Predictive optimization of sliding mode control using recurrent neural paradigm for non-linear DFIG-WPGS during distorted voltage

Omar Busati Alzain\textsuperscript{1,*}, Xiangjie Liu\textsuperscript{2}

\textsuperscript{1}omarbusati@ncepu.edu.cn, \textsuperscript{2}liuxj@ncepu.edu.cn

\textsuperscript{1,2}The State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, School of Control and Computer Engineering, North China Electric Power University, Beijing-102206, China, ORCID iD: \textsuperscript{1}0000-0003-0798-0817, \textsuperscript{2}0000-0002-9116-518X

\textsuperscript{1}School of Electrical Engineering, Sudan University of Science & Technology, Khartoum, Sudan

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\textbf{Abstract:} Dynamic characteristics of the doubly-fed induction generator (DFIG)-based wind power generation (WPGS) are fully non-linear. And therefore, issues such as stability and achieving high efficiency, especially under harmonics behavior, are challenges that assess the control strategy reliability to find the perfect dynamic solution. This discussion offers a control strategy for the separated stator-port power using a predictive sliding mode strategy with a resonant function (PSMC-R) based on a deep recurrent neural network (DRNN). DRNN is formed as a low-order Taylor series formula. PSMC-R predicts the perfect switching surface path and regulates the distorted non-linear DFIG with several dynamic aims. This approach reduces excessive chatter while violating the sliding surface path range of the classical SMC switch-part. Also, PSMC-R handled the fundamental and 5th-/7th-type harmonic wave at the positive synchronous +dq-reference level of the machine dynamic quantities without further dissociation computations of the components. Dynamic results of a 1.5 MW DFIG-WPGS are simulated by using Matlab-package and presented good dynamic characteristics, less pulsation ratio of variables, and optimal sliding chatter of PSMC-R during various operating scenarios compared to the other classical regulation approaches.

\textbf{Key words:} Double fed induction machine, wind engine unit, sliding surface controller, harmonic wave, regulation of power system

\textbf{Nomenclatures}

\begin{tabular}{ll}
\textit{i}_s, \textit{i}_r & Stator- and rotor-port current vector. \\
\textit{\textit{v}}_s, \textit{\textit{v}}_r & Stator- and rotor-port voltage vector. \\
\textit{\psi}_s, \textit{\psi}_r & Stator- and rotor-port flux vector. \\
\textit{R}_s, \textit{R}_r & Stator- and rotor-port resistance. \\
\textit{L}_m & Common-inductance. \\
\textit{L}_s, \textit{L}_r & Stator- and rotor-port inductances. \\
\textit{L}_{\textit{ps}}, \textit{L}_{\textit{pr}} & Stator- and rotor-port outflow-inductances. \\
\omega_e & Stator angular speed. \\
\omega_r, \omega_s & Rotor-port, synchronous angular speed. \\
\theta_e, \theta_r & Position angle of stator-, rotor-port.
\end{tabular}

\begin{tabular}{ll}
\textit{P}_s, \textit{\textit{Q}}_s & Stator-port active and reactive power and, \\
& machine electrical torque \\
\textit{\textit{S}} & Stationary level at \textit{\alpha}- and \textit{\beta}-axis. \\
\textit{\textit{d}}, \textit{\textit{q}} & Synchronous level at \textit{d}-, \textit{q}-axis. \\
\textit{s}, \textit{r} & Stator- and rotor-port variables. \\
+5\textsuperscript{\textit{t}}, 7\textsuperscript{\textit{t}} & Positive-series of the primary + and 5\textsuperscript{th}/7\textsuperscript{th}-
& degree harmonic items at \textsuperscript{\textit{5}\omega_e} and \textsuperscript{\textit{7}\omega_e}. \\
\textit{\textit{ref}} & Stationary level at (\textit{\alpha}\textsuperscript{\textit{r}}, \textit{\beta}\textsuperscript{\textit{r}}), and (+) synchronous
& reference level at \textsuperscript{\textit{dq}}\textsuperscript{\textit{t}}, \textsuperscript{\textit{5\textsuperscript{\textit{t}}}}, \textsuperscript{\textit{7\textsuperscript{\textit{t}}}}.
\end{tabular}

\textsuperscript{*Correspondence:} omarbusati@ncepu.edu.cn, omarbusati@gmail.com
1. Introduction

