The Simplified Model of Back-To-Back PWM Converter

Xutao Li1, a, Saijun Yuan2, *, Di Zhang1, b, Cunxi Bai1, c, Huibiao Yang1, d, Zhiguo Hao2, e and Jingdong Xu2, f
1Ningxia Electric Power Research Institute, Ningxia Key Laboratory of Electrical Energy Security, Yinchuan, 750002, Ningxia, China
2School of Electrical Engineering, Xi’an Jiaotong University, Xi’an 710049, Shaanxi, China

*Corresponding author e-mail: ysj201388@stu.xjtu.edu.cn, alee_abner@126.com, baelict@vip.sina.com, baicunxi@126.com.cn, dhuibiaoyang@163.com, ezhghao@mail.xjtu.edu.cn, fxjd_xjtu@xjtu.edu.cn

Abstract. This paper proposes a simplified model of PWM converter, which is proved to be effective in saving simulation time. Take doubly-fed wind power system as an example, the PWM converter is simplified in two aspects: a) the AC side of converter precisely and flows the output voltage reference; b) ignore the power loss of converter, which means the AC side power equals to DC side. Based on the two assumptions, the voltage of AC side could be replaced by a voltage-controlled voltage source, and the DC side could be replaced a controlled current source. By this way, the complex IGBTs converter is simplified to an equivalent circuit. Simulation with specific model and simplified model then performed in PSCAD/EMTDC. By comparing their waveforms and simulation speed, the correctness and benefits of the proposed model are verified.

1. Introduction
In the context of the traditional energy depletion and serious environmental issues, the renewable energy generation developed rapidly all around the world. Wind and solar energy penetration are rapidly increasing over the past decades due to many benefits such as cleanliness, short construction cycle, and low running cost. Nowadays, the doubly fed induction generator (DFIG) and the direct-drive wind generator (PMSG) are the most employed generator for wind turbines above 1MW due to the advantages of variable speed constant frequency based operation and decoupled control of active and reactive power. Wind turbines and solar PV plants both connect to grid through converters. PMSG uses full power converters. DFIG, however, as the converter only manages the rotor power, its converter can be rated at around 25%–35% of the generator rating.

PSCAD/EMTDC is a widely-used simulation platform, which provides various converters’ models. Like all popular simulation software, its simulation speed of electromagnetic transient simulation software mainly depends on two factors: number of model nodes and simulation time per step. Most of the existing new energy generation units are connected to grid through fully-controlled converters which are using power width modulation technology (PWM). In order to precisely simulate the switch breaking process of converter, the simulation time per step should not be set larger than 10μs. For large scale grid-connected new energy station, small simulation time per step will lead to dimension disaster, which finally breaks down the simulation.
To solve the problem of simulation speed, the previous research proposed a method. This method divides hundreds of wind turbines into several group according to their wind speed or rotor speed. Then, for each group, use an equivalent DFIG wind power system to replace a large group of wind farm. In this way, the number of converters decreased, and the simulation time is largely shortened. For another respective, this paper proposed a simplified model, which decreases the nodes of each PWM converter. Similarly, it is expected to accelerate the simulation process.

This paper has been organized as follows. Take DFIG for example, the model of simplified PWM converters is introduced in Section 2. In Section 3, the simulation case of proposed simplified model is carried out to validate the effectiveness on time saving. Finally, the conclusion is reached in Section 4.

2. Modelling of simplified converter
Since the high frequency signals are usually ignored when research on the influence of system relay protection due to new energy injection, the equivalent simplified model mainly makes sure to guarantee the low frequency (0-100Hz) characteristics. The simplified model described in this section mainly concerns the consistency of power flow, voltage and current characteristics between the specific model and simplified model, under both normal conditions and grid faults.

Doubly-fed wind turbine connects to grid not only through directly stator-connection, but its rotor windings also connects to grid through AC-DC-AC back-to back PWM converter. Among three typical renewable energy generation systems mentioned in Section 1, the control of DFIG VSC converters is the most complex. Thus, in this section, taking DFIG system for example, the process of simplifying PWM converter model is clearly introduced. Similarly, the converters in PMSG and PV array could be simplified in the same way.

