Harmonic Energy Metering Method for High Proportion of Renewable Energy Access

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Abstract. Realizing low carbon operation of power grid and high proportion of clean energy consumption is one of the important ways for power grid companies to implement the energy security strategy of "Four Revolutions and One cooperation" and help achieve the goal of "carbon peak and carbon neutrality". The harmonic content of new energy grid formed by massive new energy access is far greater than that of traditional power grid. Traditional electric energy metering schemes can hardly meet the new demand of electric energy metering in new energy grid. After analyzing the disadvantages of traditional electric energy metering schemes in power generation and consumption scenarios, a new electric energy metering scheme taking harmonics into account is proposed. The scheme can realize fundamental wave energy metering, fundamental wave generation and harmonic energy metering. Based on the above measurement function, the user compensation and harmonic penalty strategy of the new electric energy metering scheme are analyzed, and the calculation method of the user electric energy cost under the new electric energy metering scheme is given. Finally, an example is given to prove that the new scheme can guarantee the benefits of power supply enterprises and users.

Keywords: Harmonic energy metering · Renewable energy access · User compensation · Harmonic penalty strategy

1 Introduction

Energy security and environmental pollution have become the focus of global attention. At the 75th United Nations General Assembly, my country took the lead in pro-posing the strategic goal of "carbon peaking and carbon neutrality" [1, 2]. As an important hub and energy consumption platform for various energy conversion and transmission, the power system plays an important role in the realization of the "dual carbon" goal. Critical use [3, 4]. In order to reduce the proportion of primary energy, new energy grids, which include lots of distributed new energy sources, have been widely concerned and are becoming increasingly popular. The output power of new energy power generation

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equipment has volatility and randomness, which is caused by the uncertainty of new energy. The volatility and randomness will cause random fluctuations in the voltage amplitude of the new energy grid connection point, so severe challenges are imposed on the grid stability [5, 6]. Meanwhile, the harmonic components are injected into the grid by the new energy grid-connected converter, which easily causes the current waveform distortion and grid voltage. Excessive har-monic components can cause noise, heat and even damage to primary equipment such as transformers, cables and reactors [7, 8]. At the same time, in terms of energy measurement, harmonics will also lead to inaccurate measurement.

At present, domestics and foreign scholars have carried out certain research on the accuracy of new energy grid-connected measurement [9–11]. For example, the two-way electric energy measurement method is proposed [12], which can encourage users to use new energy efficiently and generate more electric energy. It provides a measurement algorithm to improve the measurement accuracy of the electric energy meter, and can realize the measurement of harmonic electric energy, etc., but it does not fully consider the characteristics of the two-way flow of electric energy in the new energy grid and the high harmonic content, and does not consider the harmonics in depth [13, 14]. The role of electric energy metering in ensuring the interests of users and power supply enterprises as well as harmonic control has not been considered in depth to ensure the legitimate interests of users and power supply enterprises by using the function of harmonic energy metering.

Design a new electric energy metering scheme to effectively distinguish fundamental and harmonic electric energy, accurately measure the fundamental wave electric energy usage of users in the new energy grid, and formulate corresponding punishment measures to urge power generation users in the new energy grid to actively con-duct harmonic control. It is a feasible and effective solution to ensure power quality. This paper analyzes the factors that generate new energy grid harmonics and their impact on electric energy measurement, and proposes a new energy metering scheme which considers the harmonics of new energy grids. The fundamental wave power of each user in the power grid has a great role in promoting the formation of a reasonable order of power supply and consumption and improving the power quality of the power grid.

2 Harmonic Generation Mechanism of Renewable Energy Connecting to Power Grid

Grid harmonics are trigonometric function components whose frequencies are integer multiples of grid current or voltage after Fourier series expansion in one cycle [15]. We can expand the current and voltage functions in the grid as the sum of constant terms and infinite trigonometric functions because they satisfy the existence condition of Fourier series. The Fourier series expansion result can be obtained.

$$f(t) = a_0 + \sum_{h=1}^{\infty} [a_h \cos(h\omega t) + b_h \sin(h\omega t)] \tag{1}$$

Here, a_0 is a constant term. And a_0 represents of the power grid's DC component. h is the harmonic order. a_h and b_h are the cosine and sine coefficients of the h-order harmonic component, respectively. ω is the angular frequency.

