Introduction. The increasing use in the industrial sector of powered systems electronically and controllable, motivated by the improvement of their performance, has led to a proliferation of static converters. Among these most common structures and the most attractive are the Pulse Width Modulation (PWM) voltage rectifier [1].

Participation in system services must be on an equal footing with conventional energy which presents the constraints of distance from the electricity network and the constraints of fuel transport, as well as the periodic maintenance of the installations [3].

In recent literatures, authors have investigated the potential technical impacts in voltage regulation, active and reactive power variations, transformers loading, current and voltage harmonics causes with renewable energy integration [4-6].

In the resolution of harmonics disturbances problems, many researchers used the sinusoidal PWM approach and implement it in Wind Energy Conversion System (WECS) to ameliorate the harmonic content on the output voltage waveform [7]. Space vector modulation technique possesses remarkable performance in 3-level PWM topologies [8]. Other techniques involving modulation methods at a low switching frequency that have attained more demand in a broader field of function are staircase forms and the associated polluting effects, mainly caused 

Purpose. For guarantee the satisfying quality of power transmitted to the electrical grid, while ensuring reduction of current ripples and output voltage harmonics. Novelty. This work proposes a new smart control, based on a predictive current control of the three level neutral point clamped inverter, used in Wind Energy Conversion System (WECS) connected to grid, based permanent magnet synchronous generator, powered by a hysteresis current control for the rectifier. This new formula guarantees handling with the influence of harmonics disturbances (similar current total harmonic distortion), voltage stress, switching losses, rise time, over or undershoot and settling time in WECS. Methods. The basic idea of this control is to choose the best switching state, at the power switches, which ameliorates the quality function, selected from order predictive current control of WECS. Results. Practical value. Several advantages in this intelligent method, such as the fast dynamic answer, the easy implementation of nonlinearities and it requires fewer calculations to choose the best switching state. In addition, an innovative algorithm is proposed to adjust the current ripples and output voltage harmonics of the WECS. The performances of the system were analyzed by simulation using MATLAB/Simulink. References 33, table 3, figures 11.

Key words: hysteresis current control, permanent magnet synchronous generator, predictive current control, wind energy conversion system, three level neutral point clamped inverter.

Introduction. The increasing demand for performance and efficiency of converters and power drives, the development of new control systems must take into account the real nature of these types of systems. Converters and dimmers power are nonlinear systems of a hybrid nature, including elements linear and nonlinear and a finite number of switching devices. Signals input for power converters are discrete signals that control the ‘opening and closing’ transitions of each component. Problem. In the multilevel inverters connected to grid, the switching frequency is the principal cause of harmonics and switching losses, which by nature, reduces the inverter’s efficiency. Purpose. For guarantee the satisfying quality of power transmitted to the electrical grid, while ensuring reduction of current ripples and output voltage harmonics. Novelty. This work proposes a new smart control, based on a predictive current control of the three level neutral point clamped inverter, used in Wind Energy Conversion System (WECS) connected to grid, based permanent magnet synchronous generator, powered by a hysteresis current control for the rectifier. This new formula guarantees handling with the influence of harmonics disturbances (similar current total harmonic distortion), voltage stress, switching losses, rise time, over or undershoot and settling time in WECS. Methods. The basic idea of this control is to choose the best switching state, at the power switches, which ameliorates the quality function, selected from order predictive current control of WECS. Results. Practical value. Several advantages in this intelligent method, such as the fast dynamic answer, the easy implementation of nonlinearities and it requires fewer calculations to choose the best switching state. In addition, an innovative algorithm is proposed to adjust the current ripples and output voltage harmonics of the WECS. The performances of the system were analyzed by simulation using MATLAB/Simulink. References 33, table 3, figures 11.

Key words: hysteresis current control, permanent magnet synchronous generator, predictive current control, wind energy conversion system, three level neutral point clamped inverter.
modulation, space vector control [9, 10], selective harmonic elimination [10, 11] and sliding mode control for Permanent Magnet Synchronous Generator (PMSG) [12].

