Research Article

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LVRT enhancement of DFIG-driven wind system using feed-forward neuro-sliding mode control

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Abstract: Power generation losses arise in doubly fed induction generator (DFIG) system due to grid faults. The system's protection should ensure that the wind turbine (WT) generator meets the grid requirements through a low voltage ride through (LVRT) technique. This article proposes the feed-forward neuro-second order sliding mode (FFN-SOSM) control for the LVRT enhancement under voltage sag. This controller operates with the levenberg marquardt (LM)-super twisting (ST) algorithm for the uncertainties of the DFIG system. The LM-ST algorithm-based proposed controller is subjected to stability analysis. The advantages of the proposed controller are that it reduces the system parameter's peak values and harmonic distortion of the system during grid disturbance. The performance of the proposed controller is compared with existing controllers in the literature with the help of MATLAB/SIMULINK. The hardware-in-loop (HIL) validates these simulation results performed on the OPAL-RT setup. Based on the studies, it is found that the proposed controller enhances the LVRT performance of the WT-DFIG system under transient conditions.

Keywords: WT, DFIG, LVRT, FFN, SOSM

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1 Introduction

Wind energy is more prominent among renewable sources due to its significant grid penetration [1]. This penetration requires specific grid codes as a safety measure. As a result, grid codes ensure the successful low-voltage ride through (LVRT) for wind turbine (WT) generators during grid integration. The doubly fed induction generator (DFIG) is more preferred in WT generators mainly due to its low losses and less cost over the PMSG during the grid integration. The DFIG is sensitive to voltage variations in the grid [2]. These grid variations are due to grid faults. The DFIG has to be disconnected from the grid if the voltage recovery does not happen within the 750 ms as referred by the Danish grid codes. This disconnection of the DFIG from the grid raises the power generation losses. Moreover, these variations in the grid voltage damage the power converters and grid stability if the controller design is improper. The literature has presented various control strategies for the DFIG system under fault conditions.

The sliding mode control (SMC) is used for the stator and grid current control, where it improves the tracking performance and rides through the fault [3]. In ref. [4], the direct power control of variable speed using SMC under disturbance conditions is detailed. The researchers emphasized the SMC's dynamic behaviour and chattering effect under unbalanced conditions, and to overcome these constraints, a higher-order SMC is developed [5]. In ref. [6], the authors used the neural network (NN) in the DFIG system to reduce system parameter ripples and harmonic distortion of the rotor current. The stator active and reactive power were controlled using both neural and SMC approaches for determining the sensitivity to uncertainties [7]. Improved control strategies of DFIG-based WT generators are given in Table 1.

According to the literature, under the fault condition, parameters of the DFIG system raise to peak conditions, unable to ride through fault, and stability gets disturbed. Consumption of reactive power and variations in the frequency of the system leads to disconnection with the grid. Many authors have reported that SMC has a

Table 1: Improved control strategies of DFIG-based WT generator system

Author	Controller strategy	RSC	GSC	Targetted parameters	Application	Complexity	Remarks
[8]	Robust SMC	Yes	No	P, Q	WT-Grid	Simple	Error signals between references and measured rotor currents are presented
[9]	FOSM	Yes	No	T_{em}	WT-Grid	Simple	Fractional order uncertainty is integrated into control law to compensate parameter uncertainties
[10]	IPISMC	Yes	No	P	WT-Grid	Moderate	Extra input is added to compensate the estimation error
[11]	FDI-based ANN	No	No	A_{mabc}, ϕ_{abc}	WT-Grid	Moderate	Single ANN identifies the fault type
[12]	DTC-based ANN	Yes	No	T_{em}, ϕ, β	WT	Moderate	Conventional switching table by voltage selector based on the ANN
[13]	ASMC & AFC	No	Yes	V_{dc}	WT-Grid	Complex	Centre of Gaussian member function changes as per the crisp values
[14]	API	No	Yes	V_{dc}	WT-Grid	Moderate	According to fuzzy rules, PI gain is adapted with error
[15]	LM-SMC	No	Yes	V_{dc}, Q	WT-Grid	Simple	Sliding condition makes surface an invariant set surface

FOSM: fractional order sliding mode control, IPISMC: intelligent proportional-integral sliding mode control, FDI: fault detection and identification, DTC: direct torque control, ASMC: adaptive sliding mode controller, AFC: adaptive fuzzy controller, API: adaptive proportional integral, A_{mabc} : amplitude values of phases a, b, c , ϕ -phase angle, T_{em} -electromagnetic torque.

drawback of chattering effect, harmonic distortion, and insensitivity to uncertainties. Although higher-order SMCs have been developed, less improvement of transient behaviour during the unbalanced condition and ride through fault has been noticed. A few researchers have applied the NN controller under fault conditions, which resulted in more system parameter variations. Interestingly, we studied the combination of SMC and NN controller and found that it has resolved most of the drawbacks cited earlier.

