A Review on DTC-SVM Method with back-to-back Converter Connected to the Permanent Magnet Generator and Comparison with DTC in the Matrix Converter

Soroush SadeghBayan[1], Alireza Siadatan [2*], Ebrahim Afjei[3]
1- Department of Electrical Eng., Faculty of Technical & Engineering, West Tehran Branch, Islamic Azad University Tehran, Iran.
Soroushsadeghbayan@gmail.com
2- Young Researchers and Elite club, West Tehran Branch, Islamic Azad University, Tehran, Iran.
*Corresponding Author; siadatan@wtiau.ac.ir
3. Department of Electrical Eng., Faculty of Electrical Engineering, Shahid Beheshti University, Tehran, Iran.
e-afjei@sbu.ac.ir

Received: June 2017 Revised: June 2017 Accepted: August 2017

ABSTRACT:
In this paper, the direct torque control torque based on space vector modulation (DTC-SVM) for permanent magnet synchronous generator connected to the variable-speed wind power generation system will be discussed. One of the most widely used converters in industry to convert voltage is back to back converter that is used due to its good features. The main use of space vector modulation is in the voltage source inverters and 3-phase current source. DTC method reduces the limitations and complexity of operation, so the price of Replay torque and flux machines are high which made the DTC-SVM method as an alternative. The possibility of over-voltage matrix converter is on both sides. In some methods, sampling frequency is required and is some high frequency is required. The sampling frequency in the spatial vector modulation method is far less than the direct control of the torque with the matrix converter.

KEYWORDS: PMSG, Direct Control Torque, Ac-dc-ac Convertor, Space vector Modulation, Matrix Converter.

1. INTRODUCTION

The abundant advantages of Permanent-Magnet Synchronous Generator (PMSG) such as high efficiency, simplicity in control, power density, and high reliability have been considered as the good reasons for the replacement of induction generators. In the past, one of the controlling way, regarding PMSG, was Field Oriented Control (FOC), having its own specific disadvantages including heavy reliance and high dependency to motor parameters and rotor speed.

Direct Torque Control (DTC) was proposed in 1986, now considered as one of the control methods. DTC has many advantages including simplicity, independency to motor parameters and etc. but variable switching frequency, complexity and high distortion are considered as its disadvantages [2]. Nowadays, Back to Back Convertors are one of the most useful convertors for the conversions of AC voltage, at the side of generator, to a desired AC voltage, at the side of Net [3].

When Space Vector Modulation was introduced, it resulted in providing more accurate and continuous voltage vector [4]. A quasi-sliding controller, utilizing relatively low auricular sampling (e.g. 5 KHz or 10 KHz), was proposed for the rotor position estimation and the relation of stator variable, based on the current model of PMSG in a wider application range and domain. Optimized Torque Steering by which the maximum propulsion control of power output of Wind Turbine, without requiring wind speed measurement or rotor position sensors, is provided, is directly gained through the rotor estimation speed for DTC. In comparison with the current and prevalent DTC, the suggested Space Vector Modulation Direct Torque Control provides a fixed transmission frequency so that it significantly decreases a lot of fluctuations of torque and flow, and it also protects the system dynamic reactions. The increase of considerations in relation to energy crisis as well as environmental pollution has significantly expanded the use of wind energy in last two decades. Among the different wind power generating systems, Variable-Speed Wind Turbine Generators have gained much of attention due to high efficiency of energy production in them and too low torque impact [6]. In such systems, WTGs can act with the maximum output power for receiving the maximum wind power by the speed regulation of their main axis [7]. We have understood that Permanent-magnet synchronous generators (PMSG) are appropriate for the wind power generation systems due to their advantages such as high output power density, high efficiency, and high reliability [8]. Additionally, a PMSG, with many poles, can directly attach to a wind turbine, without using a driving force transmission box, gear box, so that it significantly decreases the manufacturing, operating and repairing costs [9]. These advantages have caused WTGs based on PMSG, having direct driving force, to be introduced as the most efficient equipment in the multi-MW marine applications.

Usually, in the control systems, PMSGs get benefits from a control method of detached streaming in which, in a reference frame, circulating simultaneous dq is used [10]. The efficiency of these vector controls with regulated streams is highly relied on the accurate data of rotor position. To produce accurately detached signals with Park transformation, it is required to use an electromechanical position gauge [11]. In recent decades, one method was proposed for Direct Torque Control and it was used in the Permanent-magnet synchronous generators (PMSG) in order to eliminate the dependency of control systems to rotor positions and machine variables [12], [14]. In DTC systems, inverter and machine are considered to be integrated so that stator voltage vectors can be directly chosen for the creation of difference among reference torque, real torque and stator streaming connection. This method not only eliminate the complex calculation of converting the reference frame and the high dependency of the detached streaming control to the system variables but also perform faster torque reactions [15]. Additionally, the studies conducted by the researchers have caused DTC to be utilized in high efficient motorized and automated systems. For instance, ABB has begun to manufacture related industrial products [16].

The basis of DTC designation is founded on two bases: magnetic induction measurement and Switching Sensor Technology (SST). Despite this fact, the performance of SST-DTC is simple, its weakness, the frequency of unstable switch with extreme impact in the stream and rotor is inevitable and obvious. For a WTG, irregular impacts of torque result in the creation of excess stress on the main axis, decrease the turbine circulation life and make loud noises [32]. Many researchers have tested many approaches for these problems, one of which is the integration of a space vector modulation (SVM) with DTC, an effective method. In other hand, the efficiency of a DTC system is significantly relied on the stator flux linkage because both control variables, torque and stream, are formed by the stream continuity [17]. In common designations of DTC, flux linkage is formed by the integration of stator induction voltage, although other factors such as voltage increase of direct stream in conductor and the stator resistance changes upon errors accumulation, it decreases the integration efficiency. Although these issues, as it was stated in reference [18], can be compensated, the performance of algorithms in applied systems are so perplexing. In the reference [19], a sliding mode controller was prepared for rotor position estimation for the sensor less control of PMSMs [29]. A stator flux controller has used a sliding mode approach, though in order to reach sliding mode, high sampling rates (e.g. 20 KHz) or many samplings are required and it needs many computing resources and it is limited in the performance of applied systems. Collision problem, using the application of sign change, is another fundamental problem which is needed to be performed in sliding mode controller.