2.1. Converter’s Equivalent Model of DFIG
The generic structure of doubly-fed wind turbine is shown as Fig. 1. As usual, right side of the back-to-back converter is called grid side converter (GSC), and the right side called rotor said converter (RSC), correspondingly. The control of GSC is designed to maintain the DC-link voltage. RSC, on another hand, control the output power of wind turbine. In different controlling method, the voltage reference of converters AC side is different. However, thanks to controllable switching elements, converters realize the good performance of renewable energy generation.

![Figure 1. DFIG-based wind turbine.](image)

Since the rotor side converter’s control is more complex, this paper uses the rotor side converter for example. RSC’s equivalent model is shown in Fig. 2. We often use the two-level voltage source converter (VSC) model in PSCAD’s library, and the switching loss could be set. Ignoring the power loss of witching, the mathematical model in Fig. 2 is shown as following.

$$
\begin{align*}
\frac{du_a}{dt} &= -R_{ia}i_a - L_{ia}\frac{di_a}{dt} - S_{ia}U_{dc} = u_{ib} - R_{ib}i_b - L_{ib}\frac{di_b}{dt} - S_{ib}U_{dc} \\
\frac{du_b}{dt} &= -R_{ib}i_b - L_{ib}\frac{di_b}{dt} - S_{ib}U_{dc} = u_{ic} - R_{ic}i_c - L_{ic}\frac{di_c}{dt} - S_{ic}U_{dc} \\
\frac{CdU_{dc}}{dt} &= S_{ia}i_{ia} + S_{ib}i_{ib} + S_{ic}i_{ic} - i_{load}
\end{align*}
$$

(1)
Figure 2. Equivalent model of RSC.

Where $u_{r_{a,b,c}}$ represents the three phase AC voltage applied on rotor windings; $S_{r_a}, S_{r_b}$ and $S_{r_c}$ are the ON/OFF status function of three arms for each phase, $S_{r_a} = 1$ means the upper IGBT is turning on.

Since the converter usually uses no-neutral line connection, the sum of three phase’s current is zero according to Kirchhoff’s current law.

$$i_{a} + i_{b} + i_{c} = 0 \quad (2)$$

Then, (1) could be furtherly written as (3).

$$\begin{align*}
L_{r_a} \frac{d i_{a}}{dt} & = u_{a} - i_{a} R_{r_a} - (u_{a} + u_{b} + u_{c}) / 3 - [S_{r_a} - (S_{r_a} + S_{r_b} + S_{r_c}) / 3] U_{dc} \\
L_{r_b} \frac{d i_{b}}{dt} & = u_{b} - i_{b} R_{r_b} - (u_{a} + u_{b} + u_{c}) / 3 - [S_{r_b} - (S_{r_a} + S_{r_b} + S_{r_c}) / 3] U_{dc} \\
L_{r_c} \frac{d i_{c}}{dt} & = u_{c} - i_{c} R_{r_c} - (u_{a} + u_{b} + u_{c}) / 3 - [S_{r_c} - (S_{r_a} + S_{r_b} + S_{r_c}) / 3] U_{dc} \\
U_{dc} & = C
\end{align*} \quad (3)$$

Equation (4) describes the phase-to-phase voltage of converter’s AC side, based on the switching operation.

$$\begin{align*}
u_{ab} & = (S_{r_a} - S_{r_b}) U_{dc} \\
u_{bc} & = (S_{r_b} - S_{r_c}) U_{dc} \\
u_{ca} & = (S_{r_c} - S_{r_a}) U_{dc}
\end{align*} \quad (4)$$

Then, the AC side phase voltage of converter could be converted from (4).