In connection to resolving these drawbacks, in this article the feed-forward neuro second-order sliding mode (FFN-SOSM) control is proposed. This is a rotor side controller, which enhances the LVRT technique by reducing the system parameter's peak values and minimizes the system's harmonic distortion during voltage sag. Moreover, in this proposed controller, interconnected processing neurons with a training algorithm provide a better output response. The contributions of this article are summarized as follows:

- (i) This article proposed the FFN-SOSM controller for LVRT enhancement of the DFIG system.
- (ii) The simulation results of this proposed controller under voltage sag are validated with the hardware-in-loop (HIL) conducted on the OPAL-RT setup.
- (iii) This article focuses on improving the transient response of parameters such as real power, reactive power, rotor current, DC-link voltage, and electromagnetic torque during the sag condition.
- (iv) The LM-ST algorithm is adopted in the proposed controller.
- (v) The stability analysis of the proposed controller strengthens the transient performance of the DFIG system.
- (vi) The proposed controller suppresses the harmonic distortion and reduces the peak values of system parameters under fault condition.

Thus, this article is organized into different sections. In Section 2, modeling of the DFIG-based wind energy conversion system (WECS) is addressed. Section 3 presents proposed controller FFN-SOSMC designing. In Section 4, stability analysis is done for the proposed controller; Section 5 discusses the simulations and experimental validations, and followed by the conclusion in Section 6.

2 Modeling of the DFIG-based WECS

The WT's mechanical power output is set by,

Figure 1: Basic layout of the WT generator with DFIG.

$$P_m = \frac{1}{2} \rho C_p(\lambda, \beta) A V_\infty^3, \quad (1)$$

where P_m is the mechanical power transmitted to the shaft, C_p is the power co-efficient, and it relies on pitch angle of the rotor blades (β) and tip speed ratio (λ), V_∞ is the wind velocity (m/s), ρ is the air density (1.225 kg/m^3), and A is the rotor area (m^2).

The calculated power co-efficient is given by,

$$C_p(\lambda, \beta) = C_1(C_2 - C_3\beta - C_4\beta^2 - C_5)e^{-C_6}, \quad (2)$$

where $C_1 = 0.5$, $C_2 = 116/\lambda_i$, $C_3 = 0.4$, $C_4 = 0$, $C_5 = 5$, $C_6 = 12.5/\lambda_i$, and $\frac{1}{\lambda_i} = \frac{1}{(\lambda + 0.08\beta)} - \frac{0.035}{(\beta^3 + 1)}$.

The tip speed ratio is given by,

$$\lambda = \frac{\omega R}{V_\infty}, \quad (3)$$

where, ω is the rotor rotational speed in rad/s and R is the radius of the rotor blade in m .

Besides, DFIG is one of the variable speed wind generators, whose speed varies by approximately $\pm 30\%$ of the rated speed [16]. Moreover, the basic layout of the DFIG-based WECS is shown in Figure 1. DFIG is essentially a wound rotor, where the stator is associated directly while the rotor is linked to the grid with a back-to-back (B2B) converter [17,18].

The DFIG is modeled using the set of stator and rotor equations, which are given in equation (4). These equations are a combination of differential equations. The stator and rotor dynamic voltage equations are given in a synchronous reference frame. Furthermore, the voltage equations are useful in determining the electromagnetic torque, real power, and reactive power [19].

