Torque Ripple Reduction in PMSG for Standalone Wind Energy System Using Three Level DTC with A Dither Signal

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Abstract: In this paper, focused on direct torque control (DTC) for permanent magnet synchronous generator direct driven standalone variable speed wind turbine. The machine side converter (MSC) employed three-level DTC with dither signal strategy proposed for minimizes the torque & flux ripple. The triangular signal used as a dither signal & injected in a hysteresis band controller of torque & flux comparator. The optimum magnitude of the triangular wave is 3% of its rated torque & flux used in order to reduce acoustic noise. The proposed strategy minimizes torque & flux ripple as compared to conventional two-level DTC technique. Three-level SVPWM strategy employed for a load-side converter (LSC) in order to reduce harmonic distortion.

Keywords: Three level DTC; Dither Signal; Three level SVPWM; PMSG.

Introduction

The development of new technologies in the region renewable energy for generating clean and pollution free energy, special attention is given worldwide. In recent years, Renewable energy technologies such as solar, tidal, biomass, geothermal & wind energy are gaining attention in the energy market globally. The wind energy technology is one of the most emerging renewable energy technologies[1]. Nowadays, back-to-back Voltage Source converters for direct driven wind generation system with Permanent Magnet Synchronous Generator (PMSG) have been widely applied [5].

The advantages of the direct driven PMSG generator compared to a generator with a gearbox are increased reliability and the reduction of the weight of the whole system. The PMSG constructed with a large number of poles and operated at low speed. The results of directly coupling the generator with a wind turbine allow for the elimination of a gearbox installation and a reduction of maintenance costs [2], [7]. Fixed-speed wind turbine generator system WTGS and variable-speed WTGS are the type of the wind turbine generator system. In the beginning wind power development the fixed -speed WTGS has been applied. However, it has disadvantages like low power quality & less efficiency [3]. These disadvantages overcome variable speed generation systems. Variable wind speed generator have advantages such as improved wind generation energy, exact maximum power from the turbine [14].

In [3] PMSG directly coupled to wind turbine & it is controlled vector control (Field Orientation Control) using PI controller. However, in vector control d-q coordinate transformation required [11]. Without d-q coordinate transformation, direct torque control (DTC) with switching table & DTC with space vector pulse width modulation (DTC-SVPWM) has high dynamic performance. In DTC- SVPWM has expense of increased complexity is the highlights of implementing a DTC [13]. It is to control the torque and flux linkage by selecting one of the voltage vectors generated by a VSI [9], [12].
DTC worked in either torque control method or speed control method. In speed controller, difference between reference speed & generator speed which is error given to Proportional & integrative (PI) controller which generates reference torque command. This reference torque compared with actual estimated torque in hysteresis controller. On this the torque error, appropriate voltage vectors selected so that actual torque tracks the reference torque and thus generator rotor rotate its reference speed. In variable Wind speed, to extract more power, to maintain the Tip speed ratio ($\lambda_i$). Thus, reference speed variation accordingly wind speed, this can be conclude that speed error results in ripples in torque, thus deteriorating the steady-state performance. Torque ripples is directly proportionally to stator current, resulting in an increment in harmonic distortion of stator current [8]. This drawback reduced by multilevel converter such as three level neutral clamped converter (3-L NPC). In [14] five-level inverter-fed to load employed for reduce the harmonic reduction.

In this paper focused on three level NPC based DTC with dither signal based PMSG direct drive wind turbine & three-level Space vector pulse width modulation (3-L SVPVM) has been proposed. Typical configuration of Wind Energy Conversion System illustrated in figure 1. The stator winding of PMSG connected to a full-scale, back-to-back Voltage Source Converter system, which consist of the Machine Side Converter (MSC) and the load Side Converter (GSC). This model simulated in MATLAB/ Simulink 2016a & its quick response comparatively Induction generator.

This paper is structured as follows. In the section II, presents the modeling of wind turbine, Direct drive, PMSG & power converter. The Section III, presents the proposed control methodology of PMSG i.e. DTC with dither Signal, modelling of DC bus, Pitch angle controller, & 3- Level SVPWM finally; the last section presents the simulation waveform results & conclusion.