$$\begin{align*}
v_{a} & = [S_{r_a} - (S_{r_a} + S_{r_b} + S_{r_c}) / 3] U_{dc} \\
v_{b} & = [S_{r_b} - (S_{r_a} + S_{r_b} + S_{r_c}) / 3] U_{dc} \\
v_{c} & = [S_{r_c} - (S_{r_a} + S_{r_b} + S_{r_c}) / 3] U_{dc}
\end{align*} \quad (5)$$

With (3) and (5), the mathematical model of RSC is

$$\begin{align*}
L_{r_a} \frac{d i_{a}}{dt} & = u_{a} - i_{a} R_{r_a} - u_{d0} - v_{a} \\
L_{r_b} \frac{d i_{b}}{dt} & = u_{b} - i_{b} R_{r_b} - u_{d0} - v_{b} \\
L_{r_c} \frac{d i_{c}}{dt} & = u_{c} - i_{c} R_{r_c} - u_{d0} - v_{c} \\
U_{dc} & = C
\end{align*} \quad (6)$$

Where $u_{d0}$ is the zero sequence rotor voltage.
2.2. Method of PWM Converter’s Simplification

Based on (6), in order to simplify the RSC, two assumptions are applied: a) the AC side output voltage $v_{ra} \ v_{rb} \ v_{rc}$ following the control loop’s output reference voltage $v_{ra.ref} \ v_{rb.ref} \ v_{rc.ref}$, precisely and instantaneously; b) ignoring the switching power loss. Then, the AC side power equals to DC side. Based on this two assumptions, the following two equations are correct.

$$\begin{cases} v_{ra} &= v_{ra.ref} \\ v_{rb} &= v_{rb.ref} \\ v_{rc} &= v_{rc.ref} \end{cases}$$ (7)

$$P'_{dc} = v_{ra.ref}i_{ra} + v_{rb.ref}i_{rb} + v_{rc.ref}i_{rc} = P_{dc} = u_{dc}i_{dc}$$ (8)

The procession of IGBT/Diode’s switching is ignored. In previous modeling, the voltage reference is firstly used to generate PWM pulses, which lately control converter’s switching. The AC side voltage is unsmooth stepping voltage which is pretty close to sine wave. Before connecting to rotor windings, a series R-L choke is needed to filter the harmonics. This proposed method doesn’t concern the high frequency components. Substituting (7) into (6), in AC side, three voltage controlled voltage source are respectively connected to rotor side R-L choke. Moreover, except voltage equivalent, the power flow between both sides should also be concerned. Since the power loss is ignored and the DC link voltage maintains unchanged, the DC side current could be calculated as the right side of (8). A current controlled current source parallel with capacitor transfer the AC side power to DC side. By this way, the complex converter is replace by controlled sources, and the proposed simplified converter is shown in Fig. 3.

![Proposed Simplified Model of RSC.](image)

To be noticed, the two assumptions are not correct under some circumstances. The assumption a) is not suitable for over modulation, which is caused by too large voltage reference. When saturation of $V_{ref}$ is included in control part, over modulation will not happen. The error brought by assumption b) is usually inessential since the IGBT conducting resistance is about 0.1ohm.

3. Simulative Results

In order to evaluate the correctness in simulation and advantages in time saving, two simulation models of doubly-fed wind turbine respectively based on detailed converter model and simplified converter model are built on PSCAD/EMTDC simulation platform.

3.1. Structure of Simulation System

The simulative physical model is shown in Fig. 4. The wind farm consists of a doubly-fed wind farm with an installed capacity of 50 MW. It is connected to the 110kV bus through two transformer, and then sent to the 110kV system with double 110kV transmission line.
A three phase fault $f_1$ is applied in the middle of T-Line 1 at 0.5s, and is cleared after 0.3s. During the fault period, the DFIG is controlled by low voltage ride through (LVRT) rather than maximum wind power tracking strategy. The active power reference decreases to zero while wind farm is required to output proper reactive power. After the fault is cleared, the reactive output power reference soon drops down to 0, and the active power gradually increase to normal reference. Since the voltage sag during fault is 40%, the rotor current does not reach the 2 times of rated value. The Crowbar protection doesn’t work and the DFIG is under control. The voltage and current of T1’s 35kV side are measured.