Globally, the power generation based on wind-wave (WPG) has expanded rapidly within these years for growing
global natural energy sources needs [1]. Flux and voltage orientation types of vector control are general strategies
applied during the usual operating characteristics of DFIG-WPGS [2, 3]. WPGS is entirely non-linear and
unprotected from disturbance status types that decrease the system effectiveness, concerned classical controllers
[4]. Accordingly, several topics have dealt with various enhanced control designs, such as a robust controller
that has been analyzed in the stationary- or synchronous-level to improve the paradigm performance toward
DFIG terminals [5, 6]. The optimization algorithm for the model predictive regulation approach (MPC) gives
extensive regulation features to handle the DFIG. An optimum predictive voltage vector is derived based on
the direct power control without the need to extract the negative chains of stator-port current to enhance
its sequences and mitigate electromagnetic torque vibrations during an unbalanced network state [7]. Given
the harmonics status, the predictive estimation compensator decreases the torque hesitation associated with
stator-port current and flux [8]. The predictive regulation enhanced the torque and flux by adding ripple
regulation term with the standard cost function to deal with torque ripple during an ineffective control action
[9, 10]. MPC regulation-based stator-port current injected the predicted stator-port current at \(dq\)-plane to
generate the rotor-port converter control signals without complex separations processes in the harmonic items.
Which simplifies the regulation items, decreases the algorithm’s burden, and enhances its dynamic robustness
[11]. The sliding mode approach (SMC) is widely introducing to regulate the DFIG-WPG with unpredictable
wind behavior, uncertainty changes, and external disturbances due to the insensitivity properties for unwanted
dynamic deviations. SMC power regulation approach (SMC-DPC), using the influential extended power and
adapted control based on the backward-steps procedure (ABS-SMC), is offered to deal with DFIG [12, 13].
Present network design recommends reducing the maintenance and operational costs and the possibility of
overcome malfunctions. The network-port is associated with the DFIG stator- and rotor-port through the
transformer and dual-terminals converter, respectively, which may cause undesirable increases in rotor-port
current. These dynamic challenges are influential for taking into account during advanced control design.
Consequently, additional smart control approaches have been proposed to discuss DFIG behaviour under unusual
voltage dips conditions [14–17]. The SMC model deal effectively with the applicable system during these cases
due to its rapid reaction to correct unwanted dynamic perturbations [18, 19]. A high-degree SMC has been
offered for the DPC toward DFIG’s terminals [20] and speed-control toward turbine (WT) [21]. The Integral
I-SMC directly controlled the DFIG’s torque under unbalanced system voltage that alleviates the ripples impact
on the torque and stator-port power in [22]. An I-SMC-based torque control manipulated voltage drop effects
and reduced the vibration of stator-port power and mechanical torque (MT) for the DFIG system. Also, DPC
strategy-based DFIG regulation via I-SMC has regulated the stator-port power and compensated the power
oscillations using resonant units running at a double value of actual frequency [23]. Three regulation targets
have been adopted depend on the current of the stator-port, power during the stable condition, and damped
vibrations of MT. The study in [14] offered ISMC-DPC with two scenarios, such as collapse and distortion
in the network-area voltage, for mitigating the dynamic harmonic effects on the DFIG. The actual behavior
of the nonlinear and inductive effect of the power system equipment, with power electronics converters units
leads to the emergence of harmonics sequences, which causes a significant change in the fundamental sinusoidal
wave structure of system variables, especially the \(5^{th}/7^{th}\)-degree of harmonic. The appearance of harmonious
fluctuations in the power feed unit results in MT vibration and high energy dissipation through the machine core.
The electrical communities have identified standards for reducing harmonic ratios on acceptable operational limits along the generation line, and the most famous are IEEE-519 and ERG5/4-1 [18]. In [23, 24], I-SMC with multi-resonance elements suppressed the harmonic effect and restricted the tracking deviation of DFIG variables sequences that may be present under unusual network voltage conditions. The multi-resonant integral law modified the sliding surface elements based on the SMC approach to manipulate the deformed voltage at the positive $dq$-reference-level. This strategy provided good tracking behavior and attenuated the oscillation on the stator-port power and response of MT for the DFIG [25]. Generally, the stable and transient behavior of DFIG has been regulated during the normal and abnormal operating conditions in previous studies without providing a more detailed analysis of the effect of different kinds of harmonics. The previous SMC regulation investigations frequently presented the classical chattering signal based on their sliding quantities, signs, and restrictions that may affect sliding behavior on the efficient surface to realize dynamic targets. This paper presents PSMC-R utilizing the predictive sliding chattering signals based on a deep recurrent neural network (DRNN) of the DFIG-WPG stator-port power under $5^{th}/7^{th}$-degree harmonic related to voltage. The PSMC-R has a sliding formula like an ordinary PI structure which contains a predictive sliding term, with the addition of resonant compensator unit oscillated at 6-times the feeder frequency. The required stator-port power is necessary to derive many control characteristics with different modes of operation. The results show that the PSMC-R control presents the best dynamic tracking, low overshoot, and fluctuation of electrical quantities compared to SMC, PI, and PIR controllers during various operation cases. Moreover, the frequency of stator/rotor-port sinusoidal current wave has remained constant.

2. DFIG-WPGS structure representation

2.1. Mathematical description of DFIG

The transient circumstances of the DFIG are complicated for design due to the influence of the variations on the inner parameters, such as coil inductance and stator- and rotor-port resistors associated with the inherent variations in magnetic fields. Thus, as displayed in Figure 1, the DFIG as an un-complex corresponding circuit can be deduced based on some propositions for the usual- and distorted voltage running conditions. The initial proposition considers that the non-linear sequences of DFIGs can be extracted based on the (+) synchronous scheme ($dq$) related to angular speed $\omega = \omega_e$. In addition, the + harmonic progression items (HPI) on the main variables are shaking at $-5\omega_e$ and $7\omega_e$ as revealed in Figure 2. The rated values of the system are calculated along per unit scale (pu). Also, assuming the machine structure that includes the airflow is a symmetrical structure to idealize the DFIG circuit. In general, the stationary-references ($\alpha\beta$) of the DFIG dynamic quantities ($F$) were specified as following [26]:

$$F_{\alpha\beta} = F_{\alpha\beta+} + F_{\alpha\beta5-} + F_{\alpha\beta7+} = |F_{\alpha\beta+}| e^{j\phi_1} + |F_{\alpha\beta5-}| e^{-j5\phi_5} + |F_{\alpha\beta7+}| e^{j7\phi_7}$$

(1)

where $\phi_1 = \omega_e t + \varphi_+,$ $\phi_5 = 5\omega_e t + \varphi_5$ and $\phi_7 = 7\omega_e t + \varphi_7$, also, $\varphi_+,$ $\varphi_5$ and $\varphi_7$ are the primary phase retard

![Figure 1. Equivalent paradigm of the DFIG at $dq$+-level.](image1)