SECTION II:

Figure 1 shows the model of WECS consists of horizontal axis wind turbine direct driven PMSG through mechanical coupling shaft, rectifier connected to capacitor, & output of capacitor to inverter fed to load.

2.1 Wind turbine model

The power developed by wind in the turbine blades, which written in the form according the following equation:
The relationship between power coefficient \( C_p(\lambda, \beta) \) and output power in p.u. (in Matlab/Simulink) for different value of wind speed \( V_w \) in p.u. is clearly shows in figure 2.

Figure 3 shows the relationship between the generated output power \( W \) vs Wind speed \( V_w \) (m/s). WECS works in between cut in speed \& Cutoff speed i.e.3 m/s to 25m/s [3], [20].

Figure 4 shows that the power coefficient \( C_p \) is most extreme at a specific estimation value of tip speed ratio, which is called as optimum tip speed ratio \( \lambda_{opt} \).
To extract a maximum power from wind, the Wind turbine should consistently work at $\lambda_{\text{opt}}$. By using the MPPT (Maximum Power Point Tracking) technique can be controlling the rotor speed of permanent magnet synchronous generator.

$$\omega_{\text{opt}} = \frac{\dot{\lambda}_{\text{opt}} \cdot V_w}{R} \quad (6)$$

The torque equation of the turbine as;

$$T_t = \frac{P_e}{\omega_m} \quad (7)$$

Therefore, the torque equation will be,

$$T_t = \frac{0.5 \rho \pi r^2 v_d^2 c_p(\lambda, \beta)}{\omega_m} \quad (8)$$

2.2 Direct Driven

Wind turbine direct driven PMSG have absent of gearbox, can avoid the problem of wear and tear of gear & less maintaince, it can help wind turbine operate more reliable. The expression is the angular speed of the PMSG rotor $\omega_e$ and rotor mechanical speed $\omega_g$ can written as; [2]

$$\omega_e = P_n \cdot \omega_g \quad (9)$$

Where $P_n$ is no. of pole pair.

The dynamic torque equation expressed as; [3]

$$T_{\text{em}} - T_t = J \frac{d\omega_m}{dt} + F \omega_m \quad (10)$$

Where, $T_{\text{em}}$ is Electrimagnetic torque, $J$ is total inertia of the PMSG shaft & $F$ is wind turbine friction.

2.3 PMSG model

The PMSG has advantages are high reliability, good torque response & power density per volume ratio, because of DC excitation which is replaced by permanent magnet & eliminates brushes & slip ring. Thw PMSG also eliminates the rotor circuit loss due to permanent magnet [12].

The stator phase voltage equation as;

$$V_a = R_s I_a + \frac{d\psi_a}{dt} \quad (11)$$

$$V_b = R_s I_b + \frac{d\psi_b}{dt} \quad (12)$$

$$V_c = R_s I_c + \frac{d\psi_c}{dt} \quad (13)$$

Where, $V_a$, $V_b$, $V_c$ & $I_a$, $I_b$, $I_c$ are stator voltage & current of a, b, c respectively. $R_s$ is Resistance of stator circuit, $\psi_a$, $\psi_b$, $\psi_c$ are stator flux of a, b, c axis respectively.

Figure 5 shows the park’s (abc to dq) transformation. It is needed for PMSG because, this model is transform the time varient into time invarient system. With help of park transformation, the stator volages equation in the dq reference frame as below,

The sator voltage equation as;

$$V_{ds} = R_s I_{ds} + \frac{d\psi_d}{dt} - \omega_e \psi_q \quad (14)$$

$$V_{qs} = R_s I_{qs} + \frac{d\psi_q}{dt} + \omega_e \psi_d \quad (15)$$

Where, $V_{ds}$, $V_{qs}$ & $I_{ds}$, $I_{qs}$ are the volage & current of staor on d & q axixs, $\omega_e$ is rotor angle with respect to a-axis.

