A Modulation Method with Unfixed Switching Frequency Based on Output Power for Wind Power Converter

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Abstract. The wind turbine power system is being widely used and heavily connected to the utility grid, and the total harmonic distortion (THD) is one of the major evaluation indicators of electric power quality. The characteristics of the grid-connected wind converter harmonic with variable power loading are analyzed in this paper, and a software method of the variable switching frequency based on the output power of wind power converter is investigated to improve the grid-connecting harmonic considering the widely power loading. The method is verified on a three-level Neutral-Point-Clamped converter with Sinusoidal Pulse Width Modulation through simulations at last. And the results show that the THD is improved clearly and meanwhile the power loss and junction temperature are improved.

Introduction

As the crisis of energy source has intensified and environmental awareness has promoted, renewable energy power generation is increasingly extensive nowadays. Plenty of wind power units have connected to the utility grid through converters, and the “grid penetration” becomes higher and higher[1,2]. Wind power converter connected to grid can improve the power supply capacity, but it will generate more harmonics leading to lower quality of electric energy. Now in most wind power systems the two-level converter has been replaced by multi-level converter such as three-level Neutral-Point-Clamped (3L-NPC) converter [3,4], since multi-level converter has superior performance with higher output power and lower harmonic. The harmonics generated from the output power of converters do harm to the quality of electric energy into the grid, so it is serious to improve the harmonics in wind power generation systems.

The up-and-down harmonic has bad effects on the quality of electric energy, because sometimes the fluctuation of harmonic will result in higher THD at low wind power [5]. References [6,7] have analyzed characteristics of power quality including current harmonics and presented simulation methods to study the characteristics. Reference [8] has presented experimental-based evaluation on the harmonic and interharmonic distortion of photovoltaic inverters. Moreover, reference [9] has proposed a novel online adaptive dead-time elimination method to reduce the low-frequency harmonic contents and THD, in which the current direction, the zero-crossing current region and the non-zero-crossing current region can be distinguished. Reference [10] presents an improved single-phase converter topology with double-frequency SPWM that can reduce the THD in the transformerless photovoltaic grid-connected system. These papers have studied the harmonic and provided some methods to reduce the harmonic. However, these papers do not aim at the performance of THD under annual comprehensive operating conditions of wind power converters.

In wind power generation system the wind speed is fluctuant, and then the output power is influenced with variable wind speed[11]. The large fluctuation of wind power will cause fluctuant harmonic and lower quality of electric energy. The total harmonic distortion (THD) need be further improved, not only meet the grid code, on account of increasingly higher wind power penetration.
This paper provides a new idea aimed at improving the performance of harmonics and then the quality of electric energy for the wind power converter under annual working conditions. Generally Pulse Width Modulation (PWM) is adopted in the multi-level converters and the PWM switching frequency is fixed in modulation with unchanged output power. The THD of power generation system must meet the grid code, which limits the voltage THD less than 8% and the current THD less than 5% according to IEEE 519-2014. Generally speaking, in wind power converter, the fixed PWM switching frequency is designed for the rating output power, and the requirement of the grid code aims at the rating operating condition. Then when the wind power decreases to a low level, the THD will become higher. The harmonic can be decreased through designing better filter or improve the modulation strategy, but the filter have been designed in hardware designing, while the switching frequency can be changed through software when the converter is operating. Therefore, the substance of this paper is to study a modulation strategy with unfixed switching frequency in wind power converter to optimize the harmonics and performance of wind power converters.

In the paper, the switching frequency is unfixed in the wind power generation system to achieve more stable THD and keep THD at low values on the whole. Figure 1 shows the system structure of wind power converter including controller in the paper. 3L-NPC structure is applied in the converter, and a brief exposition for the structure is given in part II. Then the relationship between the characteristics of power quality will also be analyzed. Part III introduces the idea of the proposed method, and gives the verification and comparison through simulation at last.