![Figure 2. Orientation phasor analysis during the distorted stator-port voltage.](image2)
belong to the (+) components of the basic items (BSI) and HPI which is shaking at (−5, 7) feeder frequency, respectively. The phase beams indicated the link between the stationary, rotational and synchronous levels of BSI and HPI for electrical DFIG variables as in Figure 2. Moreover, the map shows that the + d–arrow is settled on (+)–arrow stator voltage sequences that operate at \( \omega_c \). Although d–arrow of \((dq)^{-5}\) and \((dq)^{7+}\) at \(-5\ \omega_c/7\ \omega_e\) are spaced from \( \alpha \)-arrow by \(-\theta_3\) and \(\theta_7\), respectively. Derivation of the transformational relationship between the stationary level at \((\alpha\beta)\) and \((\alpha\beta)^r\), and synchronous level at\((dq)^{-5}\) and \((dq)^{7+}\) with indicators \(r+, 5−\) and \(7+\), respectively as:

\[
\begin{align*}
F_{dq}^{5−} &= F_{dq}^{−}e^{−j\omega_c t}, & F_{dq}^{7+} &= F_{dq}^{+}e^{j\omega_c t}, & F_{dq}^{r−} &= F_{dq}^{r}e^{−j(\omega_e−\omega_c)t} \\
F_{dq}^{5−} &= F_{dq}^{−}e^{j\omega_c t}, & F_{dq}^{7+} &= F_{dq}^{+}e^{−j\omega_c t}, & F_{dq}^{r+} &= F_{dq}^{r}e^{j(\omega_e−\omega_c)t} \\
F_{dq}^{7+} &= F_{dq}^{−}e^{−j\omega_c t}, & F_{dq}^{5+} &= F_{dq}^{+}e^{j\omega_c t}, & F_{dq}^{r−} &= F_{dq}^{r}e^{−j(\omega_e−\omega_c)t} \\
F_{dq}^{7+} &= F_{dq}^{−}e^{j\omega_c t}, & F_{dq}^{5−} &= F_{dq}^{−}e^{−j\omega_c t}, & F_{dq}^{r−} &= F_{dq}^{r}e^{j(\omega_e−\omega_c)t} \\
\end{align*}
\]

In Equation (2), the complex relationships referred to as +dq-reference level can be designed similar to approach into [4]. Thus, DFIG dynamics are determined to correspond to the relationships between stator/rotor-port voltages, the passed current in impedances and fluxes, \(v_{sdq}^{+}, v_{rdq}^{+}, i_{sdq}^{+}, i_{rdq}^{+}, \psi_{sdq}^{r+}\) and \(\psi_{rdq}^{r+}\) respectively [27].

\[
\begin{align*}
v_{sdq}^{+} &= R_s i_{sdq}^{+} + \frac{d\psi_{sdq}^{+}}{dt} + j\omega_c \psi_{sdq}^{+} \\
v_{rdq}^{+} &= R_r i_{rdq}^{+} + \frac{d\psi_{rdq}^{+}}{dt} + j(\omega_c − \omega_r) \psi_{rdq}^{+} \\
\psi_{sdq}^{r+} &= L_s i_{sdq}^{+} + L_m i_{rdq}^{+} \\
\psi_{rdq}^{r+} &= L_m i_{sdq}^{+} + L_r i_{rdq}^{+} \\
\end{align*}
\]

where \(L_s = L_{ps} + L_m\), \(L_r = L_{pr} + L_m\) and, \(L_{ps}, L_p,\) and \(L_m\) are the stator/rotor-port outflow-, and common-inductances impact respectively. The nominated general expression of DFIG variables is imputed to +dq-reference conditions of the basic and harmonic sequences along two frequencies (5 \(\omega_c\) and 7\(\omega_c\)) with the Equations (1) and (2) as follows:

\[
F_{dq}^{5−} = F_{dq}^{−} + F_{dq}^{5−} + F_{dq}^{7+} = F_{dq}^{5−} + F_{dq}^{7+} = e^{−j(\omega_e−\omega_c)t} + e^{j(\omega_e−\omega_c)t}
\]

where the + chains of the basic and the harmonic rippled at \(-5\ \omega_c\) and 7\(\omega_c\) were assigned by \(+,\ 5−\), and \(7+\) respectively. It can be considered that the behavior of the harmonious waves that are combined together similar to a frequency AC wave hesitating at \(±6\ \omega_e\) in dq+–plane. Also, present the 5th/7th degree of stator/rotor harmonics at the \((dq)^{-5}/(dq)^{7+}\) respectively. The non-linear variables of the stator/rotor-port can be obtained from Equations (3), (4) and (5), and reshaping the stator/rotor-port fluxes computations as in [27]:

\[
\begin{align*}
dt_{sdq} / dt &= H_1 i_{sdq} + H_2 i_{rdq} + H_3 i_{sq} + H_4 i_{rq} + n_1 v_{sdq}^+ + n_2 v_{rdq}^+ \\
dt_{sdq} / dt &= H_2 + H_3 i_{sq} + H_4 i_{rq} + H_5 i_{sq} + H_6 i_{rdq} + n_1 v_{sdq}^+ + n_2 v_{rdq}^+ \\
dt_{rdq} / dt &= G_1 i_{sq} + G_2 i_{rq} + G_3 i_{sq} + G_4 i_{rdq} + M_1 v_{sq}^+ + M_2 v_{rdq}^+ \\
dt_{rdq} / dt &= G_5 i_{sq} + G_6 i_{rq} + G_7 i_{sq} + G_8 i_{rdq} + M_1 v_{sq}^+ + M_2 v_{rdq}^+ \\
dt_{rdq} / dt &= G_9 i_{sq} + G_5 i_{rq} + G_6 i_{sq} + G_7 i_{rdq} + M_1 v_{sq}^+ + M_2 v_{rdq}^+ \\
\omega_c / dt &= P L_m / J (i_{sdq}^− i_{rdq}^− − i_{sq}^+ i_{rq}^+) − T_m / J
\end{align*}
\]

where

\[
\begin{align*}
H_1 &= \frac{R_s}{L_m} & H_2 &= +\sigma^{-1} \omega_e \omega_c \omega_m^2 & H_3 &= \frac{R_m}{L_m} & H_4 &= −\frac{\omega_m^2}{L_m} & H_5 &= −\frac{\omega_m^2}{L_m} & H_6 &= −\frac{\omega_m^2}{L_m} \\
H_7 &= +\frac{R_r}{L_m} & H_8 &= \frac{R_m}{L_m} & H_9 &= \frac{R_r}{L_m} & H_{10} &= \frac{R_m}{L_m} & G_1 &= \frac{R_m}{L_m} & G_2 &= −\frac{\omega_m^2}{L_m} & G_3 &= −\frac{R_m}{L_m} & G_4 &= +\omega_r \\
G_5 &= +\frac{\omega_m^2}{L_m} & G_6 &= −\frac{R_m}{L_m} & G_7 &= −\frac{\omega_m^2}{L_m} & G_8 &= −\frac{R_m}{L_m} & N_1 &= \frac{1}{L_m} & N_2 &= \frac{L_m}{R_m} & N_3 &= \frac{L_m}{R_m} & N_4 &= \frac{L_m}{R_m} \\
M_1 &= \frac{R_m}{L_m} & M_2 &= \frac{R_r}{L_m} & \sigma &= 1 − \frac{L_m}{R_m} L_r.
\end{align*}
\]
As equivalent approach in [26] and for the regulation design target, the $\psi_{sdq}$ coordinate is assumed to be equal to stator-port voltage $u_s$ as fixed unity value and, stator-port power and the generator-torque are specified as

