13s



(a) (b)

Figure. 8 Stator voltage waveform attained by: (a) RTO+ PI and (b) proposed method with respect to time when voltage sag of 0.5pu is created from time t=0.03s-0.13s

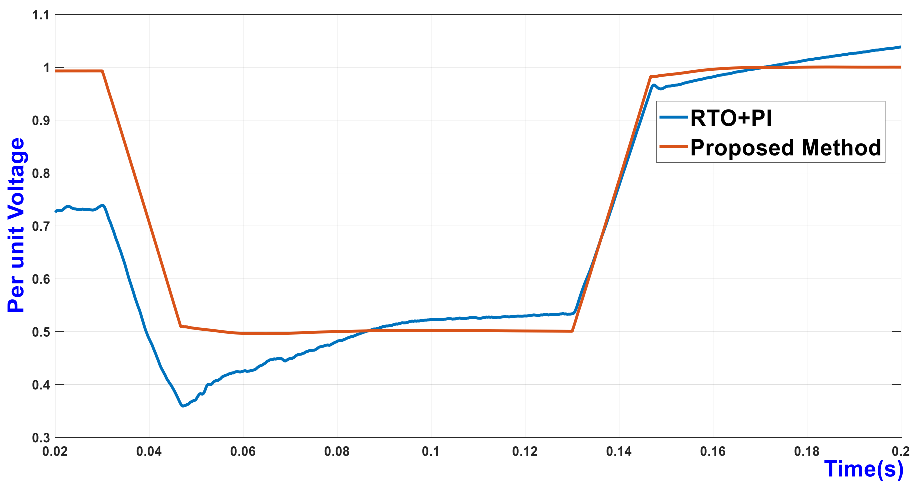


Figure. 9 Stator voltage waveform attained by: (a) RTO+PI and (b) proposed method when voltage sag of 0.5pu is created from time t=0.03s-0.13s

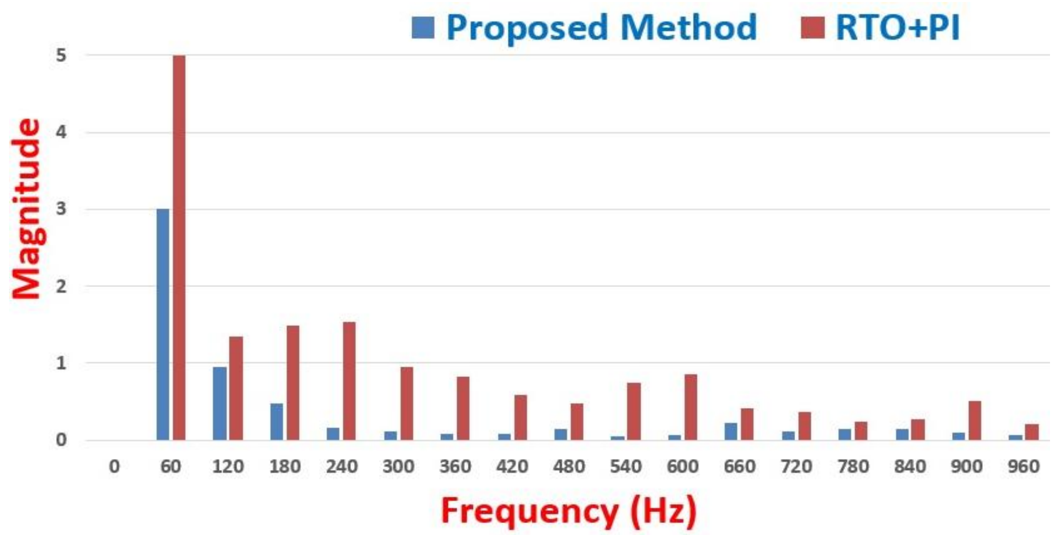


Figure. 10 THD spectrum of the rotor current using proposed method & RTO+PI controller

Table 3. THD of rotor current

Method adopted	% THD
MEHRFA [22]	3.36
GSA [23]	3.45
RTO [25]	3.21
Proposed	2.56

Table 4. Optimal gain parameters

Gain parameters	Proposed method	RTO + PI
k_p	4.8135	160.91
k_i	63.541	14.6
k_d	1	0
μ	0.049006	0
λ	0.27088	0

Table. 4 illustrates optimal gain parameters attained by proposed method & RTO+PI controller.

6. Conclusion

This work examines the effectiveness of proposed control method SLnO+GWO based FoPID controller for DFIG based WECS. The result shows that SLnO+GWO based FoPID controller performs more effectively than RTO+PI for improving LVRT under grid voltage sag without need of any auxiliary hardware. When voltage sag of 0.5pu is created from time t=0.03s-0.13s, the proposed approach was minimized the variations in reactive and active powers in DFIG and also stabilised the DC link voltage at 1150V. Moreover, the harmonic currents that mainly occurred in rotor current in a DFIG were minimized to 2.56% which is less than the RTO, MEHRFA, GSA methods. Finally, the effectiveness of the proposed model was evaluated over the methods available in literature. Thus, the enhancement of the proposed scheme has been validated effectively.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

The paper background work, conceptualization, methodology, implementation, result analysis and comparison, preparing and editing draft have been done by 1st author. The supervision, review of work, have been done by 2nd and 3rd author.

Notations

Notation	Description
V_{sd}	d- axis Stator voltage
V_{sq}	q- axis Stator voltage
I_{rd}	d- axis Rotor current
I_{rq}	q- axis Rotor current
I_{sd}	d- axis Stator current
I_{sq}	q- axis Stator current
V_{rd}	d- axis Rotor voltage
V_{rq}	q- axis Rotor voltage
R_r	Rotor resistance
L_r	Rotor inductance
R_s	Stator resistance
L_s	Stator inductance
N	Mutual inductance
ω_s	Stator pulsation
φ_{sq}	q- axis Stator flux
φ_{sd}	d- axis Stator flux
φ_{rd}	d- axis Rotor flux
φ_{rq}	q- axis Rotor flux
T_e	EM torque
T_r	Rotor torque
ρ	Air density

I	Inertia of DFIG
F	Friction coefficient
Ω	Rotor speed of DFIG
Γ(.)	Gamma function
t	Upper limit
a	Lower limit

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