Operating Model and Analyzation for Performances of THD

Operating Model of Wind Power Converter

A 3L-NPC converter model connected to the grid with a PI controller is established in MATLAB, whose power rating is 1.4MW and modulation method is Sinusoidal Pulse Width Modulation (SPWM). The dc bus voltage is 2*900V and the ac distributed rated RMS line-to-line voltage is 690V at 50Hz fundamental frequency. The output filter inductance L is 0.9mH with resistance of 16mΩ. FF1000R17IE4 is accordingly chosen as the IGBT module, of which the maximum current is 1390A and the temperature limit is 175ºC. The wind power converter system includes wind power generator, wind power converter, filter, transformer and controller. The controller collects current and voltage from the filter and generate PWM wave to the converter, the output power from the wind power generator. Double loop control is applied in the system with the purpose of width power loading tracking control. The outer loop is a power control loop, and the inner loop is current control.

3L-NPC converter is shown in Figure 2. There are three phases in the topology, phase A, B, and C, and there are four IGBTs and two neutral-point-clamped diodes in every phase. The topology has three commutation states: N, O and P. The output voltage of the phase is zero (state O), when the inner
switches $S_{x2}(x=a, b, c)$ and $S_{x3}$ are turned on with other switches turned off. The state N is obtained when the switches $S_{x3}$ and $S_{x4}$ are turned on and others are turned off, while the state P is obtained when only the switches $S_{x1}$ and $S_{x2}$ are turned on.

![Figure 2. The structure of 3L-NPC.](image)

The PWM modulation is a highly popular method, in which the artificial circuit is controlled by digital signals. The PWM waveform is obtained through a series of impulse sequences with equal amplitude controlling power switches to turn on or off. The width and gap of impulse sequence are based on the intersection of reference and carrier, and then based on the switching frequency.

**Evaluation for the Harmonic Performance of Converter at Fixed Switching Frequency**

In traditional modulation of wind power converter, the switching frequency is designed at a certain value based on the rating power. Under the operating condition, when the output power is unchangeable and it is operating at rating power (1.4MW), the switching frequency can be designed at 1.1kHz. Then the voltage THD is 1.74% and the current THD is 4.44%. When the output power ($P_{out}$) is changing from 800kW to 1400kW and the switching frequency ($F_{sw}$) is 1.1kHz, Table 1 and Figure3 show the voltage and current THD.

| $P_{out}$ (kW) | 800  | 900  | 1000 | 1100 | 1200 | 1300 | 1400 |
|---------------|------|------|------|------|------|------|------|
| Voltage THD(%)| 5.01 | 6.21 | 6.04 | 5.92 | 5.39 | 6.91 | 5.96 |
| Current THD(%)| 8.22 | 7.22 | 6.45 | 5.84 | 5.30 | 4.92 | 4.44 |

![Figure 3. The changing tendency of current THD when Pout changing linearly.](image)

As can be seen in Table 1, when the $P_{out}$ increases, the variation of voltage THD has no certain tendency but is lower than 8% absolutely. The current THD decreases from 8.22% to 4.44%. It can be
easily discovered in the module that voltage THD can maintain low while the current THD becomes higher at low-power operating state. Therefore, the current THD is the focused research object. In Figure 3, it is shown that the current THD generated from the converter decreases nonlinearly while the wind power changes from 800kW to 1400kW. The current THD is not linear, so it is hard to design a certain function to keep the current THD at low values. However, it can be considered linearly in different sections respectively, which can be observed in Figure 3. If the sections are divided evenly based on the current THD, whose range is 3%-9%, it will be easier to design a rule to control the THD at low values. Obviously, the current THD declines more quickly at low output power than at high output power and the slope becomes smaller when the output power rises.

**Evaluation for the Harmonic Performance of Converter at Unfixed Switching Frequency**

The THD at varying output power($P_{out}$) or switching frequency($F_{sw}$) is variable while the THD at unchanged $P_{out}$ and $F_{sw}$ is stable. The THD with fixed $P_{out}$ and changing $F_{sw}$ can be seen in Figure 4. It can be seen that the current THD shows a reverse to the switching frequency at changing tendency but the voltage THD does not have a certain changing tendency. When the $P_{out}$ is at rating output power and the switching frequency increases from 800Hz to 1400Hz, the voltage THD varies in the range of 6.91%-3.43%, which is lower than 8%. However the current THD is decreased from 7.31% to 3.46%, and it becomes higher than 5% while $F_{sw}$ lower than 1000Hz.