$$P_{s+} = \frac{3}{2} \left( \text{Re} \{ v_{sdq}^+ \hat{I}_{sdq}^+ \} \right)$$
$$Q_{s+} = \frac{3}{2} \left( \text{Im} \{ v_{sdq}^+ \hat{I}_{sdq}^+ \} \right)$$

$$T_x = 3pL_m \text{Im} \{ \psi_{sdq}^+ \hat{I}_{rdq}^+ \}$$

where $\hat{I}_{sdq}^+$ is a convoluted conjugate space vector of the stator-port current.

3. Control mechanism representation

3.1. Neural network mechanism structure

The regulation model is executed using standard SMC based on a predictive neural network with adding a resonant harmonic part (PSMC-R) adapted at 6-times feeder frequency as shown in Figures 3-4. It may be noted that the regular compensation unit (Rc) is a dual-action Integrator unit [28, 29]. Accordingly, the PSMC-R with a predicted sliding region for the stator-port power in $dq$ reference level can be developed to restrain the main and 5$^{th}$/7$^{th}$-degree harmonic items. According to the DRNN structure in [30, 31], the dynamic sequences of the DFIG system in Equations (6) and (7) can be formed as a non-affine NARX structure $fa$ (Nonlinear Auto-regressive eXogenous) based DRNN:

$$\bar{y}_{k+1} = f_a(\varphi_k, \varepsilon)$$

where the label $\varepsilon$ is white unevaluated noise. The regression arrays can be defined as $\varphi_k = [\bar{y}_{k+p-1}, ..., \bar{y}_{k+p-m_y}, u_{k-1}, ..., u_{k-m_u+1}]$ which uses absolute coefficients $m_y$ and $m_u$ to limit the regression vector depend on the previous shifted output ($\bar{y}$)/input ($u$) information. The new NARX affine form can be built using interior regression array and input elements $u_k$ as: $\varphi_k = [\varphi'_k, u_k]$, where $\varphi'_k = [\bar{y}_{k+p-1}, ..., \bar{y}_{k+p-m_y}, u_{k-1}, ..., u_{k-m_u+1}]$.

$$\varphi'_{k+1} = f_x(\varphi') + g_u(\varphi'), u_k + \bar{\omega}, \quad \bar{y}_k = h_y(\varphi')$$

where $f_x$, $g_u$ and $h_y$ are specified as DRNNs input and output components, also $\bar{\omega}$ is unmeasured disturbances. By re-structuring DRNNs Equation (10) to be similar to the low-rank of Taylor multi-series at the operation points $[\varphi'_o(k)]$ that is defined as previous sequences of input/output.

$$\varphi'(k+1) = f_x(\varphi'_o(k)) + \left( \frac{\partial f_x(\varphi')}{\partial \varphi'} \right)_{\varphi'_o(k)} (\varphi' - \varphi'_o) + \left( \frac{\partial h_y(\varphi')}{{\partial \varphi'}} \right)_{\varphi'_o(k)} (u - u_0) + \bar{\omega}$$

$$\Delta \varphi'_{k+1} = \hat{A}(\varphi' - \varphi'_o) + \hat{B} (u - u_0) + \delta_k$$

$$\bar{y}(k) = h_y(\varphi'_o(k)) + \left( \frac{\partial h_y(\varphi')}{\partial \varphi'} \right)_{\varphi'_o(k)} (\varphi' - \varphi'_o)$$

$$\Delta \bar{y}_k = \hat{C}(\varphi' - \varphi'_o)$$
Step-1: Load Input/Output data sequences of DFIG.

Step-2: Construct low-degree Taylor formula from RNN networks model (10), and define its layers, nodes, functions and ports.

Step-3: Initialize the RNNS weight.

Step-4: Train and validate the RNN.

Step-5: If MSE = Tolerance, No

Step-6: Get the linear RNN model (11).

Re-evaluate the weight.

Yes, Get the controller signal Umpc (21).

Minimize Object Function J (32)

Low-degree Taylor model (12)

Constraints

J < Tolerance

No

Apply stator-port power deviation in SMC-R unit as shown in Figure 11.

Obtain the converter switches PWM based on Uabc as shown in Figure 11.

Get the controller signal Umpc (21).

Initialize the Prediction Routine parameters

Define the linear steady-state model (12), sliding reference inputs, sliding output signals (30-39), control and prediction horizon, and sample intervals.

Set the constraint values of Input/Output (32).

Obtain the total control action Uabc (33), as a summation of resonant unit output Ure, SMC output, and predicted Umpc.

Initialize the SMC-R parameters

Read the calculated reference inputs of power and actual power Ps-Qs, which is calculated from +dq items.

Figure 5. The FAST-based wind turbine model

Figure 6. The training steps of the DRNN as (a) random data of inputs, (b) the DRNN verification for +dq (solid) and (dashed-trained data) and (c) the predicted errors. (A) +d-axes of the stator-port current. (B) +q-axes of the stator-port current.