Figure 2: Block diagram for training using LM algorithm.

$$\begin{aligned} U_{ds} &= \frac{d}{dt}(\lambda_{ds}) - \omega_s \lambda_{qs} + R_s I_{ds} \\ U_{qs} &= \frac{d}{dt}(\lambda_{qs}) + \omega_s \lambda_{ds} + R_s I_{qs} \\ V_{dr} &= \frac{d}{dt}(\lambda_{dr}) - (\omega_s - p\omega_r) \lambda_{qr} + R_r I_{dr} \\ V_{qr} &= \frac{d}{dt}(\lambda_{qr}) - (\omega_s - p\omega_r) \lambda_{dr} + R_r I_{qr} \\ T_e &= \frac{3}{2} p \frac{L_m}{L_s} (\lambda_{qs} I_{dr} - \lambda_{ds} I_{qr}) \\ P_s &= \frac{3}{2} (U_d I_{ds} + U_q I_{qs}) \\ Q_s &= \frac{3}{2} (U_q I_{ds} - U_d I_{qs}), \end{aligned} \quad (4)$$

Figure 3: Block layers: (a) layer 1 and (b) layer 2.

where U and V are the constant grid voltage and the voltage controlled, λ stands for flux, p is the number of pole pairs, R_s is the stator resistance, and R_r is rotor resistance.

Besides, the designing of the SMC for DFIG system works on the Lyapunov application. The basic idea of the SMC technique is to bring the system state vector towards the sliding surface and the system slides to the desired equilibrium point on that surface. The sliding surface defines a system's relative degree, and higher-order SMC regulates it.

To define the sliding surface, the fundamental equation is given by

$$S(X) = \left(\frac{d}{dt} + \lambda \right)^{n-1} e(X), \quad (5)$$

where $e = X^* - X$ is the error, n is the relative degree, and λ is a positive co-efficient.

In addition, the discontinuous function (Δu) in control laws of SMC is replaced by a smooth approximation to overcome the chattering effect. The higher order is good for the chattering effect, but the main problem is that more information is needed. Notably, the implementation of an n th order controller requires the knowledge of $\dot{S}, \ddot{S}, \dots, S^{n-1}$.

FFN can be accomplished to execute a particular function by the adjustment of weight. The FFN solves the problems of less computational time with the help of LM algorithm. The block diagram for training using LM algorithm is shown in Figure 2. This algorithm is

(a)

(b)

Figure 4: Clustering of weights centres: (a) sample hits 1 and (b) sample hits 2.

analysed by computing the Jacobian matrix and weight-updating training process. The detailed training procedure of LM algorithm can be studied as per ref. [20].

The LM algorithm is given by

$$W_{(k+1)} = W_k - (J_k^T J_k + \mu I)^{-1} J_k e_k, \quad (6)$$

where W_k is the current weight, W_{k+1} is the net weight, e_k is the last total error, J_k is a Jacobian matrix, I is the identity matrix, and μ is combination co-efficient.

E_{k+1} is the current total error, and E_k is the last total error.

Figure 5: Proposed controller diagram of FFN-SOSM.

Figure 6: Lyapunov function convergence: (a) 3-D graph and (b) 2-D graph.

3 Proposed controller FFN-SOSM designing

The switching controls of stator real and reactive power are chosen for improving the dynamic response and are given by

$$S_P = (P_s^* - P_s) + c_P \int (P_s^* - P_s) dt, \quad (7)$$

$$S_Q = (Q_s^* - Q_s) + c_Q \int (Q_s^* - Q_s) dt, \quad (8)$$

where c_P and c_Q are added to eliminate steady-state errors, P_s^* is the stator real power reference, and Q_s^* is the reference value of stator reactive power.

The time derivatives of S_P and S_Q are given by ref. [7]:

$$\begin{aligned} \dot{S}_P = & \frac{L_m}{\sigma L_s L_r} u_s \left[(R_r - c_P \sigma L_r) i_{rd} - \sigma \omega_{s1} L_r i_{rq} + \omega_{s1} \frac{L_m}{L_s} \lambda_s \right] \\ & + P_s^* + c_P P_s^* - \frac{L_m}{\sigma L_s L_r} u_s u_{rd} \end{aligned} \quad (9)$$

$$\begin{aligned} \dot{S}_Q = & \frac{L_m}{\sigma L_s L_r} u_s \left[(-R_r - c_Q \sigma L_r) i_{rq} - \sigma \omega_{s1} L_r i_{rd} \right. \\ & \left. - c_Q \frac{\sigma L_r}{L_m} \lambda_s \right] + Q_s^* + c_Q Q_s^* + \frac{L_m}{\sigma L_s L_r} u_s u_{rq}. \end{aligned} \quad (10)$$

The rotor side converter (RSC) voltages control the stator active and reactive power of the DFIG and are given by

Figure 7: Network's Lyapunov function.