**System for application generator.** In the studied system, we are interested in the wind rotor PMSG and its use for the production of electrical energy from wind power. The variable speed configuration is represented in Fig. 1.

![Fig. 1. PMSG-based WECS](Image)

The rotor is connected to a rectifier (rotor side converter). A predictive control applied to Three Level Neutral Point Clamped (3L-NPC) inverter (grid side converter), which is placed in the output of the rectifier converter. A predictive control applied to Three Level

**1. The modeling of the turbine.** The turbine rotate speed is depending on wind speed; this makes it possible to know the wind torque applied to the wind turbine. This modeling is based on bibliographic cross-checking or additional information from brochures from different manufacturers [13]:

\[ P_{awr} = \frac{1}{2} \rho \pi \rho \beta \lambda \omega Y^3 \]  
(1)

where \( P_{awr} \) is the aerodynamic power; \( c_p \) indicates the performance coefficient of the wind generator; \( \lambda \) is the speed ratio (rad); \( \beta \) is the inclination angle of the blade, which depicts the orientation angle of the blades; \( \Omega \) is the turbine rotation speed; \( R \) is the blade radius; \( \nu \) is the wind speed; \( \rho \) is the air density (1.22 kg/m\(^3\) at atmospheric pressure at 15 °C); the Betz limit is that the coefficient \( c_p(\lambda, \beta) \) does not exceed the value 16/17=0.59 [13, 14].

**2. Modeling of the multiplier.** The multiplier adapts the turbine rotation speed to the PMSG rotation speed. For this we grant a multiplier between the turbine and the PMSG, the latter is mathematically modelled by the following equations:

\[ C_g = \frac{C_s}{G} \]  
(3) and \( \Omega_b = \frac{\Omega_{mech}}{G} \).  
(4)

The mechanical equations:

\[ \frac{C_t}{G} - C_g = \frac{J_t}{G^2} + J_g \frac{d\Omega_{mech}}{dt} + \left( f_s + f_g \right) \Omega_{mech}; \]  
(5)

\[ J_t + J_g = J \]  
(6) and \( f_s + f_g = f \).  
(7)

So, the mechanical equations are:

\[ C_{mech} = J \frac{d\Omega_{mech}}{dt}; \]  
(8)

\[ C_{mech} = C_g - C_{cm} - C_{vis}; \]  
(9)

\[ C_{vis} = f \Omega_{mech}; \]  
(10)

where \( C_{mech} \), \( C_t \), \( C_g \), \( C_{cm} \), \( C_{vis} \) are the mechanical, wind, electromagnetic and viscous torques, respectively; \( J, J_t, J_g \)

are the total, turbine and generator inertias; \( f, f_s, f_g \) are the coefficient of total friction, viscous friction of the turbine and of the generator; \( G \) is the ratio of the speed multiplier; \( \Omega_{mech} \) is the generator rotation speed (fast axis).

**3. PMSG modeling.** By choosing a d-q reference frame synchronized with the stator flux [3, 14, 15] are next.

The equations of tensions:

\[ \begin{align*}
V_{sd} &= R_s I_{sd} + \frac{d\phi_{sd}}{dt} - \omega_s \phi_{sq}; \\
V_{sq} &= R_s I_{sq} + \frac{d\phi_{sq}}{dt} - \omega_s \phi_{sd}; \\
V_{rd} &= R_r I_{rd} + \frac{d\phi_{rd}}{dt} - (\omega_s - \omega)\phi_{rq}; \\
V_{rq} &= R_r I_{rq} + \frac{d\phi_{rq}}{dt} - (\omega_s - \omega)\phi_{rd}; \\
J \frac{d\Omega}{dt} &= C_{em} - C_r - f_r \Omega_r.
\end{align*} \]  
(11)

The equations of the flux:

\[ \begin{align*}
\phi_{sd} &= L_s I_{sd} + M I_{rd}; \\
\phi_{sq} &= L_s I_{sq} + M I_{rq}; \\
\phi_{rd} &= L_r I_{rd} + M I_{sd}; \\
\phi_{rq} &= L_r I_{rq} + M I_{sq}; \\
C_{em} &= \frac{M}{L_s} (\phi_{dr} - \phi_{qr}) I_{dr}.
\end{align*} \]  
(12)