Figure 7. Flow-chart of the PSMC-R design based on DRNN
3.2. PSMC-R mechanism structure

Most earlier studies presented a discrete-time sliding structure with a sliding surface scheme using a proportional or an integral part law, which is defined using system variables, or sometimes the sliding range is designed to be a specified path [32–34]. In this study, the sliding law is identified like the PI formula to find the optimal control action, and the state error is set as

\[ \Delta e_k^+ = \Delta x_k^+ - \Delta x_k^{ref} \]  \hspace{1cm} (13)

where \( x_k^+ \) is the signal of the expected input. Sliding-surface function (s) can be described as PI formula

\[ \Delta s_{k+1}^+ = k_p \cdot \Delta e_k^+ + k_i \cdot \Delta s_{k+1}^+ \]  \hspace{1cm} (14)

The \( \Delta \)-plane of sliding chatter path \( s^+ = \{ s_{k-1}^+ | s_{k-1}^+ = 0, \ k = 1, 2, \ldots \} \), and the integration deviation is

\[ \Delta \xi_k^+ = \Delta e_k^+ + \Delta \xi_{k-1}^+ \]  \hspace{1cm} (15)

Replacing Equation (12) into Equation (13)

\[ \Delta x_{k+1}^+ = \Delta x_k^+ - \Delta x_k^{ref} = \dot{A} \Delta x_k^+ + \dot{B} \Delta u_k^+ + d_k^+, \ d_k^+ = \delta_k^+ - \Delta x_k^{ref} + \dot{A} \Delta x_k^{ref} \]  \hspace{1cm} (16)

The identical control signal \( U_{c,k}^+ \) is offered to be a solution at \( \Delta s^+ = \Delta s_{k+1}^+ - \Delta s_k^+ = 0 \). [35]

\[ \Delta s_k^+ = k_p \cdot e_k^+ + k_i \cdot (e_k^+ + \xi_k^+) = (k_p + k_i) \Delta e_k^+ + k_i \Delta \xi_k^+ \]  \hspace{1cm} (17)

Re-forming Equation (17) based on Equation (16) to find the sliding term array as

\[ \Delta s_k^+ = G_m \cdot \dot{A} \Delta x_k^+ + \dot{B} \Delta U_{c,k}^+ + d_k^+ + k_i \Delta \xi_k^+ \]  \hspace{1cm} (18)

The applied identical control comprises a one-ahead shift disturbance that can be formed as

\[ \Delta U_{c,k}^+ = - \left( G_m \dot{B} \right)^{-1} (- \Delta s_k^+ + G_m \dot{A} \Delta x_k^+ + G_m d_{k-1}^+ + k_i \Delta \xi_k^+) \]  \hspace{1cm} (19)

Re-define the sliding sequence as \( s_{k+1}^+ = s_k^+ = 0 \). Thus, Equation (19) is determined as

\[ \Delta U_{c,k}^+ = - \left( G_m \dot{B} \right)^{-1} (G_m \dot{A} \Delta x_k^+ + G_m d_{k-1}^+ + k_i \Delta \xi_k^+) \]  \hspace{1cm} (20)

This investigation uses the predicted switching-part based on predictive control (pc) instead of the common switching-part of SMC \( \Delta U_{w,k} = K_m \text{sign} (\Delta s) + \eta \Delta s \) to extend the functional control space and coerce the system states to realize the sliding attributes. Consequently, the general formula of control action can be expressed as

\[ \Delta U_k^+ = \Delta U_{c,k}^+ + \Delta U_{w,k}^+ = \Delta U_{c,k}^+ + \Delta U_{pc,k}^+ \]  \hspace{1cm} (21)

The border layer \( \hat{\Delta} \) is described for constraining the state of chatter as follows

\[ \begin{cases} 1, & s^+ > \hat{\Delta} \\ k_s, & |s^+| \leq \hat{\Delta}, \ k = 1/\hat{\Delta} \\ -1, & s^+ < -\hat{\Delta} \end{cases} \]  \hspace{1cm} (22)

Thus,

\[ \Delta U_k^+ = - \left( G_m \dot{B} \right)^{-1} (G_m \dot{A} \Delta x_k^+ + G_m d_{k-1}^+ + k_i \Delta \xi_k^+ + G_m (k_m \text{sign} (\Delta s_k^+) + \eta \Delta s_k^+)) \]  \hspace{1cm} (23)

Replacing Equations (23), (21) into Equation (18), the future sequences of sliding term can be composed as

\[ \Delta s_{k+1}^+ = G_m \left( \dot{A} \Delta x_k^+ + \dot{B} \left( \Delta U_{c,k}^+ + \Delta U_{pc,k}^+ \right) + d_k^+ \right) + k_i \Delta \xi_k^+ = \Delta s_k^+ + G_m \dot{B} \Delta U_{pc,k}^+ + G_m \Delta \xi_k^+ \]  \hspace{1cm} (24)

\[ e_k^+ = d_k^+ - d_{k-1}^+ \]  \hspace{1cm} (25)

is an approximated error vector representing the disturbance under restriction

\[ |e_k^+| = d_k^+ - d_{k-1}^+ \leq \hat{\Delta}_d \]  \hspace{1cm} (26)
1. As indicated in Equation (24) with setting \( \Delta \tilde{u}^+ (k) = \Delta U_k^{+pc} \), the sliding status is expressed compactly as
\[
\Delta s_k^+ = \Omega \Delta s_k^+ + \Phi \Delta \tilde{u}_k^+ + \Gamma \epsilon_k^-,
\]
\[
y^+_k = H \Delta s_k^+
\]  
(26)

2. In Equation (26), the constant matrices are expressed as
\[
\Omega = [I \ 0], \ \Phi = [G_m B] = \begin{bmatrix}
0.433 & 0.039 \\
0.014 & 0.432
\end{bmatrix}, \ \Gamma = [G_m] = \begin{bmatrix}
0.15 & 0 \\
0 & 0.15
\end{bmatrix} \text{ and } H = \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}. \text{ An ordinary augmented formula is derived from Equation (26) using new variables } x_k^+(k) = \begin{bmatrix} \Delta s_k^+(k) \\ y_k^+(k) \end{bmatrix}^T \ [4].
\]