This article proposes the designation of a DTC based on SVM for the PMSG wind turbines, with direct driving force in which the control of Maximum Power Point Tracking (MPPT) is done without measuring wind speed generator rotor position [31] and it results in creating the sensor less control of speed or the position for WTG systems. The optimized torque control which is produced by MPPT algorithm can be directly used in the DTC system, usually creating external speed control loop in the vector control system. To minimize the upload of CPU in performing applied systems, a stator flux controller, in a quasi-sliding mode, has been proposed that is of low sampling rate, regularly lower than 10 KHz, and are used for achieving the high accurate stator flux control in the wide domain of PMSG. With the adoption of the suggested designation, torque impacts and flux decrease and they protect fast kinetic reaction of the system in comparison with common DTC designations. The suggested design of DTC is useful through simulation in PMSG wind turbines, with direct driving force and output power of 1.5 MW, and the provided experimental results is valid for the PMSG wind turbines with direct driving force and output power of 2.2 KW.

2. MODELING A PMSG WIND TURBINE

The generator proposed in the present article is a PMSG generator. The equations used for the modeling are as following:

$$\frac{di_d}{dt} = \frac{1}{L_d}\left[u_d + p\omega_g L_q i_q - R_d i_d\right] \quad (1)$$

$$\frac{di_q}{dt} = \frac{1}{L_q}\left[u_q + p\omega_g \left(L_d i_d - M i_f\right) - R_q i_q\right]$$

(2)

$$T_e = \frac{3}{2} p \lambda_f i_q \quad (3)$$

Where:

Id and Iq : stator streams

Ud and Ud : stator voltages
P: the number of pairs of poles
Lq and Ld : stator inductance
Rd and Rq : stator resistance
M : Mutual inductance
If : rotor equivalent circuit
Yf : Quick magnetic flux
PMSG dynamic equations in park transformations are as following:

$$\frac{di_{s\alpha\beta}}{dt} = A.i_{s\alpha\beta} + \left(\overrightarrow{u_{s\alpha\beta}} - \overrightarrow{e_{\alpha\beta}}\right) \quad (4)$$

$$A = \begin{bmatrix} -\frac{R_s}{L_s} & 0 \\ 0 & -\frac{R_s}{L_s} \end{bmatrix}, \; B = \begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \end{bmatrix}, \; \overrightarrow{e_{\alpha\beta}} = \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix}$$

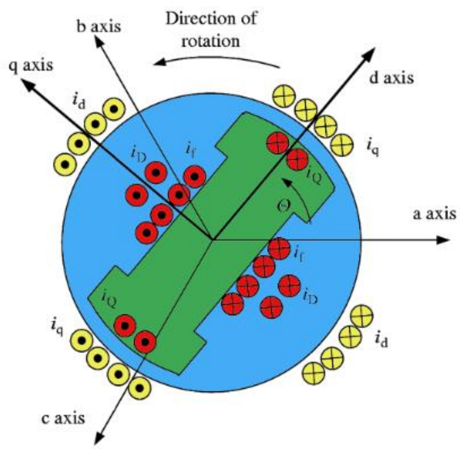


Fig. 1. d-q axis in a synchronous machine

3. DIRECT TORQUE CONTROL (DTC) BY CONVERTERS BACK TO BACK

3.1. back to back convertor (ac-dc-ac)

Back to back convertor, so called ac-dc-ac is one of the powerful electronic convertors, used in the wind turbines. In the present article, back to back convertor is used for the PMSG wind turbines having variable speed. In order to have a good application of the back to back convertor, dc-link voltage, according to equation 5, must increase to a level of at least twice the peak voltage network:

$$V_{dc} = 2\sqrt{2}V_g \quad (5)$$

Ac-dc-ac convertor consists of two three-phase classes. To analyze the circuit of the convertor in real points, the average switch modeling is used.

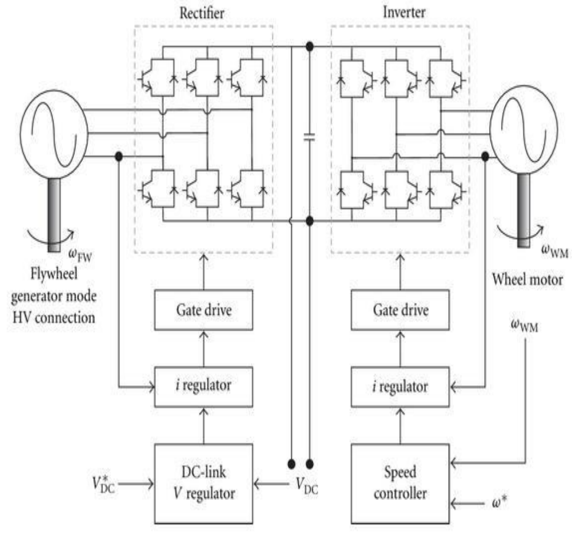


Fig. 2. Circuit switching

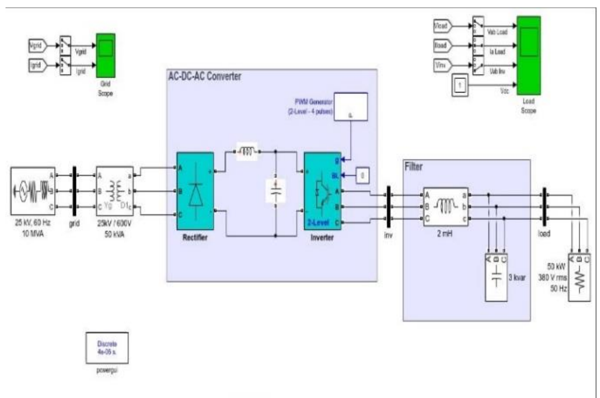


Fig. 3. Circuit switching simulation in Matlab

The system relations and equations of the convertor of the generator is as following:

$$\begin{aligned} V_a &= R_i i_{ai} + L_i \frac{di_{ai}}{dt} + V_{dc}\frac{2S_a - S_b - S_c}{3} \\ V_b &= R_i i_{bi} + L_i \frac{di_{bi}}{dt} + V_{dc}\frac{-S_a + 2S_b - S_c}{3} \\ V_c &= R_i i_{ci} + L_i \frac{di_{ci}}{dt} + V_{dc}\frac{-S_a - S_b + 2S_c}{3} \end{aligned} \quad (6)$$

Accordingly, voltage relations for the convertor of the network is as following [20]:

$$\begin{aligned} v_a &= -R_o i_{ao} - L_o \frac{di_{ao}}{dt} + V_{dc}\frac{2D_a - D_b - D_c}{3} \\ v_b &= -R_o i_{bo} - L_o \frac{di_{bo}}{dt} + V_{dc}\frac{-D_a + 2D_b - D_c}{3} \\ v_c &= -R_o i_{co} - L_o \frac{di_{co}}{dt} + V_{dc}\frac{-D_a - D_b + 2D_c}{3} \end{aligned} \quad (7)$$

The power electronic convertors have important roles in the systems of converting energy. For instance, wind turbines, in variable speed, act in accordance with the available wind speed [20]. The produced voltage, through wind turbine in the generator terminals, has variable and alternative domain. Therefore, the produced power, before being delivered to the network, must go through a process [20]. The convertors are separated by the dc link. The field of generator consists of 6 IGBT keys [20].

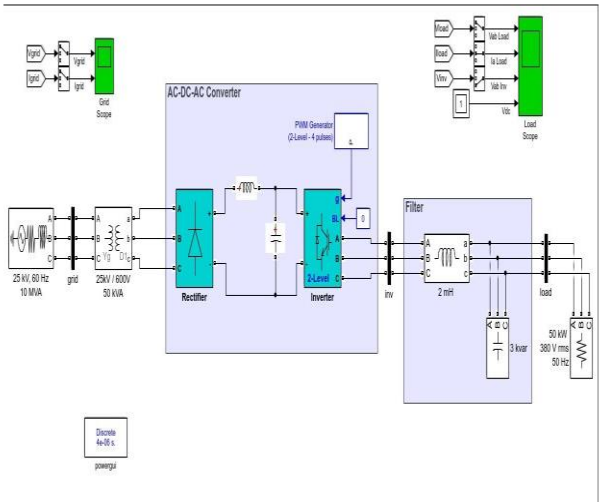


Fig. 4. Ac-dc-ac converter-simulated turbine system at PMSG wind

3.2. Direct Torque Control

One of the most efficient methods in controlling electrical machines is DTC method. DTC method decreases vector restrictions and complexities. This results in the increase of torque and flow ripples. Moreover, these problems are negligible due to the simple benefits of the method and at the same time they are somewhat eliminated through using some methods [30].

What makes this control method more powerful and strong is its dependency to the machines parameters. In other hand, to construct the stator flux as well as torque, the only parameters of motor which must be measured is the stator resistance. Thus, the sensitivity of control system to the changes of machines parameters, while working, is so low and in this control method also needs to have flux location (Stator flux angle).

The basic principle of DTC is that it directly selects stator voltage vectors regarding the errors happening between reference value and the torque and flux value. The investigation and the control of flux and torque is performed by non-linear transformations on the Hysteretic Controllers [22]. If there is no interdependency of the transformations to each other, a bilayer controller for the control of stator flux and a three-layer control for the control of torque were used [22].

The equations of stator voltage can be written as following:

$$u_s = R_s I_s + \frac{d\psi_s}{dt} \qquad (8)$$

And by forgoing stator resistance, the stator flux equation is as following:

$$\psi_s = \int (u_s)dt \qquad (9)$$

From the equation (9), it can be understood that the stator flux vector has direct influence on the control of stator flux vector.

In the DTC method, the stator flux vectors can be divided into 6 symmetric areas, according to non-zero voltage vectors [23].

$\left(-\frac{\pi}{6},\frac{\pi}{6}\right)$ First area, $\left(\frac{\pi}{6},\frac{\pi}{2}\right)$ Second area

$\left(\frac{\pi}{2},\frac{5\pi}{6}\right)$ Third area, $\left(-\frac{5\pi}{6},\frac{5\pi}{6}\right)$ Fourth area

$\left(-\frac{5\pi}{6},-\frac{\pi}{2}\right)$ Fifth area, $\left(-\frac{\pi}{2},-\frac{\pi}{6}\right)$ Sixth area