The torque equetion of the PMSG ($T_{\text{em}}$) is,

$$T_{\text{em}} = \frac{3}{2} \frac{P_n}{2} (\psi_{ds} I_{qs} - \psi_{qs} I_{ds}) \quad (16)$$

Where, $P$ is pair of pole.
2.4 Power Converter

In this paper, Figure 1 shows the back-to-back converter (B2B). The B2B converter has two Voltage Source Converters (VSC) and a capacitor in between them.

These first VSC can work as a generator side converter i.e. generated ac voltage rectified to DC. The capacitor acts as a filter for the voltage ripple produced by the VSC. Next, is DC converted AC through the load side inverter. The capacitor DC-link voltage always more than the peak voltage of the load voltage [9]. The rectifier circuit of the PMSG side is controlled by hysteresis current based FOC & load side converter is controlled by three-level SVPWM technique.

SECTION III

3.1 Control of system

In this section, the DTC controlled strategy used for PMSG, DC bus voltage, and three level (NPC) SVPWM technique used for the load side converter.

3.1.1 Direct Torque control:

The machine side converter (MSC) controls the rotor speed of the PMSG to extract achieve max. Power from variable speed wind energy conversion system. In DTC method, Torque directly control by angle between the stator and rotor reference frame. According switching pattern the voltage vector selected for controlling the converter speed & torque. In conventional DTC, there drawback is generate torque ripple.

The Eques. no.16 expressed In the stator flux reference frame, the torque of PMSG in terms of the amplitude of stator flux and torque angle.

\[
T_e = \frac{3 P_m}{4 L_d L_q} \left[ 2\psi_f L_q \sin(\theta) - |\psi_s| (L_q - L_q) \sin(2\theta) \right]
\]  

Where, ∂-torque angle (the angle between stator and rotor flux vector)

For a salient for PMSG, namely, L_d = L_q = L_s, the equation can be simplified as:

\[
T_e = \frac{3 P_m}{4 L_s} |\psi_s| \psi_f \sin(\partial)
\]

Eques. (18), the torque directly controlled by regulating the torque angle ∂. If the amplitude of the ψ_s is kept constant. Furthermore, the torque increases with the increase of ∂.

Control of the Amplitude of Stator Flux

The stator flux linkage in the γ & β stationary reference frame expressed as;

\[
\begin{align*}
\psi_s &= \int (V_s - R_i I_s) dt \\
\psi_s &= V_s dt + \psi_{s|t=0}
\end{align*}
\]

Where, R,i, is fraction of voltage so it neglected. \(\psi_{s|t=0}\) Is initial value of flux at t=0

3.1.2 Torque & flux estimator

The torque equation of the PMSG (Tem), can be obtained from Eques. No. 16
Flux equation of PMSG in dq reference frame as;
\[
\psi_{ds} = L_d I_{ds} + \psi_f
\]
\[
\psi_{qs} = L_q I_{qs}
\]  
(21)

(22)

Where, \(\psi_f\) is permanent magnet flux.

The stator flux linkage is
\[
\psi_s = \sqrt{\psi_{ds}^2 + \psi_{qs}^2}
\]  
(23)

To find the sector angle \(\theta_s\) expressed as;
\[
\theta_s = \arctan \left( \frac{\psi_{qs}}{\psi_{ds}} \right)
\]  
(24)

### 3.1.3 Proposed Direct Torque Control

In proposed DTC, figure 6 shows block diagram, the scheme includes three level Direct Torque Control (DTC) & two hysteresis relay controllers [4]. DTC is a stator flux oriented scheme and based on the hysteresis band control of both flux and torque.

The stator flux controller imposes the time duration of the active voltage vectors, which move the stator flux along the reference trajectory. The torque controller determines the time duration of the zero voltage vectors, which keep the torque within hysteresis tolerance band. At every sampling time, the voltage vector selection block selects the switching state, which reduces the instantaneous flux and torque errors.

![Figure 6 Detailed DTC with Dither signal for machine side converter](image-url)
3.1.3 Hysteresis comparator

Five-level torque comparator as shown in figure 7a and 7b, three-level flux comparator are employed for three-level inverter based DTC.