3. The associated matrices of sliding law in Equation (30) can be defined as
\[
\frac{\Delta s_k^+}{\Delta s_k^-} = \begin{bmatrix}
A_n \\ B_n \\ C_n \\ D_n
\end{bmatrix} \begin{bmatrix}
A_m \\ B_m \\ C_m \\ D_m
\end{bmatrix} \begin{bmatrix}
E_n \\ F_n \\ G_n \\ H_n
\end{bmatrix}
\]
\[
y_k^+ = \begin{bmatrix}
0 \\ I_q \\ 0 \\ 0
\end{bmatrix} \begin{bmatrix}
\Delta s_k^+ \\ y_k^+ \\ \epsilon_k^+
\end{bmatrix}
\]
(27)

4. \( Np \) and \( Nc \) are defined as the prediction of the sliding status deviation and control horizon step. Formula (27) uses the horizon range to expand the difference sliding sequences based on predictive control inputs as
\[
y_k^+(k+Np) = C_n A_m^{Np} x_k^+(k) + C_n A_m^{Np-1} B_n A_m \Delta \tilde{u}^+(k) + C_n A_m^{Np-2} B_n \Delta \tilde{u}^+(k+1) + \cdots + C_n A_m^{Np-Nc} B_n \Delta \tilde{u}^+(k+Nc-1) + C_n E_n \epsilon^+(k+Np-1)
\]
(28)

5. Define the predicted output of sliding, subsequent series of control, and deviation of disturbances arrays as
\[
\tilde{y}_k(k) = \begin{bmatrix}
y_k^+(k+Np) \\
\epsilon_k^+(k+Np)
\end{bmatrix} \in \mathbb{R}^{N_c}, \quad \Delta \tilde{y}_k(k) = \begin{bmatrix}
\Delta x_k^+(k+Np) \\
\Delta \epsilon_k^+(k+Np)
\end{bmatrix} \in \mathbb{R}^{N_c}
\]
(29)

6. The compact form of equivalent output progressions under prediction is derived as
\[
\tilde{y}_k(k) = E \tilde{y}_k(k) + M \Delta \tilde{u}_k(k) + \Lambda \epsilon^+(k)
\]
(30)

7. The associated matrices of sliding law in Equation (30) can be defined as
\[
E = \begin{bmatrix}
C_n A_m \cdots C_n A_m^{Np-1}
\end{bmatrix}^T, \quad M = \begin{bmatrix}
C_n B_n \\ C_n A_n B_n \\ \vdots \\ C_n A_m^{Np-1} B_n
\end{bmatrix} \begin{bmatrix}
C_n E_n \\ C_n A_n E_n \\ \vdots \\ C_n A_m^{Np-1} E_n
\end{bmatrix}
\]
\[
\Lambda = \begin{bmatrix}
C_n A_m E_n \\ C_n A_n E_n \\ \vdots \\ C_n A_m^{Np-1} E_n
\end{bmatrix}
\]
(31)

8. Minimization rule of the cost function based on problem Equation (30) is defined as [4]
\[
J(k) = \sum_{i=0}^{N_c-1} ||y^+e(k+i[k]) - y(k+i[k])||^2_{G_i} + \sum_{i=0}^{N_c-1} ||\Delta u(k+i[k])||^2_{M_i}
\]
(32)

9. where \( y^+e \) is the items of desired input, \( y \) is the items of output progressions, \( Io \) and \( G \) are the + definite weight matrices within a restricted range of input/output. The restriction term \( \Delta \tilde{d} \) in Equation (25) is a quasi-sliding value that makes the sliding response close to the sliding path in a short steps and also removes chattering behavior [35, 36]. The complete control law is comprised of \( Rc \) unit as
\[
u_r^+ = u_{Rc}^+ + U_{k,dq}^+
\]
(33)
Figure 8. Bode spectrum of (a) resonant function (b) PSMC-R controller (c) open control-loop trajectory.

The discrete-time Tustin paradigm-based second-degree double-task integral compensation $R_c$ unit is connected with the PSMC in a parallel connection.

$$R_c = sK_{ro}/(s^2 + (\pm 6\omega_c)^2) \bigg|_{s = \frac{\omega_c}{2\tau}}$$

(34)

The gains of $R_c$ unit are defined as $K_{ro} = 56.3$ and $K_{ro} = 43.8$. Thus, the magnitude against the 300 Hz is 30.1 dB within the inversion points around $\pm 90^\circ$ in the Bode curve based on the resonant unit, as shown in Figure 8(a). The PSMC-R and open-loop path Bode curve in Figure 8(b) and Figure 8(c) for $P_s$ show that the magnitude at 300 Hz are (32.3dB) with the phase degree swing around $0^\circ$, and (98.6dB) with the phase degree swing around $-90^\circ$ respectively. Thus, these characteristics of magnitude and phase values are broad enough to decrease the control deviation and suit the compensation mechanism. Moreover, the multiple complicated-coefficients filter MCCF used to extract the main signals and their harmonic chains for the overall system under the supply distortion [37], as shown in Figure 9.

Figure 9. MCCF filter with a cut-off frequency $\omega_{cut}$.

Figure 10. The public diagram of DFIG-WPGS.

Figure 11. Diagram of the PSMC-R technique for the DFIG.

Figure 12. The internal connections of the PSMC-R control unit.
4. Analysis of the results