The electromagnetic torque becomes:

\[ C_{em} = \frac{3}{2} M \frac{1}{L_s} (\phi_{dr} I_{ds} - \phi_{dr} I_{ds}). \]  
(13)

The stator and rotor active and reactive powers are expressed by:

\[ \begin{align*}
P_s &= \frac{3}{2} (V_{sd} I_{sd} + V_{sq} I_{sq}); \\
Q_s &= \frac{3}{2} (V_{sq} I_{sd} + V_{sd} I_{sq}); \\
P_r &= \frac{3}{2} (V_{rd} I_{rd} + V_{rq} I_{rq}); \\
Q_r &= \frac{3}{2} (V_{rq} I_{rd} + V_{rd} I_{rq}).
\end{align*} \]  
(15)

where \( R_s, R_r \) are the stator and rotor resistances; \( L_s, L_r, M \) are the stator, rotor, mutual inductances, respectively; \( I_{sd}, I_{sq}, I_{rd}, I_{rq} \) are the stator and rotor currents in the d-q frame; \( \omega_{dr}, \omega_{qr} \phi_{dr}, \phi_{qr} \) are the stator and rotor flux in the d-q frame; \( p \) is the number of pairs of poles; \( P_s, Q_s, P_r, Q_r \) are the stator and rotor active and reactive powers; \( V_{sd}, V_{sq}, V_{rd}, V_{rq} \) are the stator and rotor voltage components in the d-q frame; \( \omega_s \) is the speed of stator magnetic field; \( \omega_e = \omega_s - \omega \) is the angular speed of rotor; \( \omega \) is the mechanical angular speed.

PMSG and turbine parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
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</table>

<table>
<thead>
<tr>
<th>PMSG and turbine parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PMSG parameters</td>
<td>Turbine parameters</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>( P_s = 1680 ) W</td>
<td>( R = 1.8 ) m</td>
</tr>
<tr>
<td>( V_s = 110 ) V</td>
<td>( J = 0.07 ) kg·m²/s²</td>
</tr>
<tr>
<td>( f = 50 ) Hz</td>
<td>( G = 1 )</td>
</tr>
<tr>
<td>( f_s = 0.9585 ) Ω</td>
<td>( \rho = 1.25 ) kg·m³</td>
</tr>
</tbody>
</table>
Hysteresis current control.

1. Modeling of the rectifier. The rectifier bridge consists of three arms with six bipolar transistors antiparallel with diodes. These switches are controlled by closing and opening (pulse time closing «0» and opening «1»). And in the same arm the switches operate in a complementary way \((K_a = K_d')\) to avoid the short circuit [16]. The model of bridge rectifier is depicted in Fig. 2.

![Fig. 2. Bridge rectifier](image)

The different switching and combination states of the PWM rectifier switches are shown in Table 2.

### Table 2

<table>
<thead>
<tr>
<th>K</th>
<th>(S_a)</th>
<th>(S_b)</th>
<th>(S_c)</th>
<th>(V_{ab})</th>
<th>(V_{bc})</th>
<th>(V_{ac})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>(U_{dc})</td>
<td>0</td>
<td>(-U_{dc})</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>(-U_{dc})</td>
<td>(-U_{dc})</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>(-U_{dc})</td>
<td>(U_{dc})</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>(-U_{dc})</td>
<td>0</td>
<td>(U_{dc})</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>(-U_{dc})</td>
<td>(-U_{dc})</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>(U_{dc})</td>
<td>0</td>
<td>(-U_{dc})</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>(-U_{dc})</td>
<td>0</td>
<td>(U_{dc})</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>(0)</td>
<td>(0)</td>
<td>(0)</td>
</tr>
</tbody>
</table>