Figure 7a–b show the comparator of the dither signal added, where triangular waves employed as the dither signals in the error blocks. The torque error & flux error has to be reduced to adding dither signal i.e. triangular signal. In this paper, a triangular dither signal injected of minute amplitude (3% of rated torque and 3% of reference flux as hysteresis band in torque control and flux control loops respectively) in the error block.

In three level NPC converter, increases no. of sequences to employed for switching table. In the case of 3-level converter, sequence voltage 211 is similar to the sequence 100 so 221 is like 110, etc. Therefore, we have 19 combinations of vectors achievable voltages including zero sequence [6]. Figure 8 shows the six-sector division and utilization of all Voltage vectors.

Figure 8 six-sector division and utilization of all Voltage vectors
Table 1 shows Switching table for three level DTC, it is possible to obtain six sector, twenty-four none zero vector & three zero vector.

| $\Delta \phi_s$ | $\Delta T_e$ | S1   | S2   | S3   | S4   | S5   | S6   |
|----------------|-------------|------|------|------|------|------|------|
| 1              | 2           | 220  | 020  | 022  | 002  | 202  | 200  |
|                | 1           | 210  | 120  | 021  | 012  | 102  | 201  |
|                | 0           | 200  | 220  | 020  | 022  | 002  | 202  |
|                | -1          | 202  | 210  | 120  | 021  | 012  | 102  |
|                | -2          | 202  | 200  | 220  | 020  | 022  | 002  |
| 0              | 2           | 120  | 021  | 012  | 102  | 201  | 210  |
|                | 1           | 120  | 021  | 012  | 102  | 201  | 210  |
|                | 0           | 120  | 021  | 012  | 102  | 201  | 210  |
|                | -1          | 120  | 021  | 012  | 102  | 201  | 210  |
|                | -2          | 120  | 021  | 012  | 102  | 201  | 210  |

3.1.4 Pitch angle controller

The pitch angle is kept constant at zero degree at wind speed is rated. Beyond the cut out speed, the pitch angle is proportional to the speed deviation from rated speed. The control system illustrated in the following figure [16].

![Pitch angle controller](image)

**Figure 9** Pitch angle controller

3.2 SVPWM

3.2.1 3-Level Neutral Point Clamped (NPC) Inverter

Realizing SVM for more than two-level inverter (conventional six-switch inverter) called Multi level Inverter MLI [19]. Three phase three level neutral point clamped inverter employed for DTC induction motor drives [18]. NPC multilevel inverters synthesize the stepped level of the output voltage from DC capacitor voltages, Figure 9 shows the, A 3-level NPC-MLI inverter consists of (k-1) capacitors i.e. two capacitor on the DC bus link, 2(k-1) power switching devices i.e. 4 switches per phase and 2(k-2) clamping diodes i.e two diodes per phase [17].
Any of the three-phase n-level space vector diagram (SVD) can be separated into six sectors (Si), where i = 1 to 6. These sectors are further separated into \((n - 1)^2\) sub triangles \((\Delta_{i,j})\) where j = 0 to 3 and i = 1 to 6. Hence, the n-level SVPWM consists of \(n^2\) switching states. For 3 level SVPWM has 27 switching states, shown in Figure 10 of voltage vector diagram, out of which have three null voltage vector others are non zero vector. Each Sector have four triangles.

**Figure 10** Three level NPC Inverter

According to voltage amplitude, divided them into four segment are zero voltage VZ, Medium voltage VM, Small voltage VS & Large voltage vector VL. Table 2 shows the three-level SVPWM inverter switching states.

**Figure 11** Voltage vectors of three-level NPC inverter **Figure 12** Voltage vectors of NPC in sector-I

| Switching Symbols | Q1 | Q2 | Q3 | Q4 | Output Voltage |
|-------------------|----|----|----|----|----------------|
| 1                 | ON | ON | OFF| OFF| \(V_{dc}/2\)   |
| 0                 | OFF| ON | ON | OFF| 0              |
| -1                | OFF| OFF| ON | ON | \(-V_{dc}/2\)  |
Table 3 Three-level inverter Space vector Diagram switching states.