According to the general schematic diagrams of DFIG-WPGS in Figure 10, the control unit PSMC-R is presented with its internal connections, as shown in Figures 11 and 12. The rated DFIG parameters and quantities are defined in Table 1. The regulator principle for DC-tied voltage is designed based on a bidirectional-tied converter toward network-port based on the space vector modification SVM standards to conform to the approach described in [38]. Figure 13 illustrated that the system responses depend on different control types, identified along the time from 0 to 1.25 sec while the harmonic regulator unit is inactive within 0-0.5 sec for the PI regulator. At the interval time 0-1 sec, the traditional PI, PIR-Naslin, and SMC control are applied to the system during the occurred harmonic condition. Also, after 1 sec is depleted, the offered PSMC-R control at +dq-level allowed to control the stator-port power during harmonic growth. However, within the time interval classified as a PI regulator and before the submitted control approach for harmonic, the graphical results in Figures 13 confirmed that the regular controller is unreliable in dealing with harmonic sequence components on the stator power dq-reference level. Thus, the stator-port current is exceedingly malformed that exhibited in Figure 13(c). Furthermore, the active 300 Hz oscillation is provided momentarily on stator-port power and MT in Figure 13 (a, b and g). In Figure 14, the effect of PI without the harmonic regulator unit is shown as the spectral range of the harmonic sequence versus frequency range during the 0-0.5 sec time range for the stator- and rotor-port current. Due to the feeder voltage deformation, the 5th/7th-degree harmonic series at frequency 250/350 Hz are also originated in stator-port current and magnetic intensity into the machine air slots. In Figure 13 (d), the AC rotor current actual frequency of 5 Hz is produced from these characteristics and involves harmonic sequences with corresponding frequencies of 295 Hz and 305 Hz for types 5th and 7th-degree, respectively influences rotor-port waveform. When the PIR-Naslin, SMC, and PSMC-R were enabled at 0.5, 0.75, and 1 sec respectively, as formed in Figures 13 (a and b), the (+) successions of primary and harmonic items with (5th-/7th-types) are produced on the stator power that conveniently adapted with fast response growth. Explicitly, the harmonic components of stator power based on offered controller achieved a

![Figure 13](image_url)

Figure 13. The results as (pu) for 4% and 3% of 5th/7th harmonic types during distorted voltage (a) active power, (b) reactive power. (c) AC stator-port currents. (d) AC rotor-port currents (e) +d-axis rotor-port current. (f) +q-axis rotor-port current. (g) Generator electromagnetic torque. (h) DC-link voltage.
low tracking error conduct between the desired signals and estimated performance. To view the preference of
PSMC-R, the max-oscillation rate of Ps and Qs associated with 300 Hz, the $5^{th} / 7^{th}$-degree sequences terms of
harmonics on stator current, rotor current associated with 5 Hz, electromagnetic torque, and the DC-voltage,
are scheduled clearly in Table 2. The PSMC-R mechanism is capably attaining the control functions, as shown
in Figures 13 and Table 2. Furthermore, the desired and dynamic reaction has achieved a good tracking error
while decreasing 5 Hz-harmonic waves for the rotor current. Also, it presented high mitigation in MT pulsations
associated with 300 Hz and $5^{th} / 7^{th}$-degree harmonics on stator-port active power and current, which presents
the regular heating process in the rotor windings while reducing the losses associated with harmonics waves.

Further assessment is presented during 5% ratio for each $5^{th} / 7^{th}$-type HPI on voltage in Figure 15.
As shown in Figure 15, immediately after voltage distortions occur at 1 sec, the compensation function inside
the PSMC-R accurately regulates 300 Hz components related to the $-5 \omega_c$ and $7\omega_c$ hesitations at the $+dq$
reference level attenuate the introduced harmonics. The PSMC-R control gives smoother fluctuations for the
model responses, especially for stator power and MT during the distortions of the network voltage in Figures 15
(a, b and g), respectively. Besides, the fluctuation rates of $dq$-stator-port active/reactive power and MT are
around ($\pm 1.46$, $\pm 3.1$, $\pm 4.66$ and $\pm 5.11\%$), ($\pm 1.26$, $\pm 3.55$, $\pm 4.38$ and $\pm 4.48\%$), ($\pm 2.19$, $\pm 3.73$, $\pm 5.64$, and
$\pm 6.18\%$), respectively, whereas, the average of DC voltage fluctuation is ($\pm 1.98$, $\pm 2.44$, $\pm 3.89$ and $\pm 4.32\%$)
for PSMC-R, SMC, PIR-Naslin and PI, as shown in Figure 15 (h). Also, Figures 15 (e and f) offer that the
oscillation rates of the $dq$-rotor current are ($\pm 3.2$, $\pm 3.95$, $\pm 6.41$, and $\pm 7.26\%$) and ($\pm 2.96$, $\pm 4.31$, $\pm 4.88$ and

Table 2. Results of comparative analysis for different control mechanisms

<table>
<thead>
<tr>
<th>HPI</th>
<th>Pulsation (%)</th>
<th>PI</th>
<th>PIR</th>
<th>SMC</th>
<th>PSMC-R</th>
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<tr>
<td>$I_s$</td>
<td>$5\omega_c$</td>
<td>$\pm 4.90$</td>
<td>$\pm 3.16$</td>
<td>$\pm 1.91$</td>
<td>$\pm 0.54$</td>
</tr>
<tr>
<td>$I_r$</td>
<td>$7\omega_c$</td>
<td>$\pm 4.40$</td>
<td>$\pm 3.40$</td>
<td>$\pm 1.60$</td>
<td>$\pm 0.52$</td>
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<tr>
<td>$I_{29}\omega_c$</td>
<td>$\pm 3.10$</td>
<td>$\pm 3.40$</td>
<td>$\pm 1.99$</td>
<td>$\pm 0.90$</td>
<td></td>
</tr>
<tr>
<td>$I_{30}\omega_c$</td>
<td>$\pm 3.40$</td>
<td>$\pm 3.10$</td>
<td>$\pm 1.89$</td>
<td>$\pm 0.90$</td>
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</tr>
<tr>
<td>$P_s$</td>
<td>$\pm 4.71$</td>
<td>$\pm 4.34$</td>
<td>$\pm 2.46$</td>
<td>$\pm 1.08$</td>
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<tr>
<td>$Q_s$</td>
<td>$\pm 1.74$</td>
<td>$\pm 4.22$</td>
<td>$\pm 4.01$</td>
<td>$\pm 2.06$</td>
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<td>$Te$</td>
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<td>$\pm 2.97$</td>
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<td>$\pm 4.70$</td>
<td>$\pm 2.47$</td>
<td>$\pm 2.03$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 14. Harmonic curve for (a) Stator-port current at 50 Hz. (b) Rotor-port current at 5 Hz.