8 possible states of the switches:

\[
V_b = f_a U_{dc}; \quad V_c = f_e U_{dc}; \quad \text{(19)}
\]

where:

\[
f_a = \frac{2S_a - (S_b + S_c)}{3}; \quad \text{(21)}
\]

\[
f_b = \frac{2S_b - (S_a + S_c)}{3}; \quad \text{(22)}
\]

\[
f_c = \frac{2S_c - (S_a + S_b)}{3}; \quad \text{(23)}
\]

8 possible states of the input voltage \(V\) in a complex plane \(\alpha-\beta\) [20]:

\[
V_{k+1} = \frac{2}{3} U_{dc} e^{\frac{jk\pi}{3}} \quad \text{for} \quad k = 0...5; \quad \text{(24)}
\]

\[
V_\gamma = V_0 = 0.
\]

8 voltage vectors noted as \(V_0(0 0 0)\) – \(V_7(1 1 1)\) are presented in Fig. 3, where \(V_{ab}, V_{bc}, V_{ac}\) are the complex voltages; \(f_a, f_b, f_c\) are the rectifier switching function; \(U_{dc}\) is the rectified voltage; \(S_a, S_b, S_c\) are the switching states of the rectifier; \(V_a, V_b, V_c\) are the simple voltages.

![Fig. 3. Presentation of voltage vector \(V_k\)](image)

2. Functional representation of the PWM rectifier in the three-phase reference. The voltage equations for the balanced three-phase system without neutral can be written as (Fig. 3):

\[
\bar{e} = \bar{V}_1 + \bar{V}; \quad \text{(25)}
\]

\[
\bar{e} = RI + L \frac{di}{dt} + \bar{V}; \quad \text{(26)}
\]

\[
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} =
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} +
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}; \quad \text{(27)}
\]

The rectifier input voltage can be written as:

\[
V_{in} = U_{dc} \left( S_n \frac{n}{3} \sum_{n=0}^{c} S_n \right), \quad \text{(28)}
\]

where \(S_n = 0\) or \(1\) are the state of the switches, where \((n = a, b, c)\). In addition, we can write the DC bus current as:

\[
C \frac{dU_{dc}}{dt} = i_c. \quad \text{(29)}
\]

The current in the capacitor can also write:

\[
I_c = I_{dc} - i_c. \quad \text{(30)}
\]

Also, the current \(i_c\) is the sum of the currents of each phase by the state of its switch [16]:

\[
C \frac{dU_{dc}}{dt} = S_{a1} i_a + S_{b1} i_b + S_{c1} i_c - i_c. \quad \text{(32)}
\]

So, the AC side of the rectifier:

\[
L \frac{di_a}{dt} + R i_a = e_a - U_{dc} \left( S_a - \frac{1}{3} \sum_{n=0}^{c} S_n \right); \quad \text{(33)}
\]

\[
L \frac{di_b}{dt} + R i_b = e_b - U_{dc} \left( S_b - \frac{1}{3} \sum_{n=0}^{c} S_n \right); \quad \text{(34)}
\]

\[
L \frac{di_c}{dt} + R i_c = e_c - U_{dc} \left( S_c - \frac{1}{3} \sum_{n=0}^{c} S_n \right); \quad \text{(35)}
\]

where the network voltages are expressed by:

\[
e_a = E_a \sin(\omega t); \quad \text{(36)}
\]

\[
e_b = E_b \sin(\omega t - 2\pi/3); \quad \text{(37)}
\]

\[
e_c = E_c \sin(\omega t + 2\pi/3). \quad \text{(38)}
\]

The above equation can be summarized as:

\[\text{Equation}\]

**Electrical Engineering & Electromechanics, 2024, no. 2**
1. Modeling inverter 3L-NPC. The power and control circuit of a 3L-NPC inverter connected to grid is shown in Fig. 6. Each phase of three-phase 3L-NPC inverter consists of 3 arms constituted of 4 switches (S1, S2, S3, S4) connected in series and 2 median diodes (D1 and D2). The midpoints of switches (S2 and S3) of each phase are connected to the load and the midpoints of diodes (D1 and D2) are connected to the neutral point [24, 25].