Figure 8: HIL setup in OPAL-RT 4510 simulator.

Table 2: 1.5 MW DFIG-based WT parameters

Symbol	Quantity	Value
R_s	Stator resistance	0.023 pu
R_r	Rotor resistance	0.016 pu
L_s	Stator inductance	0.18 pu
L_r	Rotor inductance	0.16 pu
L_m	Mutual inductance	2.9 pu
p	Pole pairs	3
R	Blade radius	35 m
b	Rotor friction coefficient	0.00015 N * m * s/rad
J	Rotor inertia	765.6 kg * m ²
n_g	Gearbox ratio	62.5
β	Pitch angle	0°
ρ	Air density	1.2 kg/m ³
λ_{opt}	Optimal tip speed ratio	6.325
ω_s	Grid angular frequency	2π50 rad/s
$\sqrt{u_{ds}^2 + u_{qs}^2}$	Grid voltage	575 V (rms)

Table 3: Specifications of OPAL-RT 4510 simulator

1	Real-time simulation software	RT-LAB
2	Real-time operating system	Linux REDHAT
3	FPGA	Xilinx KINTEX-7
4	Sampling time	200 MHz
5	CPU	Intel Xeon E3 4-core 3.5 GHz
6	Connectivity	Ethernet RS-232
7	High-speed optical interface	4 SFP sockets, up to 5 Gbps
8	Analog I/O systems	16 channels
9	Digital I/O systems	32 channels

$$\begin{aligned}\frac{\partial \dot{S}_p}{\partial u_{rd}} &= \frac{-L_m u_s}{\sigma L_s L_r} \neq 0, \\ \frac{\partial \dot{S}_Q}{\partial u_{rq}} &= \frac{L_m u_s}{\sigma L_s L_r} \neq 0.\end{aligned}\quad (11)$$

Here, if the partial derivatives of S_p and S_Q are equal to zero, then equivalent control terms in equation (12) would be zero. Then, it leads to poor controller performance. Furthermore, the control laws are applied on the rotor side voltages, which are given by,

$$\begin{aligned}u_{rd} &= \Delta u_{rd} + u_{rdeq}, \\ u_{rq} &= \Delta u_{rq} + u_{rreq},\end{aligned}\quad (12)$$

where Δu_{rd} and Δu_{rq} are control terms, and u_{rdeq} and u_{rreq} are equivalent control terms by letting $\dot{S}_p, \dot{S}_Q = 0$.

Equation (12), composed of switching control terms, which converges the sliding surface to zero in finite time

Figure 9: Danish grid code.

Figure 10: LVRT capability of DFIG without grid fault with the proposed controller: (a) rotor current, (b) real power, (c) reactive power, (d) DC-link voltage, and (e) electromagnetic torque.

Figure 11: LVRT capability of DFIG with the proposed controller under 60% voltage sag (i) and (g) stator voltage (ii) and (h) rotor current (iii) and (i) active power (iv) and (j) reactive power (v) and (k) DC-link voltage (vi) and (l) electromagnetic torque. (I) Simulation results. (II) HIL results.

with the help of super-twisting algorithm. In addition, this algorithm speeds up the system response and reduces the steady-state errors.

The rotor side voltages are applied with FFN-SOSM controller and are given by

$$\begin{aligned} \Delta u_{rd} = & K_{p1} \sqrt{|S_p|} \text{purelin}(LW^{2,1} \text{tansig}(IW^{1,1}p + b^1) \\ & + b^2)(S_p) + K_{p2} \int \text{purelin}(LW^{2,1} \\ & \times \text{tansig}(IW^{1,1}p + b^1) + b^2)(S_p) dt, \end{aligned} \quad (13)$$

$$u_{rdeq} = \frac{\sigma L_s L_r}{L_m u_s} [P_s^* + c_p (P_s^* - P_s)] + R_r i_{rd} - \sigma \omega_{sl} L_r i_{rq} + \frac{\omega_{sl} L_m}{L_s} \lambda_s, \quad (14)$$