Figure 15. The results as (pu) for 5% of $5^{th} / 7^{th}$ harmonic types during distorted voltage (a) active power.(b) reactive power. (c) AC stator-port currents. (d) AC rotor-port currents (e) $+d$-axis rotor-port current. (f) $+q$-axis rotor-port current. (g) Generator electromagnetic torque. (h) DC-link voltage.
±5.99%) for the PSMC-R, SMC, PIR-Nasl and PI respectively. In the real-time running of WPG, the wind speed is frequently changing, and the turbine speed controller may not provide a fast response to an abrupt change in the four operating regions. That may lead to reduce the efficiency or damage the system equipment. PSMC-R strategy is applied with a down-/upward slope of the rotor speed between 1640 and 1170 rev/min (1.093 pu – super-synchronous to 0.8 pu sub-synchronous mode). The downward region occurred at the time interval 0.4-1.05 sec shown in Figure 16(b). The stator voltage maintains the $5^{th}/7^{th}$ HPI values as 4% and 3%. The emulated power response in Figure 16 explained that the provided method carried out better dynamic performance through numerous degrees of rotor speed. The rate of an amount attributed to stator-port active power and ETM was decreased from 1 to 0.73 pu with an increasing oscillation ratio from 2.2% to 10.2%, and 1 to 0.71 pu with increasing oscillation ratio from 3.2% to 19.2% in the interval time 0.4-1 sec respectively, as in Figure 16 (a, b and g). As seen, under the introduced control system, an increase in 300 Hz wave signals appeared as high ripples on the produced stator power and MT signals during the harmonics deformation with changed speed. In Figure 16, the PSMC-R regulator gave a good performance during numerous of rotor-port speed degrees and ripples of the torque stress on the generator. Figures 16 (e and f) illustrated that the current capacitance ratio of the rotor-port decreased by about 50.6%, with the oscillation ratio increasing from 3.2% to 19.2% in the interval time of 0.4-1 sec, respectively. Also, in Figures 16, the PSMC-R carried out good tracking performance of stator power, stator, and rotor current at (+dq) reference level, with smaller overshoot, less current oscillation ripple during 100% of stator power and fast response during variation of rotor speed. Besides, PSMC-R maintained constant sequence periods for stator current and proper DC voltage tracking at its nominal path; meantime, it has adapted the sequence for rotor current at 0.4 and 1 sec, as in Figures 16 (c, h and d), respectively. Further dynamic analysis of the PSMC-R is achieved during the wind movement variation between cut-in and the rated speed (15 m/sec) along 0.4-2 sec, as shown in Figure 17 (a). In Figure 17 (c and d), the regulation units of DFIG-WPGS generate a low value of the generator power and torque that swing at

![Figure 16](image1.png)

**Figure 16.** The results as (pu) during changing in the rotor- velocity (a) active and reactive power. (b) rotor-port velocity. (c) AC stator-port currents. (d) AC rotor-port currents (e) +d-axis rotor-port current. (f) +q-axis rotor-port current. (g) Generator electromagnetic torque. (h) DC-link voltage.

![Figure 17](image2.png)

**Figure 17.** Dynamic results based on (a) wind profile that changes between cut-in speed (3.5m/s) and nominal speed (15m/s). (b) Generator power (pu). (c) Generator torque (pu).
Figure 18. The results as(pu) with various parameters alterations for (a) active power. (b) reactive power. (c) AC stator-port currents. (d) AC rotor-port currents (e) +d-axis rotor-port current. (f) +q-axis rotor-port current. (g) Generator electromagnetic torque. (h) DC-link voltage.

0.25 pu and −0.3 pu around the cut-in wind speed along (0.4-1 sec and 1.5-2 sec) respectively, based on the selection mechanism of the maximum power. Besides, when the wind movement increases with a sufficient speed to allow the WT to run in the classified speeds range, the DFIG-WPGS can deliver the power toward the grid and increase the generator torque to swing around the nominal values along 1-1.5 sec. The parameters variation test is performed by assuming that coil inductance parameters are changed based on the inherent variations in the interior machine magnetic behavior during sudden operating changes. Besides, the expected changing resistors values of stator and rotor are involved while discarding their windings leakage differences. This test offered PSMC-R during the same hypothesis in the first dynamic test. In Figure 18, the mutual inductor and stator/rotor resistor coefficients values are decreased -50% in the FC-I test, and also -50% and +50% are included to mutual inductor and resistors in FC-II test respectively, besides +50% has been added to all specified coefficients in FC-III test. In general, Figures 18 (a, b and g) show that the PSMC-R mechanism gives smoother fluctuation rates of the stator-port active/reactive power and MT around (2.09, 1.3, 2.0 and 1.6%), (2.87, 3.21, 3.1 and 3.02%), (2.84, 3.4, 2.51 and 2.9%) for the NC, FC (I,II,III) tests respectively. Whereas, the average of DC voltage fluctuation is (3.91, 3.56, 3.3 and 3.02%) for the NC, FC (I,II,III) tests, as shown in Figure 18 (h) respectively. Also, Figures 18 (e) to (f) offer that the oscillation rates of the dq-rotor current are (4.6, 5.1, 5.02 and 4.7%) and (8.21, 7.7,8.8 and 8.6%) for the NC, FC (I,II,III) tests, respectively. All results demonstrate that the dynamic realization of the proposed PSMC-R gave satisfactory durability during the extreme changes of the stator, rotor, and combined inductive parameters.

5. Conclusion
This topic has discussed PSMC-R that contains predictive sliding chattering signals based on the deep-recurrent neural network for the stator-port power model of the non-linear DFIG-WPG under 5th and 7th-degree deformation voltage. The PSMC-R finds the optimum variables with different process modes by reformulating the conventional SMC based on the required power using a predictive term to expect the best points in the sliding plane using the quadratic algorithm module feature plus compensation unit. Simulation results showed that the designed prediction algorithm-based sliding chatter law of the SMC-R approach presented the best dynamic tracking and low overshoot and fluctuation of energy quantities compared to classical control approaches during various operation terms. Besides, the frequency of stator-port sinusoidal current wave has remained constant. Also, the components of stator-port power collected from basic and 5th and 7th-degree is promptly manipulated using the PSMC-R approach to avoid successive dismantling of the components.
References