| Switching vector name | Total no. of states | Switching states | Output voltage of states |
|-----------------------|---------------------|------------------|--------------------------|
| V_Z                   | 3                   | [111], [000], [-1-1-1] | 0                        |
| V_S                   | 12                  | [100], [0-1-1], [110], [00-1], [010], [101], [011], [100], [001], [110], [101], [0-10] | Vdc/2                     |
| V_M                   | 6                   | [10-1], [01-1], [-110], [-101], [0-11], [110], [101], [0-10] | √3/2 Vdc                 |
| V_L                   | 6                   | [1-1-1], [11-1], [-11-1], [-111], [-1-11], [1-11], [1-11]; | Vdc                      |

3.2.2 Voltage Vector & Time Calculation of Switching

Figure 11 displays the voltage vectors V_{S1}, V_{M1} & V_{S2} are create the triangle. This formed triangle is subdivided into four triangles; these are 1, 2, 3 and 4. In the SVPWM, assume voltage reference V_{ref} & to find its closest three vectors structure SVD to decrease the harmonic components of the output voltage and the current. The time of each vector calculated by vector calculation. Assume, reference voltage in the triangle 3 shown in Figure 12, the time of each voltage vector can be obtained by the following equations.

\[ V_{S1} \cdot T_a + V_{M1} \cdot T_b + V_{S2} \cdot T_c = V_{ref} \cdot T_s \]  \hspace{1cm} (25)

\[ T_a + T_b + T_c = T_s \] \hspace{1cm} (26)

Where, 

\[ V_{S1} = \frac{V_{dc}}{2}, V_{M1} = \sqrt{3} V_{dc} \cdot e^{\frac{\pi}{6}}, V_{S2} = \frac{V_{dc}}{2} \cdot e^{\frac{-\pi}{6}} \] \hspace{1cm} (27)

Substituting Eques. (27) In Eques. (25)

\[ \frac{V_{dc}}{2} \cdot T_a + \sqrt{3} V_{dc} \cdot \left( \cos \left( \frac{n}{6} \right) + i \sin \left( \frac{n}{6} \right) \right) \cdot T_b + \frac{V_{dc}}{2} \left( \cos \left( \frac{n}{3} \right) + i \sin \left( \frac{n}{3} \right) \right) \cdot T_c = V_{dc} (\cos \theta + i \sin \theta) \cdot T_s \] \hspace{1cm} (28)

Separate the real and imaginary parts of the Eques. (28)

\[ \frac{V_{dc}}{2} \cdot T_a + \sqrt{3} V_{dc} \cdot \left( \cos \left( \frac{n}{6} \right) \right) \cdot T_b + \frac{V_{dc}}{2} \left( \cos \left( \frac{n}{3} \right) \right) \cdot T_c = V \cdot \cos \theta \cdot T_s \] \hspace{1cm} (29)

\[ \sqrt{3} V_{dc} \cdot \left( \sin \left( \frac{n}{6} \right) \right) \cdot T_b + \frac{V_{dc}}{2} \sin \left( \frac{n}{3} \right) \cdot T_c = V_{dc} (\sin \theta) \cdot T_s \] \hspace{1cm} (30)

The values of T_a, T_b and T_c by solving Eques. (31), Eques. (32) and Eques. (33)

\[ T_a = T_s \left[ 1 - 2K \sin(\theta) \right] \] \hspace{1cm} (31)

\[ T_b = T_s \left[ 2K \sin(\theta + 60) - 1 \right] \] \hspace{1cm} (32)

\[ T_c = T_s \left[ 2K \sin(\theta - 60) + 1 \right] \] \hspace{1cm} (33)

Where, \( K = \frac{2}{\sqrt{3}} \cdot V_{dc} \)

4. Results

This simulation results carried out in Matlab/ Simulink. In this simulation considered two cases are Variable wind speed (i.e. generator speed Around 40 RPM) & constant wind speed(generator speed Around 40 RPM) figure 13 shows the wind speed profile, Figure 14 & 15 shows the reference speed & actual speed of generator.
The electromagnetic torque developed by PMSG for variable speed & constant wind speed. Figure 16 comparison shows that the proposed DTC controlled with dither signal having smooth torque response compared to with without dither signal.

