New Energy Generation Converter Harmonic Evaluation Based on Operation Data

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Abstract. The research on the harmonic mechanism and features of new energy generation units is crucial for ensuring safe and stable operation of new energy generation. In this paper, a big data analysis method suitable for the operation data of new energy power plant is used to analyse the harmonics generated by PWM modulation and dead zone effect of switching devices and the interharmonics generated by DC side voltage fluctuation. The simulation analysis verifies the harmonic characteristics of new energy power converter, the model basis of new energy power generation operation evaluation and power grid connection certification.

1. Introduction
Photovoltaic plants and wind farms deliver energy to grids or local AC loads through inverters. Harmonics generated by inverters which contain a large number of power electronic components is featured by broad-frequency domain. Harmonic resonance caused by the network resonance will bring severe harm to power grids[1-2]. Harmonic mechanism of power electronic devices is complex, so simple equivalent superposition of harmonic sources cannot meet the demands for studying harmonic features of new energy generation systems. Therefore, it becomes a primary issue of grid-connection certification of new energy generation to analyse harmonic mechanism of power units in detail to build a model, and evaluate harmonic features of new energy plants.

Taking photovoltaic array output characteristics and maximum power point tracking (MPPT) into account, this thesis studies harmonic and inter-harmonic mechanisms of photovoltaic inverters, including harmonics and inter-harmonics produced by PWM switch modulation, deadband effect of switching devices, etc., analyses their features and deeply researches the rotor-side converter of typical doubly fed wind units, harmonic mechanisms caused by magnetic coupling between the rotor and stator and interactive laws among them. Through simulation modelling, this thesis verifies the analysis results and provides model foundation for operational evaluation and grid-connection certification of new energy generation.

2. Research on harmonic mechanism

2.1. Harmonic mechanism of directly-driven wind units / PV inverter
Inverters in both the PV power system and directly-driven wind units will produce high frequency harmonics when Pulse-Width Modulation (PWM) is adopted to covert DC to AC. As they will flow to the grid via filters, the quality of grid power will be affected[3-4]. Figure 1 is a schematic diagram of the structure of the PV power system and directly-driven wind units[5]. Besides, the deadband effect caused by switch components will also yield a certain number of harmonics which can affect the grid power. Owing to the DC voltage-stabilizing capacitor, the voltage remains constant at the steady state and harmonics yielded by machine-side converters won’t affect the grid. Hence, only consider the influence of harmonics yielded by the grid-side converters can be considered.

Harmonics of directly-driven wind units / PV inverters are mainly caused by PWM switch modulation, the deadband effect of switch components, etc., among which the former is highly frequent and the rest is slowly frequent. For PWM modulation, SPWM is widely used in practical projects because of its simplicity, reliability, and well-developed technology[6-7].

The inverter adopts bipolar natural sampling SPWM modulation and the fundamental component of the voltage can be estimated as follows through Fourier analysis of inverter output voltage $U_{ab}$:

$$U_{ab1} = \frac{\sqrt{3}}{2} U_{dc} M \sin(\omega t + \varphi + \frac{\pi}{3}) \quad (1)$$

Where $U_{dc}$ denotes DC-side voltage; $M$ denotes modulation ratio; $\omega$ denotes modulation wave and angular frequency.

Through the analysis of two conditions when $n$ is even and $n$ is odd, the harmonic analysis of SPWM can be summarized as follows:

- In fundamental component $U_{ab1}$, when modulation degree $M = 1$, the voltage utilization ratio is 0.886.
- In harmonics, there is no integral multiple of harmonics of carrier frequency and no integral multiple sideband harmonics of 3 multiples of modulation frequency.
- harmonic component $m \omega_c \pm n \omega_f$, whose amplitude is as:

$$\frac{4U_{dc}}{m\pi} J_n \left(\frac{m\pi M}{2}\right) \sin\left(n\frac{\pi}{3}\right) \quad (2)$$

For switching frequency often used in converters, corresponding high content harmonic numbers can be derived as shown in Table 1 according to the analysis above.

| Switching Frequency | High Content Harmonic Frequency |
|---------------------|--------------------------------|
| 1500                | 28, 32, 59, 61                |
| 2000                | 38, 42, 79, 81                |
| 6400                | 126, 130, 255, 257            |
| 10000               | 198, 202, 309, 401            |
2.2. Harmonics yielded by deadband effect of switch components

Fully-controlled power electronic components usually used in rectifiers and inverters in new energy generation system mainly include IGBT, power MOSFET, etc. The dead time of main parameters in the use of the switch component IGBT will affect harmonic features of the inverter[8]. The harmonic mechanism of switch components’ deadband effect is related to the continuing current circuit of inverter power devices. Its principle is illustrated as follows. Take A-phase bridge arm for example. Assume that $i_a$ that flows out of the bridge arm is positive; $i_a$ that flows into the bridge arm is negative, as shown in Figure 2.