Common new energy sources such as photovoltaics and wind power are attached to the grid through converters which based on power electronic devices. Power electronic devices are affected by factors such as the modulation strategy of pulse width modulation technology and the basic characteristics of switching devices [16].

It mainly pays attention to the effect of new energy on grid power metering on the AC side, and analyzes the harmonic characteristics of the AC side of the converter. The sinusoidal pulse width modulation control strategy, which is a control strategy with simple algorithm, is widely used in new energy grid-connected converters. SPWM generally use bipolar control strategy. After Fourier series decomposition, the fundamental component is

$$U_{ab} = \frac{\sqrt{3}}{2} m U_{dc} \sin\left(\omega_\tau t + \varphi + \frac{\pi}{3}\right) \tag{2}$$

where m denotes the modulation degree. The DC side voltage of the converter is denoted by U_{dc}. ω_τ denotes the frequency of the modulating wave. φ is the phase angle.

The harmonic component frequency is $k\omega_z + n\omega_r$. Here, ω_z denotes the carrier frequency. k denotes the carrier frequency multiple. n is the modulation wave frequency multiple. The harmonic amplitude modulation and dc side voltage and modulation ratio, frequency and modulation wave and carrier frequency about [17]. For power grid harmonics, harmonics are usually represented by the total distortion rate of the waveform.

To analyze the harmonics of the new energy grid, as shown in Fig. 1, we build a simulation model of the new energy grid in MATLAB/Simulink. It can be seen from Fig. 1 that for the power grid, the harmonics generated by the new energy grid include lots of high-frequency harmonics near integer multiple of carrier frequency and a small number of low-frequency harmonics, which is consistent with this paper.

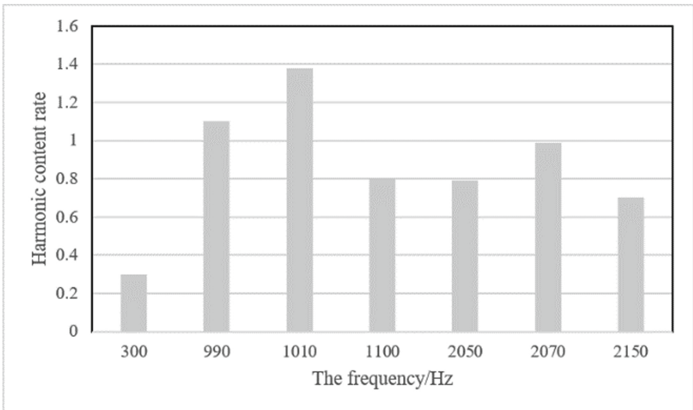

Fig. 1. Grid harmonics

3 Analysis of Influence of Harmonics on Electric Energy Metering

3.1 Analysis of Influence of Harmonics on Measurement Error of Electric Energy Meter

At present, electronic watt-hour meters, divided into analog type and digital type, have become the mainstream of the market. Digital watt-hour meter has been applied on a large scale and has gradually become the mainly choice.

The basic structure of the digital electric energy meter has been shown in the Fig. 2. The Central Processing Unit (CPU) is the core component. The microprocessor performs the numerical multiplication of power. A dual-channel A/D converter transmits voltage and current data to the microprocessor.

By calculating the instantaneous values of voltage and current after sampling, the instantaneous power can be obtained. Let the sampling interval of grid voltage and current be Δt. And $T = N\Delta t$ denotes the period of electric energy measurement. The average power P in the time T is

$$P = \sum_{d=1}^{N} \left[\frac{1}{N} u(t_d) i(t_d) \right] \tag{3}$$

Here, N is the division number of T. d is the counting parameter. $u(t_d)$ is the average voltage within t_d. $i(t_d)$ is the average current within t_d.