$$\Delta u_{rq} = -K_{q1} \sqrt{|S_Q|} \text{purelin}(LW^{2,1} \text{tansig}(IW^{1,1} p + b^1) + b^2)(S_Q) - K_{q2} \int \text{purelin}(LW^{2,1} \text{tansig}(IW^{1,1} p + b^1) + b^2)(S_Q) dt, \quad (15)$$

$$u_{rqeq} = \frac{\sigma L_s L_r}{L_m u_s} [Q_s^* + c_Q (Q_s^* - Q_s)] + R_r i_{rq} - \sigma \omega_{sl} L_r i_{rd}, \quad (16)$$

where K_{p1} , $K_{q1} = 0.1$, K_{p2} , $K_{q2} = 3$, and c_p , c_Q are tuned positive constants. The equivalent control terms are obtained after solving equations (9) and (10).

The NN pattern contains two layers, first layer (hidden layer) consists of two neurons, which are tangent sigmoid (tansig) transfer functions and second layer (output layer) contains one neuron, which is linear (purelin) transfer function. The configuration of these two layers is shown in Figure 3. Besides, cluster analysis is done for the proposed controller to identify some inherent structures present in it. This clustering representation is shown in Figure 4. This topology is hexagonal and 10-by-10 grid with 100 neurons. Figure 4 shows the neuron location and indicates the training data with each of the neurons. Besides, the proposed controller strategy of the DFIG system is depicted in Figure 5.

4 Stability analysis

The proposed controller plays an important role in the convergence of the DFIG system. The convergence of this system leads towards steady state from the trajectory state. Therefore, the mathematical equations of the FFN-SOSM controller ensure the stability and robustness of the system. The Lyapunov analysis is preferred for analysing the stability of this system. The Lyapunov function, $V: \mathbb{R}^0 \rightarrow \mathbb{R}$ near a dynamic system of solution is given by

$$\begin{aligned} V(0) &= 0 \\ V(x) &> 0 \quad \forall x \in 0, x \neq 0 \\ V(x(t_{i+1})) - V(x(t_i)) &= \Delta V(x) \leq 0 : \quad \forall x \in 0, \end{aligned} \quad (17)$$

where $x = 0$ is the solution of the system, $\mathbb{R}^0$ is the output space, and 0 represents the region enclosing the solution of the system. The trajectories are created due to faults that occurred in the system. If the proposed controller is stable during disturbance, then trajectories in the system converge to a stable state. Hence, the Lyapunov function

(a)

(b)

(c)

(d)

Figure 12: Proposed controller training on d -axis during LVRT capability of DFIG system during grid fault: (a) histogram, (b) performance, (c) regression, and (d) training.

Figure 13: Proposed controller training on q -axis during LVRT capability of DFIG system during grid fault: (a) histogram, (b) performance, (c) regression, and (d) training.

should not increase over the system's trajectories during fault. The Lyapunov function convergence to equilibrium point is shown in Figure 6. Here, this figure indicates the 3D graph and 2D graph, respectively. Also, Figure 6 indicates the convergence of the trajectories. As per equation (17), the Lyapunov function forces the system to reach a stable state.

On the other side, the effectiveness of neural function units in the proposed controller during fault is measured by computing the deviations of neural units from the equilibrium states. The total number of neurons N is approximated to

$$V = \frac{1}{N} \sum_{u \in I} \|u - w_{bmu(u,t)}\|, \quad (18)$$

where V is the network's quantization error or the network's Lyapunov function, $u \in I$ is the element for all inputs.

Here, to show $\frac{\Delta V}{\Delta t} < 0$, first $\Delta t > 0$, then numerator ΔV determines the sign. The neural unit's weighted centre, which includes the weights of the best matching unit (bmu) and its neighbour (nbr), is adjusted according to ΔV . The convergence of V to reach a stable state within ten epochs of NN learning is achieved by using equation (18) and can be seen in Figure 7. The "constructed Lyapunov function (V) depicted in Figure 7 reduces the need to verify for effective learning by each dimension as $V \in \mathbb{R}$." Therefore, the stability of the proposed controller can be assessed by this single graph (Figure 7).

5 Simulations and experimental validations

This section evaluates the performance of the proposed FFN-SOSM controller using MATLAB/SIMULINK software. HIL validates these simulation results performed on the OPAL-RT 4510 setup, as shown in Figure 8. The parameters used during simulation are listed in Table 2. The schematic control strategy for the proposed controller is shown in Figure 5.