![Figure 2. Schematic diagram of the current direction of inverter A-phase bridge arm.](image)

When $i_a$ is large than 0, the dead zone exists in two switching moments: (1) VT1 is turned on, VT4 is turned off; (2) VT1 is turned off, VT4 is turned on. Through analysis of continuing current circuits in these two dead zones, actual voltages can be derived as shown in Figure 3 (d). Similarly, when $i_a$ is less than 0, the actual voltage is shown as Figure 3 (e).

![Figure 3. Waveform of A-Phase voltage in one switching process.](image)

In Figure 3, $t_d$ denotes dead time; $t_{on}$ denotes the switched-on time of the power tube; $t_{off}$ denotes the switched-off time of the power tube; $U_{dc}$ denotes DC bus voltage. According to the analysis above, the actual output voltage differs from the ideal output voltage by one pulse tolerance voltage. The average value of tolerance voltages can be estimated through equal time-voltage area method as follows:

$$\Delta U_{AN} = \begin{cases} f_c T_d U_{dc} & i_a > 0 \\ - f_c T_d U_{dc} & i_a < 0 \end{cases}$$

(3)

Where $T_d = t_d + t_{on} - t_{off}$, $f_c$ denotes carrier frequency.

Harmonic voltage can be derived through Fourier analysis of tolerance voltages formed in dead time, i.e. subharmonic voltage $U_{T_d}$, output by the inverter can be calculated by the following formula:
\[ U_{\text{th}} = \frac{4f_c T_d U_{\text{dc}}}{n \pi} \sin n(\omega t - \varphi), \quad n = 3, 5, 7 \ldots \] (4)

Equation (4) indicates that harmonic frequency yielded by deadband effect is proportional to harmonic numbers and its number is arithmetic odd such as 3, 5, 7, etc. The harmonic amplitude is proportional to switching frequency, dead time and DC-side voltage and inversely proportional to harmonic numbers. As harmonic numbers rise, the harmonic amplitude can be negligible. Hence, the voltage caused by deadband effect is mainly subharmonics such as 3, 5, 7, 9, etc.

2.3. Inter-harmonic mechanism
Inter-harmonics is harmonics that are non-integer multiples of foundation frequency, whose spectrum can be dispersed or consequent. Inter-harmonics in the power system mainly comes from fluctuating loads, arc loads, frequency conversion speeds, induction motors, thyristors controlled by integer cycles, etc.[9] For inverters that adopt PWM modulation, inter-harmonics will be produced from AC-side of inverters when DC voltage fluctuates[10]. For convenience of analysis, it is assumed that the DC-side voltage of the inverter produces periodic fluctuation, whose periodic component is \( U_d \).

\[ \text{With the bipolar SPWM modulation, inter-harmonic component of inverter output voltage} \quad U_{ab(ih)} \text{can be derived from the analysis above.} \]

- When \( n=1, 3, 5, \ldots, m \) equals even numbers excluding integer multiples of 3:

\[ U_{ab(ih)} = \sum_{m=1}^{\infty} \frac{(-1)^{m+1}}{n \pi} \sum_{n=2}^{\infty} J_n(\frac{n m n}{2}) \cdot \sin \frac{n \pi}{3} \]

\[ \left\{ \begin{align*}
- \frac{1}{2} \cos[(m \omega_c + n \omega_r + \omega_d)t + n(\varphi - \frac{\pi}{3}) + \varphi_d] + \frac{1}{2} \cos[(m \omega_c + n \omega_r - \omega_d)t + n(\varphi - \frac{\pi}{3}) - \varphi_d] \\
+ \frac{1}{2} \cos[(m \omega_c - n \omega_r + \omega_d)t + n(\varphi - \frac{\pi}{3}) + \varphi_d] - \frac{1}{2} \cos[(m \omega_c - n \omega_r - \omega_d)t + n(\varphi - \frac{\pi}{3}) - \varphi_d]
\end{align*} \right. \] (5)

- When \( n=2, 4, 6, \ldots, m \) equals odd numbers excluding integer multiples of 3:

\[ U_{ab(ih)} = \sum_{m=2}^{\infty} \frac{(-1)^{m+1}}{n \pi} \sum_{n=3}^{\infty} J_n(\frac{n m n}{2}) \cdot \sin \frac{n \pi}{3} \]

\[ \left\{ \begin{align*}
- \frac{1}{2} \sin[(m \omega_c + n \omega_r + \omega_d)t + n(\varphi - \frac{\pi}{3}) + \varphi_d] - \frac{1}{2} \sin[(m \omega_c + n \omega_r - \omega_d)t + n(\varphi - \frac{\pi}{3}) - \varphi_d] \\
- \frac{1}{2} \sin[(m \omega_c - n \omega_r + \omega_d)t + n(\varphi - \frac{\pi}{3}) + \varphi_d] + \frac{1}{2} \sin[(m \omega_c - n \omega_r - \omega_d)t + n(\varphi - \frac{\pi}{3}) - \varphi_d]
\end{align*} \right. \] (6)

From equation (5) and (6), it can be concluded that the frequency of harmonic component caused by DC-side voltage fluctuation is \((m \omega_c + n \omega_r) \pm \omega_d\), i.e. a shift at the harmonic frequency produced by PWM modulation.