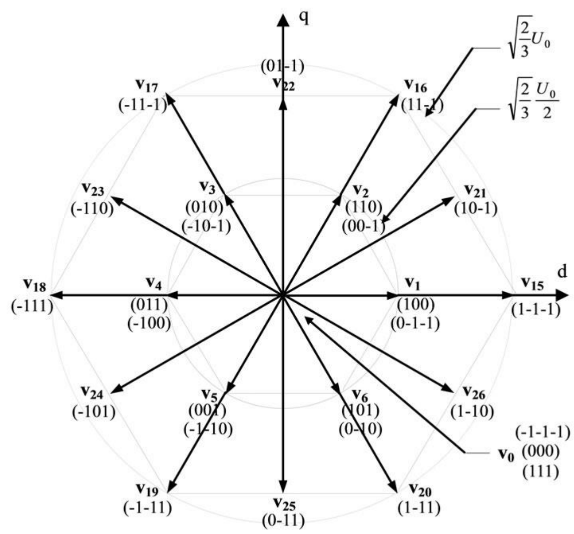


Fig. 5. Division non zero vector in DTC method

Finally, the output signals of flux and torque controllers are as following:

$$\text{If} \rightarrow |\Psi_s| \rangle |\Psi_{s\text{-ref}}| + H_\Psi \text{ (Flux increase) } d\psi_s = 1 \quad (10)$$

$$\text{If} \rightarrow |\Psi_s| \langle |\Psi_{s\text{-ref}}| - H_\Psi \text{ (Flux decrease) } d_{\psi_s} = 0 \quad (11)$$

$$\text{If} \rightarrow M_e \rangle M_{e-ref} + H_M \text{ (Torque increase) } d_{Me} = 1 \quad (12)$$

$$\text{If} \rightarrow M_e \langle M_{e-ref} - H_M \text{ (Torque decrease) } d_{Me} = 0 \quad (13)$$

In the above equations, H_M and H_Ψ are hysteresis bands of torque and flux, respectively. The appropriate voltage vector is selected by the digital values of dMe and dYs and the information of stator flux position are chosen by switching table [23]. After selecting the appropriate voltage vector, the switching table sends the control pulses to the convertor switches.

In each area, two adjacent voltage vectors which cause the creation of the lowest switching frequency are selected for the increase or decrease of stator flux domain and electromagnetic torque [24].

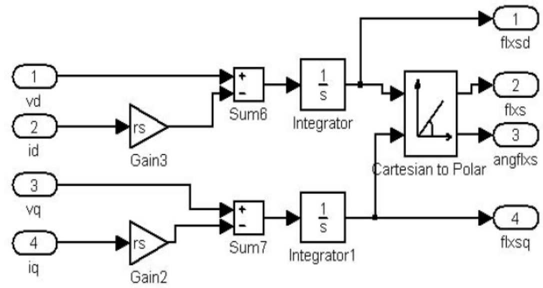


Fig. 8. Block size and angle of stator flux estimator

4. DIRECT TORQUE CONTROL-SPACE VECTOR MODULATION (DTC-SVM)

A The DTC-SVM method has been able to improve the efficiency of flux and torque to a great quantity and due to two reasons:

- Gaining fixed switching frequency
- Decreasing torque and flux ripples

In the several decades, one method (DTC) was proposed by direct torque control and in order to