In the same arm the switches operate in a complementary way connection functions of the arm switches k (a complementary way) will be given by:

\[
\begin{align*}
S_{a1} &= \overline{S}_{a2}, \\
S_{a3} &= \overline{S}_{a4}, \\
S_{a2} &= \overline{S}_{a3}, \\
S_{a4} &= \overline{S}_{a1}.
\end{align*}
\]  

(41)

where \( e_a, e_b, e_c \) are the network voltages; \( V_a \) are the instantaneous phase voltages; \( S_n \) are the switching states; \( i_c \) is the capacitor current; \( i_{ch} \) is the rectifier output current; \( E_n \) is the maximum phase voltage.

3. PWM to hysteresis band. The purpose of hysteresis controller is to force the actual current to follow the predefined reference current. In conventional hysteresis controller, the comparators switch between the fixed bandwidths, this technique only requires a hysteresis comparator per phase [21, 22].

The principle of hysteresis used in this system is expressed in Fig. 4. The switch opens if the error becomes less than \(-H/2\), it closes if the latter is greater than \(+H/2\), where \( H \) is the range (or width) of hysteresis. If the error is now between \(-H/2\), and \(+H/2\), (it varies within the hysteresis range), the switch does not switch [21, 23].

\[
L \frac{di_a}{dt} + R_i n = e_a - U_{dc} \left( S_n - \frac{1}{3} \sum_{n=a}^{c} S_n \right); \quad (39)
\]

\[
C \frac{dU_{dc}}{dt} = \sum_{n=a}^{c} i_n S_n - i_{ch}, \quad (40)
\]

where \( e_a, e_b, e_c \) are the network voltages; \( V_a \) are the instantaneous phase voltages; \( S_n \) are the switching states; \( i_c \) is the capacitor current; \( i_{ch} \) is the rectifier output current; \( E_n \) is the maximum phase voltage.

The topology of hysteresis current control PWM technique using in this configuration is shown in Fig. 5.

Implementation predictive current control 3L-NPC inverter.

The topology of hysteresis current control PWM technique using in this configuration is shown in Fig. 5. In the same arm the switches operate in a complementary way connection functions of the arm switches \( k \) (a complementary way) will be given by:

\[
\begin{align*}
S_{a1} &= \overline{S}_{a2}, \\
S_{a3} &= \overline{S}_{a4}, \\
S_{a2} &= \overline{S}_{a3}, \\
S_{a4} &= \overline{S}_{a1}.
\end{align*}
\]

(41)

The switching function on \( A, B, \) and \( C \) phase can be defined as follows:

\[
\begin{align*}
S_{k1} &= \overline{S}_{k3} \\
S_{k2} &= \overline{S}_{k4}
\end{align*}
\]

(42)

The equations of voltages \((a), (b), (c)\) of the three-level inverter, with respect to the midpoint \(\text{«}0\text{»}\) of the input voltage source is expressed as [26, 27]:

\[
\begin{align*}
V_{a0} &= (S_{a1}S_{a2} - S_{a3}S_{a4})V_{dc}; \\
V_{b0} &= (S_{b1}S_{b2} - S_{b3}S_{b4})V_{dc}; \\
V_{c0} &= (S_{c1}S_{c2} - S_{c3}S_{c4})V_{dc}.
\end{align*}
\]

(43)

The compound voltages in matrix form are:

\[
\begin{bmatrix}
V_{ab} \\
V_{bc} \\
V_{ac}
\end{bmatrix} =
\begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1 \\
-1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
S_{a1}S_{a2} - S_{a3}S_{a4} \\
S_{b1}S_{b2} - S_{b3}S_{b4} \\
S_{c1}S_{c2} - S_{c3}S_{c4}
\end{bmatrix}V_{dc}.
\]

(44)

We can define the simple voltages \((v_a, v_b, v_c)\) with respect to the neutral point \(n\):

\[
\begin{align*}
v_a &= v_{an} = v_{a0} - v_{n0}; \\
v_b &= v_{bn} = v_{b0} - v_{n0}; \\
v_c &= v_{cn} = v_{c0} - v_{n0}.
\end{align*}
\]