2.4. Harmonic feature analysis of wind units and PV inverters
The analysis above indicates that the harmonics of directly-driven wind units / PV power systems mainly comes from grid-side converters. According to the analysis of harmonic mechanism of inverters, inverter harmonics consists of PWM modulation harmonics, harmonics yielded by switching components’ deadband effect and inter-harmonics yielded by DC-side voltage fluctuation.

Harmonic amplitude of PWM modulation (mainly SPWM) is related to DC-side voltage and modulation ratio. Harmonic frequency is related to carrier frequency (switching frequency) which is mainly distributed around multiple frequency of carrier frequency, and it belongs to high-frequency harmonics. The switching component parameter which is closely related to harmonic output features of inverters is components’ dead time. The higher the switching frequency is, the larger proportion
dead time will be, and the more evident the harmonics caused by the deadband effect of components will be. The harmonic amplitude caused by deadband effect of components is related to DC voltage, modulation ratio, carrier frequency and dead time. Harmonic frequencies are mainly subharmonics such as 3, 5, 7, etc. When DC-side voltage of the inverter fluctuates, the voltage fluctuating component will be transferred to the AC-side, where non-integer multiple inter-harmonics of fundamental frequency will be yielded. For inverters composed of fully-controlled switch components, Table 2 summarizes harmonic features of directly-driven wind units / PV inverters.

| Harmonic sources       | Harmonic frequency          | Harmonic amplitude | Influencing factors                  | Features                        |
|------------------------|-----------------------------|--------------------|--------------------------------------|---------------------------------|
| PWM modulation         | High frequency (mainly around switching frequency) | Larger DC voltage, modulation ratio, carrier frequency | Determined by modulation mechanism, unavoidable |
| Deadband effect of components | Low frequency (mainly 3, 5, 7) | Smaller DC voltage, Modulation ratio, Carrier frequency, dead time | The higher the switching frequency is, the more evident it will be |
| Inter-harmonics       | High frequency (mainly around switching frequency) | Larger DC voltage, modulation ratio, slip ratio, carrier frequency | Rotor-side harmonic coupling to the stator side |

3. Simulation Analysis
A SPWM simulation model whose DC-side voltage is 800V, carrier frequency is 2000Hz and modulation ratio M is 0.9 is established in PSCAD simulation software. Figure 4 indicates the simulation result of line voltage output by switch tube when the switching frequency is 2000Hz. The most harmonic numbers are 38, 42, 79 and 81, which is consistent with theoretical analysis. Figure 5 indicates the comparison between harmonic amplitude of line voltage yielded by SPWM modulation and theoretical calculation, and they are also consistent.

Switch components’ dead time is usually several microseconds. The dead time does not take a large proportion in a switching period and the deadband effect is not evident until the switching frequency is high. Simulation results with a dead time of 6μs are shown in Figure 6-8. It can be seen that when the switching frequency is 10000Hz, the dead time makes the fifth and seventh harmonics increase evidently; when the switching frequency is 2000Hz, dead time take a smaller proportion of a switching
period and the harmonics yielded by deadband effect is not evident. Therefore, the switching frequency of high-power inverters is relatively low between 1000Hz-3000Hz and harmonics caused by deadband effect can be negligible.

In order to verify the validity of inter-harmonic analysis, periodic alternating value with the frequency of 40Hz is added to DC voltage in simulation. The analysis result of inverter output voltage waveform FFT is shown in Figure 9. It can be seen that harmonic component frequency caused by DC-side voltage fluctuation shifts at harmonic frequency caused by PWM modulation, which is consistent with theoretical analysis.
4. Conclusion
Both PV inverters and directly-driven wind units are connected to grids only through grid-side converters, so their harmonic and inter-harmonic mechanisms are similar. Harmonics and inter-harmonics are mainly produced by PWM modulation, IGBT switch dead zone and DC-side capacitor fluctuation, among which PWM modulation mostly produces high order harmonics and its harmonic numbers rises along with the increase of switching frequency. The switch dead zone mainly produces subharmonics and the higher the switching frequency is, the larger harmonics are. When DC-side capacitor fluctuates and its frequency is non-integer harmonic, inter-harmonics will be yielded at the AC side through modulation. When fluctuation frequency is integer harmonic, harmonics will be produced at the AC side.

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