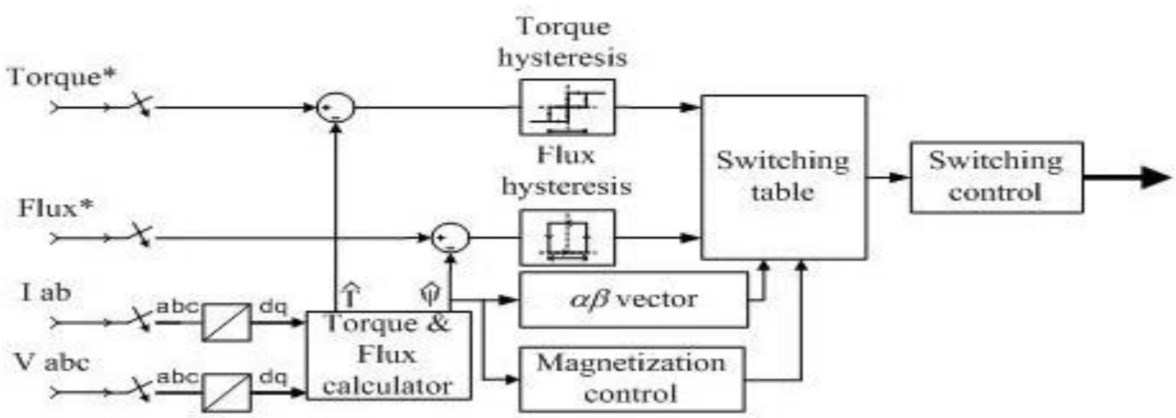


Fig. 6. Block Diagram of DTC method in Matlab

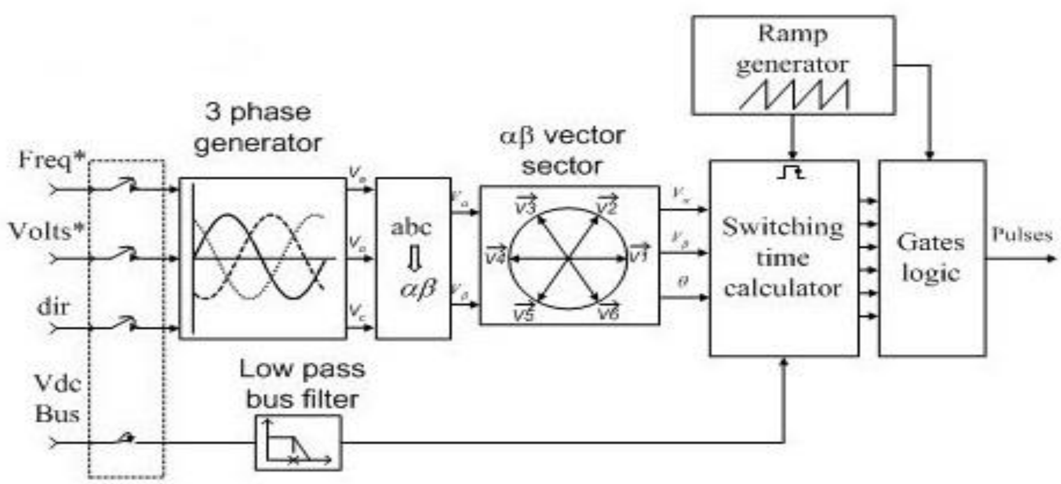


Fig. 7. Block Diagram of SVM method in Matlab

eliminate the dependency of the control systems to rotor positions and machine variables, they have been employed in permanent-magnet synchronous generator (PMSG). In DTC systems, the inverter and machine are considered as a unit so that the stator voltage vectors can be directly selected for the creation of difference between reference torque and real torque and the stator stream connection. This method not only eliminate the need to complex computation for converting reference frame and high dependency of detached stream control to the system variables but also cause more fast torque Reactions. Additionally, many studies conducted by the researchers have caused DTC to be widely used in the motorized and automatized systems, having high efficiency. The main idea DTC-SVM is based on the computation of torque equations.

$$M_e = \frac{3}{2}p[\frac{|\overline{\psi_s}|\psi_{pm}\mathrm{Sin}\theta_\psi}{L_d} - \frac{|\psi_s|^2(L_q - L_d)\mathrm{Sin}2\delta_\psi}{2L_dL_q} \quad (14)$$

By considering Ld=Lq=Ls, we have:

$$M_e = \frac{3}{2}p\left[\frac{|\psi_s|\psi_{pm}\mathrm{Sin}\theta_\psi}{L_s}\right] \quad (15)$$

In this equation:

$|\overline{\psi_s}|$: Domain of stator fixed flux

ψ_{pm} : Produced flux by permanent magnet

δ_ψ : Torque angle

P: number of pole pairs

θ_ψ : Stator flux vector

The scheme of DTC-SVM method in the generator in the figure 9 and the scheme of DTC-SVM method for PMSG wind turbine in figures 10 and 11 have been shown. [16].

In figure 9, T^* and Ψ^* are torque and stator quick magnetic flux, respectively [17]. The schematic figure of DTC-SVM is shown for a PMSG WTG or non-leading poles in figure 10 [10] in which T^* and [ψs*] are reference torque and stator flux value, respectively, and the wind turbine is directly attached to a PMSG.

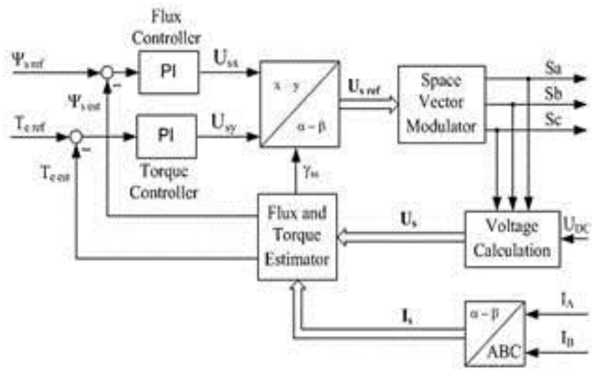


Fig. 9. Block Diagram of DTC-SVM

The produced electric power is transferred to a powerful network or conversed to charge/load through a convertor with variable frequency including a Machine-Side Convertor (MSC) and a Grid-Side Converter (GSC), attached to back to back direct stream connection. In figure 11 $\overrightarrow{\Psi_{s\alpha\beta}} = [\Psi_{s\alpha}, \Psi_{s\beta}]^T$ and $\overrightarrow{u_{s\alpha\beta}} = [u_{s\alpha}, u_{s\beta}]^T$ are leakage flux vectors of stator and the space resultant vector of stator voltage in coordinate $\alpha - \beta$ Also, $\hat{\theta}_{re}$ and $\hat{\omega}_t$ are electrical angle position of rotor and speed of rotor [25].

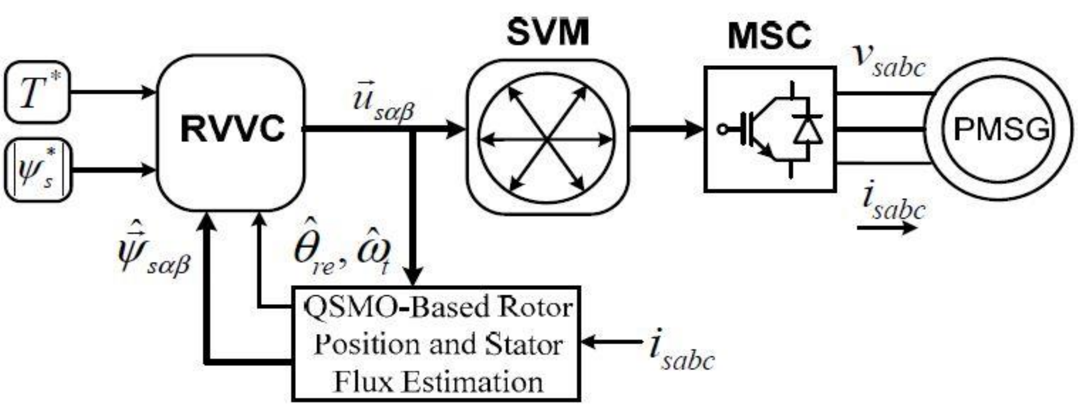


Fig. 10. Schematic of the proposed SVM-DTC for a direct-drive PMSG wind turbine.

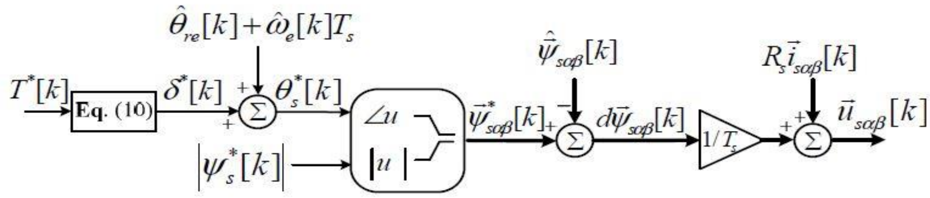


Fig. 11. Block diagram of the RVVC algorithm.