In T, the total electric energy W is

$$W = \sum_{d=1}^{N} [u(t_d) i(t_d)] \Delta t \tag{4}$$

From Eq. (4), we know that the results obtained by the digital watt-hour meter are not affected by the power factor. Non-sinusoidal electrical energy with harmonic component can be accurately measured by digital watt-hour meter.

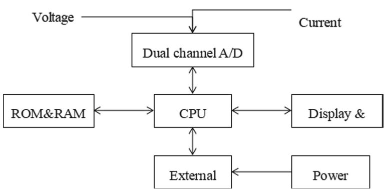

Fig. 2. Basic structure of the digital electric energy meter

Figure 3 shows the error characteristic curve. It can be seen from Fig. 3 that the error of a digital watt-hour meter is not frequency sensitive and can operate over a wide frequency response range.

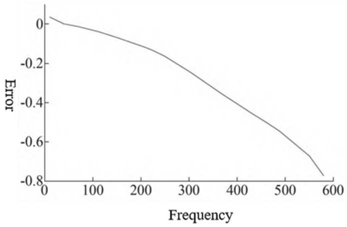

Fig. 3. The error characteristic curve of the digital electric energy meter

3.2 Analysis of the Rationality of the Current Measurement Plan

The digital electric energy meter can measure more accurately, but this does not mean that the digital electric energy meter can reasonably measure the electric energy usage of the users in the new energy grid according to the traditional measurement method. The instantaneous result of the electric energy meter during full-wave measurement is expressed as

$$P = P_1 + \sum_{h=2}^{\infty} P_h \tag{5}$$

where P_1 and P_h are the fundamental wave electric energy power. In the case of full-wave electric energy metering, the electric energy value in T is

$$W = \int_0^{\pi} P_1 dt + \sum_{h=2}^{\infty} \left(\int_0^{\pi} P_h dt \right) \tag{6}$$

As shown in Fig. 2, PL1 and PL2 linear load and nonlinear load, PG1 is the base power, PG1 flows from the generator to PL1 and PL2, part of the fundamental wave power absorbed by the nonlinear load is converted into harmonic power Ph2. Ph2 flows to system PGh and Ph1, respectively.

The access point equipped with new energy generation equipment is a nonlinear load point in new energy power grid. Lots of harmonics are sent by the users to the grid. But it is unreasonable that users can get the benefit of sending harmonic power into the grid. Another type of users, which only use electric energy and do not generate a lot of harmonics, exist in the new energy grid. These users are linear load user. Linear load users do not generate harmonics, on the contrary, linear load users may be affected by harmonic power in the grid. For linear load users, the full-wave electric energy metering will result in multiple metering of the actual electric energy used by the users.

4 A New Energy Metering Scheme Considering Harmonics

4.1 Electric Energy Metering Method in Electricity Consumption Scenarios

Users whose power generation capacity cannot meet their own needs need to obtain power from the grid in the new energy grid. These users will be focused on when analyzing the electricity consumption in the power generation scenario.

For linear load users, only basic electric energy W1 can be effectively utilized by electric equipment, the user is measured by the harmonic wave electric energy W generated by the new energy and nonlinear load. Nonlinear load users can not only effectively use fundamental electric energy W1 but also harmonic electric energy, the user's consumption of harmonic electric energy is -Wh. When the user adopts the full-wave energy metering method, the linear load user will bear the cost of low charging energy. Full wave energy metering scheme, the power supply of the power supply enterprise income to complete security, and user generated by nonlinear load har-monic power, through the network transmission, shall be borne by the user linear load harmonic electric fee, linear load caused by the user's interests is damaged, and non-linear load user lack of governance of harmonic drive. Using fundamental wave electric energy metering scheme can reduce the influence of harmonics and accurately measure the electricity consumption of users, which is in line with the interests of users. Therefore, in the case of electricity consumption, the data collected by electricity meters should be filtered to contain only fundamental wave components.