3.2. Verification on Correctness & Acceleration

As mentioned before, the simplified model mainly concerns the consistency of power flow, voltage and current characteristics with specific model. Thus, the power and current of two models’ in this simulation should be compared. Fig. 5 shows the power flows’ comparison result. The active power in the detailed converter has small amplitude fluctuation due to the high frequency component corresponding to the carrier frequency on the bus voltage. The power trends of the two simulation models are the same. Fig. 6 shows the comparison of currents. It can be seen from the figure that the voltage and current trends and amplitudes of the two simulation models are consistent after the fault. The only difference is the high frequency of the voltage waveform caused by the detail converter model’s carrier frequency component. When the voltage drop is deep, the rotor side Crowbar protection device of DFIG will act. Since the converter is locked, there is no difference between the two simulation models. Therefore, the comparison of the simulation results under this fault condition is omitted here.
Through the simulation comparison of various fault drop degrees, the simplified electrical converter model's various electrical quantity values and trends during the fault are not different from the detailed model at low frequency (0~100Hz), so this model simplification method can be used completely.

Moreover, the simulation time of two models is compared in Table 1, which proves the proposed model’s advantages in time saving.

| Time Step/μs | Detail Model | Simplified Model |
|--------------|--------------|------------------|
| 10           | 150          | 50, 31, 20, 17, 14 |
| Simulation Time/s | 10, 20, 30, 40, 50 |

4. Conclusion
This paper proposed a simplified model of PWM converter. Based on two reasonable assumptions, the complex rotor side converter of DFIG is replaced by controlled voltage source and controlled current source. A 50MW wind farm simulative model is used to verify the correctness and effectiveness. The results indicates that, compared to specific model, the proposed model’s simulation results that are very close to the detailed model. Besides, the proposed model has a significant advantage in simulation speed.

Acknowledgments
This work was supported by National Key Research and Development Program of China (2017YFB0902000), and Technology Program of State Grid Ningxia Electric Power CO.LTD (5229DK16001C).

References
[1] Lopez J, Sanchis P, Roboam X, et al. Dynamic Behavior of the Doubly Fed Induction Generator During Three-Phase Voltage Dips [J]. Energy Conversion, IEEE Transactions on. 2007, 22 (3): 709-717.
[2] Holtz J. Advanced PWM and Predictive Control—An Overview [J]. IEEE Transactions on Industrial Electronics, 2016, 63 (6): 3837-3844.
[3] Fei G, Xue A C, Ping L, et al. Research on the improvement of LVRT ability of an actual DFIG-type wind farm with Crowbar and SVG [C]// International Conference on Renewable Power Generation. IET, 2016.
[4] Shipurkar U, Strous T D, Polinder H, et al. LVRT performance of brushless doubly fed induction machines — A comparison [C]// Electric Machines & Drives Conference. IEEE, 2016.
[5] Zhao H, Tang H, Zhang W, et al. Transient characteristics research and integrated control strategy of DFIG for zero voltage ride through [J]. Power System Technology, 2016.

[6] FDB, Mantz RJ. Wind turbine control systems: principles, modelling and gain scheduling Design [M]. London: Springer. 2008.

[7] Baggu MM, Watson LD, Kimball JW, et al. Direct power control of doubly-fed generator based wind turbine converters to improve Low Voltage Ride-Through during system imbalance [M]. Palm Springs, CA. 2010: 2121-2125.

[8] Li L, Huilong Z, Tao L, et al. Transient stability mechanism of DFIG wind farm and grid-connected power system [M]. Grenoble. 2013: 1-9 Li L, Huilong Z, Tao L, et al. Transient stability mechanism of DFIG wind farm and grid-connected power system [M]. Grenoble. 2013: 1-9.

[9] Peng Z, Yikang H, Dan S. Improved Direct Power Control of a DFIG-Based Wind Turbine During Network Unbalance [J]. Power Electronics, IEEE Transactions on. 2009, 24 (11): 2465-2474.