5. SIMULATION

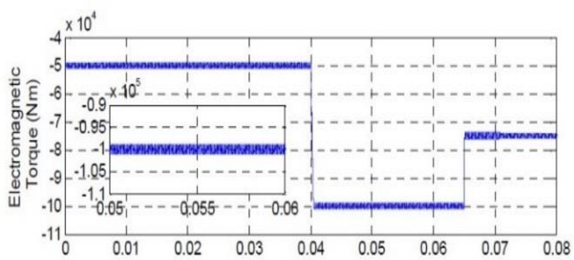
In this section, we investigate torque, stream ripple, and voltage ripple in the both DTC and DTC-SVM in a PMSG with the following characteristics:

Table 1. The PMSG parameters

Number of pole pairs	4
Voltage	230/400 volt
Power	2.2 kw
Stator resistance	2.81 ohm
Rotor resistance	2.78 ohm
Rotor inductance	8.4 Mm Henry
Stator inductance	8.4 Mm Henry
Rotational speed	1420 rpm

In the figure 12, it is observed that the torque has improved in the DTC-SVM stream. As it is shown in the table, the distance of torque impact peaks in the time of using suggested DTC are always lower than 1 KN m (0.12 % torque is permissible). However, when common DTCs are used, the distance of torque impact peaks will be, accidently and unpredictably, more than KN m (figure 2). Therefore, the use of DTC-SVM, whose change frequency is approximately a quarter of common DTCs, is suggested and they can significantly decrease torque impacts (more than 80%).

In the following section (figure 13), the simulated voltage output will be shown, and it shows that the voltage ripples are drastically reduced and the more sinusoidal output, strongly needing circuits and design, is made in this method.



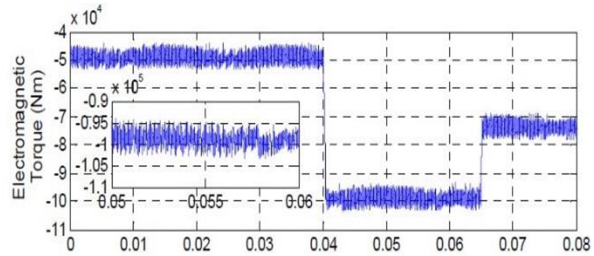


Fig. 12. Output torque of DTC-SVM (up) and in DTC (down)

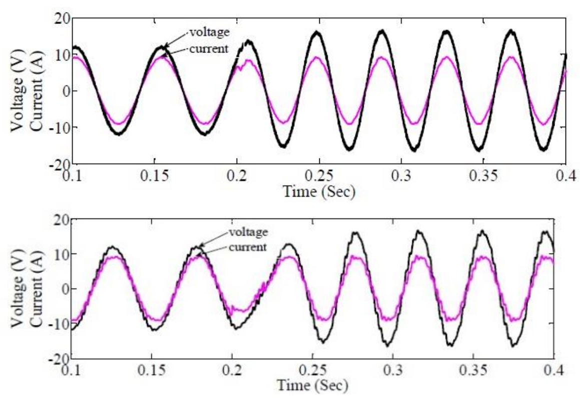


Fig. 13. Reduced voltage and current ripple in DTC-SVM method (up) compared to the DTC (down)

6. The comparison of DTC-SVM with DTC in Matrix convertor

In the wind generators, the real power is injected due to the swinging and fluctuating nature of wind energy and this causes the fluctuation of voltage and Flickr. For this reason, in order to consolidate and control the terminal voltage domain, the power control injection to the network is used. In addition to the abovementioned advantage, the reactive power control is used in the large wind generators and in wind farms, attached to the transmission network, as a means of increasing the system stability and sustainability as well as a tool for compensating local loads reactive power in the wind generators attached to the distribution and high-distribution system so that it results in casualties reduction and the network capacity [26].

The severely excess voltage in Matrix convertor's input and output causes some crucial problems for the application of the convertor due to the AC single-stage conversion, the lack of storage element, and the lack of pathway mediator of intrinsic freewheeling for passing through inductor stream [26].

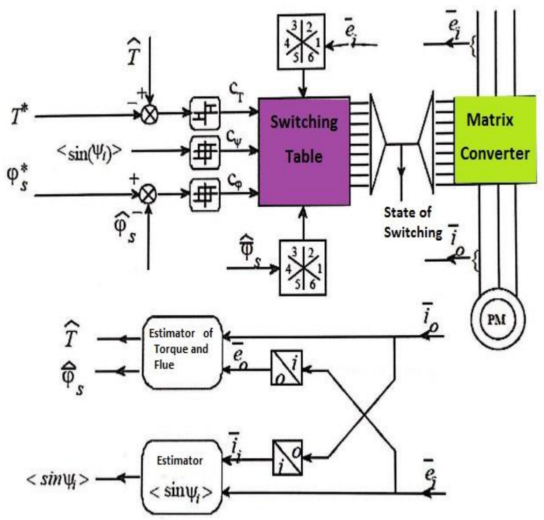


Fig. 13. Block diagram of DTC method for matrix converter

The most commonly suggested approach for the protection of matrix convertors against the excess of output and input voltage is to use clamping circuit. In this circuit, when the convertor keys are opened, the storage energy in the circuit inductors are transmitted to the clamping capacitor through the quick diodes. In the back to back convertor, if there is an error or network voltage drop at the time of controlling motor speed, the storage energy in DC link capacitor is shortly used for the protection of output voltage and the speed fixation and control [27].