4.2 Energy Metering Methods in Power Generation Scenarios

Users can make benefits by selling their electricity surplus. Therefore, Under the power generation scenarios, the fundamental electric energy measurement must be used. The transmission of harmonic energy in the power grid is harmful and useless, it occupies the transmission capacity of the power grid and affects the transmission efficiency. For users, harmonic energy cannot be used and may damage electrical equipment. Therefore, in the power generation scenario, harmonic energy needs to be measured, and the measurement data of harmonic energy is used as the basis for punishment, and the user who generates harmonic energy is punished.

A more reasonable electric energy detection method is to measure the full wave energy and fundamental wave energy respectively under the condition of electricity consumption, and obtain the harmonic energy value through simple calculation. In the calculation of user income, the measured value of fundamental electric energy is taken as the basis, and in the calculation of harmonic pollution penalty, the measured value of harmonic electric energy is taken as the basis.

4.3 Penalty Strategy of Electric Energy Measurement for Harmonic Energy

The new metering scheme not only improves the rationality of power consumption, but also improves the rationality of power generation electricity consumption. In order to make reasonable punishment for harmonic pollution and reduce the har-monic pollution behavior of users, it is necessary to design reasonable punishment strategy for harmonic pollution.

In this paper, in order to ensure the rationality of the metering scheme, harmonic energy metering, harmonic penalty calculation and user compensation calculation are introduced into the new energy grid metering scheme. It is difficult to calculate the electricity cost only by the electricity meter installed on the user's electricity metering node. A more sensible approach is to transmit all users' electricity usage information to the electricity metering data center. According to the electric energy usage information of users during charging, the data center calculates the user compensation fee according to Formula (8) and the user compensation fee according to Formula (11). The penalty fee is finally calculated by formula (13) of the total user fee, and the fee information is transmitted to the user to remind the user to pay the fee in time. Based on the current electricity metering form in most areas of China, the new energy grid metering scheme proposed in this paper is simple to implement and will not cause too high economic cost. It is a more economical and reasonable energy metering scheme.

5 Overall Measurement Scheme and Calculation Example Analysis

The new metering scheme considers the harmonic influence of new energy is shown. The metering scheme considers the fundamental and harmonic energy in the power grid. The user needs to be equipped with two electricity meters, one of which can be used for fundamental energy measurement, the other can be used for fundamental energy measurement or full wave energy measurement. The result of fundamental wave measurement is used as electric energy data transmitted to the power grid by users. The user's harmonic energy can be calculated by measuring the fundamental and full wave energy. Considering that linear load users do not transmit electricity to the grid, nor produce harmonics, only linear users are equipped with electricity meters with fundamental wave energy strategy capability to reduce costs.

Table 1. Expenditure of power supply enterprises under different electric energy metering schemes

Spending	Full wave measurement	Fundamental wave measurement	New electric energy metering
Fundamental energy purchase quantity /MWh	6, 000	6, 000	6, 000
Harmonic energy purchase quantity /MWh	120	0	0
Electric energy acquisition cost/ten thousand yuan	214.2	210.0	210.0
User compensation fee/ten thousand yuan	0	0	0.252
Total expenditure/ten thousand yuan	249.4	245.2	270.4

We compare the proposed scheme with the traditional energy metering scheme. We use MATLAB to establish a new energy grid simulation model under nonlinear load. Nonlinear load harmonic power accounts for 5% of the total absorbed power, and the electricity price is 0.57 yuan/kWh and 0.62 yuan/kWh for compensation.

Table 2. Users' electric energy charges under different electric energy metering schemes

Electricity charge item	Full wave measurement	Fundamental wave measurement	A new scheme
Basic electric energy consumption /MWh	3, 900	3, 900	3, 900
Basic electric energy charge/ten thousand yuan	276.9	276.9	276.9
Harmonic energy charge/MWh	120.00	0	0.12
Harmonic energy charge/ten thousand yuan	852	0	0
Fundamental energy generation/MWh	0	0	0
Power generation income/ten thousand yuan	0	0	0
Penalty fee/ten thousand yuan	0	0	0
Compensation fee/ten thousand yuan	0	0	25.2
Total cost/ten thousand yuan	285.4	276.9	251.7

As can be seen from Table 1 and Table 2, when the scheme proposed in this paper is used, the income of power supply enterprises is at a high level. In other words, the scheme in this paper ensures the interests of power supply enterprises.