Table 4: Result samples of the proposed controller

Parameters	Samples	MSE	R
Training	140,001	4.89081×10^{-4}	9.99754×10^{-1}
Validation	30,000	3.43415×10^{-4}	9.99827×10^{-1}
Testing	30,000	6.11082×10^{-4}	9.99692×10^{-1}

(a)

(b)

(c)

(d)

(e)

Figure 14: Comparison of SOSM and proposed controller during LVRT capability of DFIG system during grid fault: (a) rotor current, (b) real power, (c) reactive power, (d) DC-link voltage, and (e) electromagnetic torque.

Table 5: Comparison of the proposed controller with SOSMC

Parameters	SOSMC (pu)	Proposed (pu)
Rotor current	1.77	1.67
Stator real power	0.27	0.293
Stator reactive power	−0.572	−0.56
Rotor speed	1.225	1.22
DC link voltage	1.265	1.262
Electromagnetic torque	−0.072	−0.073

Figure 15: Harmonic spectrum: (a) FFN-SOSMC and (b) SOSMC.

The hardware setup for the simulation model is done through OPAL-RT 4510. The OPAL-RT is an HIL, and its specifications are given in Table 3. The simulink model is built in this OPAL-RT by creating the master and slave subsystem, as shown in Figure 8. In addition, the master subsystem includes hardware interfaces, such as OpWrite and OpTrigger block, which helps to store model data, OpCtrl block, which provides the binstream files for the simulator to execute the model, and Analog I/O block, which helps to record the waveforms in CRO. Furthermore, in the slave subsystem, the OpComm block is used to verify the offline simulation results prior to the interfacing with simulator, later the model is built in RTLAB-2020.4 software, and the model is loaded to the simulator to validate the simulator simulation results.

The voltage sag is created as a fault at PCC. The 60% of the voltage sag is active for 100 ms and after that the fault has been cleared. This proposed DFIG-based WECS model follows the Danish grid code specifications as shown in Figure 9. According to this grid code, the system under fault for 100 ms has to recover 75% of the nominal grid voltage within 750 ms, otherwise system to be disconnected from the grid.

5.1 Control performance under no fault/disturbance

The performance evaluation of the DFIG-based WT generator is carried out using the FFN-SOSM controller, and Figure 10 shows the results under no fault condition. This proposed controller enables the DFIG system for transferring the 1.5 MW of constant power to the grid without the consumption of reactive power. The rotor current is undistorted and also helps in providing the constant power. The constant DC-link voltage of 1.15 pu is maintained between the RSC and grid side converter (GSC). The electromagnetic torque is constant without affecting the rotor speed of the DFIG. The hardware validation for these simulation results of the proposed controller is not shown as it is under no fault condition.

5.2 Control performance during grid fault

The control performance of the proposed controller during voltage sag is shown in Figure 11, and the HIL setup is shown in Figure 8. Here, the hardware validation is shown for the proposed controller under the voltage sag condition. This sag is created for 100 ms, which is initiated at $t = 0.3$ s and cleared at $t = 0.4$ s. The rotor current distorts and reaches up to 1.85 pu during the fault period, but the rotor current in the hardware result is 1.2 pu as it is due to interfacing effect and changes in the initial condition settings in the model. Later it takes fraction of seconds to recover and settle. The fluctuation of active power is from 0.5 to 2.5 pu during the sag period, but in the hardware, it is showing approximated result.

Then, the reactive power varies from 0.6 to −1.1 pu and same variations can be seen in hardware results. The sag effect fluctuates the voltage even after the fault clearance. The DC-link voltage fluctuated from 1.25 to 1.2 pu during fault initiation and clearance. The hardware results are approximated to the simulation results. Moreover, the electromagnetic torque increases from −0.1 to −2.5 pu during the instant of fault and clearance of fault, respectively.

(a)

(b)

(c)

(d)

(e)

Figure 16: Comparison of FOSM and proposed controller during LVRT capability of DFIG system during grid fault: (a) rotor current, (b) active power, (c) reactive power, (d) DC-link voltage, and (e) electromagnetic torque.

The DFIG system under the fault has been discussed in three cases by comparing the first order SMC (FOSMC), second order SMC (SOSMC), and proposed controller. These cases are studied as follows:

Case A. Performance of the proposed FFN-SOSM controller in the DFIG system.