In the present article, controlling methods, in accordance with the advantages, such as theoretical complexities, load stream quality, dynamic response, sampling frequency, switching frequency, and the severity in input filter are put under investigation. According to the results gained from the simulation of DTC-SVM and the matrix convertor method, the advantages and disadvantages of each of these methods are stated.

Also, in some methods, sampling frequency and in others high frequency is required. Sampling frequency in SVM, by far, is lower than the approach of Direct Torque Control with matrix convertor.

The escalation in input filter for switching matrix convertor is considered as an important issue. The significant issue which was not concerned in previous sections is that DTC-SVM, regarding the behavior of input filter, has an important influence on the harmonic distortions caused by input filter. In other hand, the methods such as "Ventura and Roy" and space vector modulation, working through fixed switching frequency, decrease the escalation mood of input filter.

As it is shown in the figure 3-5[28], the ripple rate existed in DC voltage for each of SVM and matrix convertor can be compared and in this case, the superiority of SVM is obvious. The decrease rate of DC link voltage ripple is effective in the application of DTC route.

According to the figure 15-5 [28], the decrease of the torque harmonic distortions estimated by DTC-SVM proves this claim. In the following, according to the figures 1-5 to 3-5, an abstract of simulation results of control methods of DTC-SVM and DTC-MC is suggested.

In the table 2, a complete comparison of approaches DTC-SVM and matrix convertor has been shown. As it was stated, the SVM method, regarding theoretical basis and mathematical equations, is more complex than matrix convertor method [27]. In DTC, each switching mood effect on torque behavior, flux and input power factor, must be concerned. The big difference between these two methods is switching frequency. The approach based on SVM is working by fixed switching frequency and matrix convertor method is working by variable switching frequency. In additional to this, switching frequency is lower in SVM than matrix convertor method. In other hand, the transient response mood is more desirable in SVM-DTC.

Table 2. Comparison of space vector modulation of matrix converter

Control methods	Sampling frequency	Dynamic response	Escalation of input filter	Complexity theory	Switching frequency
SVM - DTC	low	Good	low	too high	low
MC - DTC	too high	Fast	too high	high	high

7. CONCLUSION

According to the use of PMSG wind turbines and increasing development of electrical instruments and the improvement of control methods, it can be concluded that SVM-DTC in the ac-dc-ac convertor improves the condition of torque, stream ripple, voltage and etc.

Also, it must be pointed out that the fixed switching frequency is gained through PI controller and SVM block. This method, as indicated in the text, eliminates the DTC disadvantages and it can be an appropriate alternative for DTC method in PMSG wind turbine. In the present article, the use of SVM-DTC method is proposed to decrease torque ripple stator flux of PMSG generators. In the results gained from simulation, the superiority of SVM method is obviously shown. Although the theoretical complexity of matrix convertor modulation method is less than the control method of SVM, it is not possible to simply neglect the harmonic distortions resulted from DC link voltage ripple. In both methods, load stream has been suggested with high quality. The biggest difference is that the SVM works by fixed switching frequency and matrix convertor method by variable switching frequency. Direct Torque Control is used to control the flux and output torque of the generator, but has some disadvantages, the most important of which are torque ripple and the relative high flux.

REFERENCES

[1] Y. Zhang, J. Zhu, W. Xu, and Y. Guo, **"A simple method to reduce torque ripple in direct torque-controlled permanent-magnet synchronous motor by using vectors with variable amplitude and angle,"** *IEEE Trans. Ind .Electron*., Vol. 58, No. 7,pp. 2848-2859, 2011.

[2] Z. Hao, X. Xi, and L. Yongdong, **"Torque ripple reduction of the torque predictive control scheme for permanent-magnet synchronous motors,"** *IEEE Trans. Ind. Electron.*, Vol. 59, No. 2, pp. 871-877, Feb. 2012.

[3] Masakazu Kato; Jun-ichi Itoh, **"On-line copper loss minimization control method of induction and PM motors with periodic fluctuation load,"** *Power Electronics and Applications (EPE'15 ECCE-Europe), 2015 17th European Conference on*,, pp. 978-9-0758-1522-1, 8-10 Sept. 2015

[4] D. Swierczynski, M. Kazmierkowski, and F. Blaabjerg, **"DSP based direct torque control of permanent magnet synchronous motor (PMSM)using space vector modulation (DTC-SVM),"** in *Proc. IEEE. Int. Symp. Ind. Electron.* Vol. 3, pp. 723–727, May. 2002.

[5] W. Qiao, L. Qu, and R. G. Harley, "**Control of IPM synchronous generator for maximum wind power generation considering magnetic saturation,"** *IEEE Trans. Ind. Appl.*, Vol. 45, No. 3, pp. 1095-1105, May/Jun. 2009

[6] MAO Meiqin, LIU Bin, SHEN Kai, XU Bin, CHANG Liuchen, "**Research on SVM-DTC of Speed Sensorless PMSG for the Direct-Drive Wind Generation System with CSC,"** *IEEE Trans. Ind. Appl*., Vol. 45, No. 3, pp. 1095-1105, May/Jun. 2012

[7] Y. Inoue, S. Morimoto, M. Sanada, **"Control method for direct torque controlled PMSG in wind power generation system,"** *in Proceedings of the Electric Machines and Drives Conference IEMDC '09*, pp. 1231-1238

[8] W. Qiao, X. Yang, and X. Gong, **"Wind speed and rotor position sensorless control for direct-drive PMG wind turbines,"** *IEEE Trans. Ind. Appl.*, Vol. 48, No. 1, pp. 3-11, Jan/Feb. 2012

[9] Yongqiang Lang, Bin Wu and Navid Zargari, **"A High-Power Current Source Converter Based Wind Energy System,"** *IEEE Transactions on Industry Application 2008*, Vol. 55(7), pp. 2786-2797.