(45)

The voltage equation between the midpoint of the DC power supply of the inverter and the point load neutral which is written as follows:

\[
v_{n0} = \frac{1}{3}(v_{a0} + v_{b0} + v_{c0}).
\]

(46)

Finally, the system in the matrix form is:

\[
\begin{align*}
v_a &= \frac{2}{3} \begin{bmatrix}
S_{a1}S_{a2} - S_{a3}S_{a4} \\
S_{b1}S_{b2} - S_{b3}S_{b4} \\
S_{c1}S_{c2} - S_{c3}S_{c4}
\end{bmatrix}V_{dc}; \\
v_b &= \frac{1}{3} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
S_{a1}S_{a2} - S_{a3}S_{a4} \\
S_{b1}S_{b2} - S_{b3}S_{b4} \\
S_{c1}S_{c2} - S_{c3}S_{c4}
\end{bmatrix}V_{dc}; \\
v_c &= \frac{1}{3} \begin{bmatrix}
1 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
S_{a1}S_{a2} - S_{a3}S_{a4} \\
S_{b1}S_{b2} - S_{b3}S_{b4} \\
S_{c1}S_{c2} - S_{c3}S_{c4}
\end{bmatrix}V_{dc}.
\end{align*}
\]

(47)

where \( S_{a1}, S_{a2}, S_{a3}, S_{a4} \) are the switching states of the inverter power switches; \( v_{a0}, v_{b0}, v_{c0} \) are the phase-to-neutral voltages at the output of the inverter between the phases of the load and the midpoint \(\text{«}0\text{»}\); \( v_{an}, v_{bn}, v_{cn} \) are the phase-to-neutral voltages with respect to the neutral point \(n\).

Depending on the states of the inverter, this vector can take several positions in; these positions are
designated on the vector diagram or switch hexagon shown in Fig. 7 [24, 26].

Fig. 7. Space vector diagram of a 3-L NPC inverter

2. Implementation predictive current control. The proposed predictive control strategy is based on the fact that only a finite number of possible switching states can be generated by a power converter static and that models of the system can be used to predict behavior variables for each switching state. For switching selection appropriate to apply, a selection criterion must be defined. This selection criterion is expressed as a quality function that will be evaluated for the predicted values variables to control. The prediction of the future value of these variables is calculated for each possible switching state. The switching state that minimizes the quality function is selected [28, 29]. This approximation is considered in Fig. 8.

![Block diagram of predictive current control for a 3-L NPC inverter](image)

The system model equations are given as follows:

\[
\begin{align*}
\dot{v}_{an} &= R_{ia} + L \frac{di_a}{dt} - e_{a}^p; \\
\dot{v}_{bn} &= R_{ib} + L \frac{di_b}{dt} - e_{b}^p; \\
\dot{v}_{cn} &= R_{ic} + L \frac{di_c}{dt} - e_{c}.
\end{align*}
\]

(48)

After the Clarke transformation and with the use of Euler’s method to obtain a discrete-time model of the current, the current equations are expressed as follows:

\[
\frac{di}{dt} = \frac{i(k+1) - i(k)}{T_s}.
\]

(49)

where \(T_s\) is the sampling period and \(k\) shows sampling time.

The currents \(i_{d1}, i_{d2}\) supplied by each capacitor \(C_1, C_2\) are represented by the following equations:

\[
\begin{align*}
\dot{i}_{d1}(k) &= i_{d1}(k) - H_{ia}i_a(k) - H_{ib}i_b(k) - H_{ic}i_c(k); \\
\dot{i}_{d2}(k) &= i_{d2}(k) - H_{2a}i_a(k) - H_{2b}i_b(k) - H_{2c}i_c(k).
\end{align*}
\]

(51)

The switch states function of the 3L-NPC calculates the variables \((H_{1x}, H_{2x})\) and is given by:

\[
\begin{align*}
H_{1x} &= \begin{cases} 
1 & \text{if } S_x = \alpha; \\
0 & \text{other};
\end{cases} \\
H_{2x} &= \begin{cases} 
1 & \text{if } S_x = \beta; \\
0 & \text{other}.
\end{cases}
\]