As shown in Table 2, when using the scheme proposed in this paper, the linear load user's expenditure is at a low level because the linear load user does not generate harmonics and can be compensated. Due to the harmonic penalty of nonlinear load users, their expenditure is relatively high, but users can reduce their expenditure through active coordination.

6 Conclusion

This paper analyzes the mechanism of harmonic generation in new energy grid. Compared with traditional power grid, the proportion of harmonics in new energy power grid is higher. But digital watt-hour meters are insensitive to harmonic components. Considering the defects of the existing electric energy metering methods in the new energy grid, this paper proposes a new electric energy metering scheme, which is suitable for the new energy grid. In the scheme proposed in this paper, fundamental wave electric energy, harmonic electric energy and full wave electric energy are obtained through measurement and calculation, and their functions are defined respectively, and the penalty and compensation mechanism are designed to improve the measurement scheme. The simulation experiment proves that the scheme proposed in this paper effectively guarantees the interests of users and power supply enterprise, and encourages users to reduce harmonics in the transmission network by economical means.

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References

1. Guo Guanghua, D., Ying, F.Y., et al.: Integrated energy system research complex with electricity as the core. Shandong Electr. Power Technol. **13**(8), 1–7 (2021)
2. Ye, C., Liu, R., Ba, Y., et al.: Frequency control of ULTRA-high voltage power grid with high proportion of new energy mode and performance evaluation. Power Grid Technol. **43**(2), 621–631 (2019)
3. Yu, H.B., Lin, F.T., Bai, J.F., et al.: Research on energy metering in grid connection of new energy generation. Electr. Meas. Instrum. **49**(12), 57–60 (2012)
4. Liu, Z., Xu, Y.: Tao Shun Research on quantitative assessment method of harmonic liability under new energy grid Research status and prospects. Electr. Power Autom. Equipment **40**(11), 203–213 (2020)
5. Mikhail, S., Gianfranco, C., Gianluca, Z.: Real-time event-based energy metering. IEEE Trans. Indus. Inf. **13**(6), 2813–2823 (2017)
6. Wang, H.L., Jiang, T., Wu, Y.L., et al.: Electric energy of distribution network including grid-connected generation of new energy quality analysis. Control Technol. New Energy Gener. 43(4), 20–23
7. Wang, S.J., Hu, W., Gao, X., et al.: Study on the influence of new energy grid-connected generation on power quality of distribution network. Comput. Technol. Autom. 40(2), 47–52
8. Li, Y.C., Gao, J.G., Zhang, X.H., et al.: Effect of transient power quality on power measurement. Shandong Electr. Power Technol. **46**(2), 1–5 (2019)
9. Li, J., Yang, Y., Yu, W., et al.: Review on the development of electric energy metering system. Electr. Power Syst. Prot. Control **37**(11), 130–134 (2009)
10. Mikhail, S.: Hybrid scheme for electricity metering in smart grid. IEEE Syst. J. **8**(2), 422–429 (2014)
11. Zhao, W., Peng, H., Sun, W., et al.: Quantitative analysis based on measurement error under harmonic condition energy metering solutions. Autom. Electr. Power Syst. **39**(12), 121–125 (2015)
12. Jia, J.F., Yi, H.M., Xia, X.Y., et al.: A new type of distributed energy access power system metering systems. Power Syst. Prot. Control **45**(3), 118–124 (2017)
13. Li, X.: Research and verification of electric energy metering mode considering integration of scenery and storage. Electr. Meas. Instrum. **55**(16), 100–105 (2018)
14. Dou, X.B., Yang, L., Ma, J., et al.: Improved energy metering model adapted to the dynamic characteristics of distributed photovoltaic. Electr. Power Autom. Equipment **37**(10), 34–42 (2017)
15. Xiao, H.-F., Liu, X.-P., Guo, L., et al.: A method of wavelet packet extraction for grid side resonant current information of large-scale grid-connected inverter. Electr. Force Autom. Equipment **36**(1), 129–134 (2016)