[10] Y. Inoue, S. Morimoto, M. Sanada, **"Control method for direct torque controlled PMSG in wind power generation system,"** *in Proceedings of the Electric Machines and Drives Conference IEMDC '09*, pp. 1231-1238

[11] P. Vas, **"Sensorless Vector and Direct Torque Control,"** *Oxford, U.K., Oxford University Press*, 1998.

[12] Mahmoud A. Mossa, Silverio Bolognani, **"Effective sensorless Direct Torque Control for an induction motor drive with reduced ripple contents,"** *Power Electronics, Drives and Energy Systems (PEDES*), 2016 IEEE International Conference on, 01 May 2017.

[13] A.B. Nikolic, B.I. Jeftenic, **"Direct Torque Control and Virtual-Flux Based Direct Power Control of Current Source Converter in Wind Turbine Application,"** in *Proceedings of the 14th Power Electronics and Applications Conference*, EPE 2011,

[14] C. Upendra Reddy, Kashyap Kumar Prabhakar, Amit Kumar Singh, Praveen Kumar, **"Flux estimation in DTC for wide speed range,"** *Power and Energy Society General Meeting (PESGM)*, 2016, 17-21 July 2016 1944-9933.

[15] M.F. Rahman, L. Zhong, Md.E. Haque, M.A. Rahman, **"A DirectTorque-Controlled Interior Permanent-Magnet Synchronous Motor Drive without a Speed Sensor,"** *IEEE Transactions on Energy Conversion*, Vol. 18(1), pp. 17- 22, 2003.

[16] Yao Jun, Liao Yong, **"The unit power factor control of direct-drive permanent magnet synchronous wind turbine,"** *Electrical Machines and Control*, Vol. 14, No. 6, pp. 13-20, 2010.

[17] MAO Meiqin, Liu Fuyan, Mu Junsheng, Xu Bin, **"Sensorless Control of PMSG for A Wind Power System Based on CSC,"** *IEEE 8th International Conference ICPE& ECCE2011, Korea*, Asia, July 2011, pp. 2175-2179.

[18] Zhang Chongwei, Zhang Xing, **"PWM rectifier and its control,"** *Machinery Industry Press*, 2003.

[19] D. Swierczynski, M. Kazmierkowski, and F. Blaabjerg, **"DSP based direct torque control of permanent magnet synchronous motor (PMSM) using space vector modulation (DTC-SVM),"** in *Proc. IEEE Int. Symp. Ind. Electron.*, May 2002, Vol. 3, pp. 723–727

[20] L. Tang, L. Zhong, M. F. Rahman, and Y. Hu, **"A novel direct torque controlled interior permanent magnet synchronous machine drive with low ripple in flux and torque and fixed switching frequency,"** *IEEE Trans. Power Electron.*, Vol. 19, No. 2, pp. 346-354, Mar. 2004

[21] J. Holtz and J. Quan, **"Sensorless vector control of induction motor at very low speed using a nonlinear inverter model and parameter identification,"** *IEEE Trans. Ind. Appl.*, Vol. 38, No. 4, pp. 1087-1095, Jul/Aug. 2002

[22] C. Li and M. Elbuluk, **"A sliding mode observer for sensorless control of permanent magnet synchronous motors,**" in *Proc. IEEE IAS Annual Meeting*, Sep/Oct. 2001, Vol. 2, pp. 1273-1278

[23] Z. Xu and M. F. Rahman, **"An adaptive sliding stator flux observer for a direct-torque-controlled IPM synchronous motor drive,"** *IEEE Trans. Ind. Electron*, Vol. 54, No. 5, pp. 2398-2406, Oct. 2007

[24] J. Liu, J. Hu, and L. Xu, **"Sliding mode observer for wide speed range sensor less induction machine drives: considerations for digital implementation,"** in *Proc. IEEE Int. Conf. on Electric Mach. and Drives*, May 2005, pp. 300-307

[25] Y. Zhao, W. Qiao, and L. Wu, **"Compensation algorithms for sliding mode observers in sensorless control of IPMSMs,"** in *Proc. Int. Electric Vehicle Conf.*, Mar. 2012, pp. 1-7.

[26] Y. Zhao, W. Qiao, and L. Wu, **"Oscillation mitigation for sliding-mode observers in sensorless control of IPMSMs,"** in *Proc. IEEE Transportation Electrification Conf. and Expo*, Jun. 2012, pp 1-6.

[27] H. Geng, G. Yang, D. Xu, and B. Wu, **"Unified power control for PMSG-based WECS operating under different grid conditions,"** *IEEE Trans. Energy Conversion*, Vol. 26, No. 3, pp. 822-830, Sept. 2011.

[28] Y. Zhao, W. Qiao, and L. Wu, **"Dead-time effect and current regulation Quality analysis for a sliding-mode position observer-based sensorless IPMSM drives,"** in *Proc. IEEE IAS Annual Meeting*, Oct. 2012, pp.1-7.

[29] Mehrdad Jafar Boland, Bijan Sheikhan, "**Sensorless speed control of induction motors with dtc based on EKF,"** *Majlesi Journal of Electrical Engineering*, Vol 3, No .4, 2009.

[30] HamidReza Fakharizadeh, **"Improvement of torque response and reduction of error speed in direct torque control of induction motor by fuzzy logic"** *Majlesi Journal of Electrical Engineering*, Vol. 3, No. 3, 2009.

[31] Mohsen Siami, S. Asghar Gholamian, **"Predictive torque control of three phase axial flux permanent magnet synchronous machines",** *Majlesi Journal of Electrical Engineering*, Vol. 6, No. 2, 2012.

[32] Maryam Bahramgiri, Ali Abedini, Alireza Siadatan, **"Analysis of permanent magnet wind turbine dynamics during wind fluctuations,"** *Majlesi Journal of Electrical Engineering*, Vol. 6, No. 3, 2012.