(52)

We use the Euler method to obtain the equations in discrete time which allows the prediction of DC bus voltages as follows:

\[
\begin{align*}
\dot{v}_{cl}(k+1) &= v_{cl}(k) + \frac{1}{C} i_{cl}(k) T_s; \\
\dot{v}_{c2}(k+1) &= v_{c2}(k) + \frac{1}{C} i_{c2}(k) T_s,
\end{align*}
\]

(53)

where \(i(k)\) is \(i_{d1}^p, i_{d2}^p\) and represents the current vector in stationary frame \(\alpha-\beta;\) \(i_{cl}, i_{c2}\) are the currents flowing respectively through the capacitors \(C_1, C_2\); variables \(H_{1x}, H_{2x}\) depend on the switching states; \(v_{cl}, v_{c2}\) are the voltages across DC-link capacitors \(C_1, C_2\).

3. Cost function. The objective of the current control scheme is to minimize the error between the currents measured and reference values. This requirement can be written as a cost function. The cost function is expressed in orthogonal coordinates and measures the error between the references and the predicted currents:

\[
g = \|i_{d1}^* - i_{d1}^p\|^2 + \|i_{d2}^* - i_{d2}^p\|^2 + \lambda_{dc}(v_{cl}^p - v_{cl}^*)^2.
\]

(54)

where \(g\) is the cost function; \(\lambda_{dc}\) is the weighting factor.

The evaluation of the precomputed results and the determination of future optimal control actions are made by the cost function [30-33].

4. Diagram smart current control. Predictive model algorithm applied to control the centralized 3L-NPC inverter in WECS is shown in Fig. 9. To make the necessary calculation of the equations of the predictive command Fig. 9 presents the algorithm of the deferent step of this smart control [28, 29].

Results. This section is to validate the results obtained from the model smart predictive current control of 3L-NPC inverter algorithm of WECS through eigenvalues analysis and also the comparative studies between the proposed model and the exist solution already used for PMSG connected to grid. In the first part, the results obtained after rotor side converter are illustrated in Fig. 8.

Figures 10,a,d show the applied variable change of wind profile for the studied system. Figure 10,c presents the form of the DC link voltage. The DC link voltage reference is set to 540 V, the measured voltage perfectly follows the reference signal.
Fig. 9. Smart current control algorithm

The second part shows the results after grid side converter and is illustrated in Fig. 11.

Figure 11, a clearly shows the proper tracking of the converter reference currents with small currents ripples.

It can be seen in Fig. 9, b waveform of the controlled currents $i_{\alpha}$ and $i_{\beta}$ is smooth and stable.

Figure 11, c illustrates the DC voltage ripples are low enough. The spectral analysis of the modulated voltage signal is presented in Fig. 11, g, where we noticed a drop in Total Harmonic Distortion (THD).
Conclusions.

1. In this paper, a new design and intelligent control has been proposed and implemented for wind energy conversion system based PMSG.

2. All presented results have validated the capability and effectiveness of the proposed intelligent control strategy and showed a high performance and dynamic behavior even at high power. Also, the measured DC voltage follows the reference voltage closely (transitory response 30 ms) and this proves its robustness. The control of three level neutral point clamped inverter is guarantied by smart advanced current control, which gives good results regarding THD (1.38 %) in the both of simulation and experimentation results.

3. Optimizing using metaheuristic algorithms are more precise for THD optimization and switching loss mitigation.

4. Experimental validation is the focus of future work: using DC machine for creating mechanical speed of the turbine, multiplier, PMSG, PWM rectifier, board Dspace1104, current sensors, voltage sensors, DC voltage stabilizer, control interface, three level neutral point clamped inverter, MATLAB/Simulink and control desk.

Conflict of interest. The authors of the article declare that there is no conflict of interest.

REFERENCES


Received 25.07.2023
Accepted 10.11.2023
Published 02.03.2024

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