The LM-ST algorithm-based proposed controller with NN architecture $f(IW * p + b)$ reduces the peak values of system parameters and improves the harmonic distortion of this system. The design of this controller trained the DFIG system and resulted in system optimization. These results can be observed through histogram, regression, performance plots, and epochs. Figures 12 and 13 show the d and q axis results of the DFIG system during the LVRT mechanism.

Meanwhile, in the error histogram, blue bars indicate the training data, green bars are validation data, and red bars represent testing data. The error histogram with 20 bins represents the target and predicted values after the training and can be seen in Figures 12(a) and 13(a). Substantially, validation performance plots the training errors, validation errors, and test errors with a small mean-square error (MSE). The best validation performance at 1,000 epoch is shown in Figures 12(b) and 13(b). Consider the regression, and the fit is reasonably good for the current data sets, which are above 0.93. The regression plots the output with target values with R close to unity, as shown in Figures 12(c) and 13(c). The 1,000 epochs increase the accuracy of the model and display the maximum number of iterations. The gradient measures the change in all weights regarding the change in error, μ parameter trains the NN and affects the error convergence, and val fail is a training parameter, which stops the poor performance of training data in NN. The training plots gradient, μ , and val fail with epochs are shown in Figures 12(d) and 13(d). Besides, the result samples of the proposed controller are shown in Table 4, and it shows the MSE, which reduces the computation time, and R always tends to unity.

Case B. Comparison of the proposed and SOSM controller.

Table 6: Comparison of the proposed controller with FOSMC

Parameters	FOSMC (pu)	Proposed (pu)
Rotor current	0.2	1.7
Stator active power	0.15	1
Stator reactive power	0	-0.4
DC link voltage	1.120	1.250
Electromagnetic torque	0	-1.7

The SOSM controller with the ST algorithm is insensitive to uncertainties and external disturbance. To overcome this drawback, the proposed controller is trained under the disturbance condition. According to equations (13)–(16), the system operates upon the LM-ST algorithm during the training process. The nearly 1,000 data samples are trained for accuracy and results are shown in Figures 12 and 13. Moreover, the comparison between the proposed and SOSM controller is shown in Figure 14, and also it is tabulated in Table 5. Here, peak values of the system parameters resulted during SOSM are reduced and improved the transient performance of the proposed controller under the sag.

On the other side, harmonic distortion is more in the SOSM as compared to the proposed controller. The harmonic spectrum of signum and trainlm functions of the DFIG system due to FFT are shown in Figure 15. Here, total harmonic distortion (THD) of the SOSM controller obtained from the signum function's square wave is more than 48% of the standard THD. But, the proposed controller provides less THD, as shown in Figure 15.

Case C. Comparative study of the proposed and FOSM controller.

The switching function of FOSM controller is unable to overcome the chattering effect. The LM-ST algorithm-based proposed controller significantly reduces the chattering. The comparison between the proposed and FOSM controller can be seen in Figure 16, and also it is tabulated in Table 6. Interestingly, Figure 17 represents the different set of controllers with different algorithms under the voltage sag condition. Also, this chart indicates the effective percentage improvement of LVRT for different controllers.

Figure 17: Comparative study of efficient controllers.

6 Conclusion

This article proposed the FFN-SOSM controller using the LM-ST algorithm for the DFIG system under voltage sag. The perspective of the LVRT enhancement is analysed through the proposed controller, and the conclusions are drawn as follows:

- (i) The HIL (OPAL-RT 4510) results are closely matched with the simulation results, which are validation to the proposed controller under the voltage sag.
- (ii) The model's hardware RT-LAB interface and initial condition settings are mainly responsible for the approximate matching from the exact matching, while comparing the results.
- (iii) The signum and trainlm functions have brought the modifications in the proposed controller and resulted in improving the system's performance.
- (iv) The LM-ST algorithm-based proposed controller improved the transient behaviour of certain machine parameters, such as real power, reactive power, rotor current, DC-link voltage, and electromagnetic torque under the voltage sag.
- (v) The proposed controller has suppressed the uncertainties, as it overcame the peak amplitude and harmonic distortion.
- (vi) The stability analysis of the proposed controller contributed to enhancing the transient performance of the DFIG system.
- (vii) The FFN-SOSM controller provided better results as compared to FOSMC and SOSMC.
- (viii) LVRT enhancement is achieved with improved transient performance.

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