**Figure 13** Wind profile  

**Figure 14** Generator speed RPM for variable wind speed  

**Figure 15** Constant generator speed at 40 RPM  

**Figure 16a** Torque response for variable generator speed without dither signal
Figure 16b Torque response for constant generator speed without dither signal

Figure 16c Torque response DTC with dither signal

Figure 17a-b shows the flux trajectory of PMSG using DTC without dither signal & with dither signal. Results compares, the DTC with dither signal has better response.

Figure 17a Flux response without dither signal

Figure 17b Flux response with dither signal
4.1 Torque & Flux ripple analysis

The torque ripple and flux ripple are also significant performance indices when controlling the drive. The performance parameters to judge the effectiveness of the proposed method are torque and flux ripples can be calculate as Eques. (34) and Eques. (35) [10].

\[
T_r = \frac{1}{N} \sum_{k=0}^{n} \left( (T_{e*} - T_i)^2 \right)
\]

(34)

\[
\lambda_r = \frac{1}{N} \sum_{k=0}^{n} (\lambda_{eref} - \lambda_i)^2
\]

(35)

Where, \( T_{e*} \) is average torque N.m., \( T_i \) is estimated torque, \( \lambda_{eref} \) reference flux & \( \lambda_i \) estimated flux.

Figure, 18 shows the torque ripple in variable speed wind turbine using DTC, constant speed wind turbine using DTC without dither signal & torques response DTC with dither signal. This comparison shows that DTC with dither signal have less ripple as compare to conventional DTC.

In conventional three level DTC, for variable & constant wind speed have peak-to-peak torque ripple is 10 N.m. & 16 N.m. respectively. In DTC with dither signal have peak-to-peak torque ripple is 2 N.m. so it can be conclude that 60% torque ripple has to be reduced in PMSG.

![Torque ripple response for variable wind & Constant wind using DTC without Dither signal](image1)

![Torque ripple response using DTC with Dither signal.](image2)

In DTC control system, mainly focused torque control. However, in DTC due to voltage vector, flux ripple also produced. Figure 19 shows the flux ripple in PMSG using DTC without dither signal & with dither signal. In DTC, without dither signal have peak-to-peak flux ripple is 0.08 wb. & peak-to-peak flux ripple 0.01 wb in DTC with dither signal. This can conclude that 60% flux ripple has been reduces.
Figure 19a flux ripple response without dither signal  

Figure 19b flux ripple response with dither signal

Figure 20 shows the Stator Current waveform. Compare the both results; it can be conclude that harmonics is reduces in current by using DTC with dither signal. Figure 21 Shows the DC bus voltage.

Figure 20a Ia & Ib stator current without dither signal  

Figure 20b Ia & Ib stator current dither signal

Figure 21 DC bus voltage between in back-to-back converter.

Figure 22 displays the abc voltage of NPC inverter by using SVPWM method, Figure 23 shows the load side voltage & current waveform.
Figure 22a abc Voltage of NPC inverter

Figure 22b Load side abc voltage & current waveform

Figure 23 shows FFT analysis of PWM & three level SVPWM technique. The PWM method has Harmonic percentage is 42.63% & three level SVPWM method has 0.31%. If both the results compared, three level SVPWM technique has less harmonics compared to PWM technique.

5. Conclusion

In this paper, Dither signal injected in hysteresis band controller for three level (NPC) DTC for PMSG direct driven wind turbine. The conventional two level DTC compared on the performance basis such as torque ripple, flux ripple & stator current in Matlab Simulink software.

- The proposed technique reduces the torque, flux & stator current ripple, this controller exhibits satisfactory results in comparison with the conventional DTC.
- DTC with dither signal for PMSG is Suitable employed for wind turbine because; the application of DTC with dither signal enhances the performance of the PMSG with improved flux and torque control capability. Simulation results shows the torque & flux ripple reduced by 60% of peak-to-peak.
- In addition, load side inverter three level NPC (inverter) has less (THD 0.31%) harmonics as compared to other conventional PWM inverter method.
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