![Figure 4. The changing tendency of THD when $F_{sw}$ changing linearly.](image)

![Figure 5. The power loss at linearly changing switching frequency.](image)

The power loading in the wind power generation system is changeable throughout a year. When the power loading or PWM switching frequency changes, the harmonic will be changed and then the value of THD will become fluctuant. Besides, the thermal losses and then the junction temperatures of power devices are not stable. If the switching frequency increases, the current THD will decrease, but the power losses of power devices will increase as seen in Figure 5. It can be observed that when the
switching frequency is higher, the power loss will be higher too. So the switching frequency can’t be designed too high, considering the power losses, if the converter system is established.

According to the analysis above, when the output is changing, the switching frequency can be designed to stable the THD. The current THD at linearly changing output power ($P_{out}$) and different switching frequency ($F_{sw}$) is shown in Figure 6. The output power changes from 800 kW to 1800 kW. When the switching frequency is 1.1 kHz, the current THD at rating output power is lower than 5%. When the switching frequency is 1.9 kHz, the current THD at all output power is lower than 5%. So when the output power is different, the switching frequency can be designed differently so that the current THD at any output power is lower than 5% and the power loss is not that high.

**Unfixed Switching Frequency Modulation**

Generally, the THD at rating wind power should not be higher than the upper limit of the grid code. However, the THD at low output power will become higher, which has bad influence on the quality of electric energy. Therefore the modulation strategy with flexible switching frequency is studied in the paper aimed at improving the quality of electric energy. Furthermore, since the wind power and switching frequency have influence on the power losses and junction temperatures of power devices, which has significant impact on the lifetime and reliability of IGBT modules in power converters [12,13], the thermal loading of the converter will be analyzed in the paper.

Actually, wind speed and then wind power changes continuously. In this case, the output power generated from wind is expressed as Figure 7(a). As can be seen, the rating power is 1400 kW, and the power higher than 1400 kW is cut off. It is difficult to find a certain PWM switching frequency corresponding to every value of the output power. So an idea is proposed, in which the continuous output power curve is divided into some levels from the lowest to the highest point. According to the analysis for Figure 3, the current THD changes nonlinearly when the output power changes linearly. Therefore, when the output power changes at a low level, the switching frequency need change more to keep THD at a low value comparing to the operating state at high output power.

In Figure 3, the first section of current THD (3%-4.5%) corresponds to the output power from 800 kW to 878 kW, the second section is 878 kW-1076 kW, the third section is 1076 kW-1377 kW, and the last section is 1377 kW and above. Then the output power can be divided to four levels. For convenience, Level1 is 800 kW-900 kW; Level2 is 900 kW-1100 kW; Level3 is 1100 kW-1400 kW; Level4 is 1400 kW and above in this case. And then the output power becomes ladder-shaped in Figure 7(b).
In the grid code, the current THD must be limited to 5% and the voltage THD cannot be higher than 8%. This converter is switched at 1.1kHz and then the THD can meet the grid code at the rating power. The fluctuation of the voltage THD is from 5.01% to 6.91%, while the current THD is from 4.44% to 8.22%. The current THD can meet the grid code at rating output power but cannot keep at low values when the output power decreases.

When the wind power varies, different switching frequency can be set to match different wind power in order to keep the current THD at a low level. Under this condition, considering the thermal loss, the current THD should be controlled lower than 5% but not lower than 4%. Figure 8 shows the basis of the selection for the switching frequency corresponding to every level of output power. Considering the nonlinearity of current THD, the levels are divided unevenly, and when \( P_{\text{out}} \) is at Level1, \( F_{\text{sw}} \) is set to 1.90kHz; when \( P_{\text{out}} \) comes to Level2, \( F_{\text{sw}} \) is changed to 1.7kHz; and the all values of \( F_{\text{sw}} \) can be set according to Table 2. Unlike the THD at fixed switching frequency, all of the current and voltage harmonics at unfixing \( F_{\text{sw}} \) are at low levels through verification as seen in Table 3.

| \( P_{\text{out}} \) (kW) | \( 800 \leq P_{\text{out}} < 900 \) | \( 900 \leq P_{\text{out}} < 1100 \) | \( 1100 \leq P_{\text{out}} < 1400 \) | \( 1400 \leq P_{\text{out}} \leq 1800 \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( \Delta P_{\text{out}} \) (kW) | 100 | 200 | 300 | 400 |
| \( F_{\text{sw}} \) (kHz) | 1.9 | 1.7 | 1.4 | 1.1 |

Table 3. (a) The THD at fixed switching frequency (\( F_{\text{sw}} = 1.10kHz \)).

| Wind power (kW) | 800 | 900 | 1100 | 1400 |
|-----------------|-----|-----|------|------|
| Voltage THD (%) | 5.01| 6.21| 5.92 | 5.96 |
| Current THD (%) | 8.22| 7.22| 5.84 | 4.44 |

Table 3. (b) The THD at unfixed switching frequency.

| Wind power (kW) | 800 | 900 | 1100 | 1400 |
|-----------------|-----|-----|------|------|
| Switching frequency (kHz) | 1.9 | 1.7 | 1.4 | 1.1 |
| Voltage THD (%) | 1.84| 4.07| 3.26 | 5.96 |
| Current THD (%) | 4.58| 4.74| 4.52 | 4.44 |
Comparison of Performance

In the 3L-NPC structure, the devices $S_{a1}$, $S_{a2}$ and $D_{a5}$ are taken for example, since the switches $S_{a3}$ and $S_{a1}$, $S_{a4}$ and $S_{a2}$, $D_{a6}$ and $D_{a5}$ are symmetrical respectively. In this case for traditional modulation, the rating output power is 1400kW, and the converter is switched at 1.1kHz to ensure the current THD at rating output power lower than 5%. Then the current THD with fixed switching frequency and flexible switching frequency can be seen in Figure 9. When the converter is operating at fixed switching frequency, the current THD is lower than 5% at rating output power but higher than the limit at low output power. However, when the switching frequency is changed according to the proposed rule in Table 4, the current THD is lower than 5% and higher than 4% in every period.

![Figure 9. The current THD at fixed and unfixed $F_{sw}$.](image)

Through the results of simulation, the comparison of performance between the modulation with fixed and unfixed switching frequency is obvious that the current THD with fixed switching frequency is fluctuating in the range of 4.44%-8.22%, while that with unfixed switching frequency is below 5% all time. The power loss and junction temperature of $S_{a1}$ switching frequency can be seen in Figure 10, and that of $S_{a2}$ and $D_{a5}$ can be seen in Figure 11 and Figure 12. The variations of power losses and junction temperatures of power devices at unfixed switching frequency are lower than that at fixed switching frequency. The modulation with the proposed strategy can improve the performance of harmonic, and decrease the fluctuation of power losses and junction temperatures.

![Figure 10. (a)The power loss of $S_{a1}$ at fixed and unfixed $F_{sw}$; (b)The junction temperature of $S_{a1}$ at fixed and unfixed $F_{sw}$.](image)
Conclusion

This paper investigates a modulation method with unfixed switching frequency based on output power to improve the performance of harmonic and thermal loss in wind power converter. The fluctuation of wind power have impact on the quality of electric energy and the lifetime of power devices. The proposed modulation has the ability to lower the THD at low wind power to meet the grid code and meanwhile improve the power loss and junction temperature. Besides, the strategy is a software method which is easy to be realized in commissioning converters. The verification is obtained through simulation, which are based on a 3L-NPC converter with SPWM modulation. The results verify the correctness of the theoretical analysis and the effectiveness of the proposed method.

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