Analysis of Harmonic Characteristics of Pulse Load Based on Switching Functions

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Abstract. As a kind of special nonlinear load, pulse load (PL) has the characteristics of two typical nonlinear loads. Compared with the traditional rectifier load, the harmonic characteristics of the PL are more complicated. In this paper, the harmonic characteristics of the PL is investigated. By analysing the working mode of the PL, an equivalent circuit model and a switch function model of the PL are introduced. It is analysed that the PL will inject a large number of inter-harmonics and even sub-harmonics in addition to the integer harmonics to the power system, and the harmonics are symmetrically distributed. The experiments were conducted on diesel generator sets (DGS) with PL and public grids with PL. The results show that the established model and analysis method can accurately calculate the harmonic distribution of the system, moreover, the influence of PL mode on harmonic characteristics can be revealed.

1. Introduction

With the development of power electronics technology, the power electronic characteristics of the load are more and more obvious and the load characteristic tend to be diversified. Pulse load (PL) short-time power demands are very high [1,2]. The load characteristic of PL has a cyclical character, with high peak power and low average power. Three important parameters of the PL are the peak power P, the pulse period T, and the duty cycle D. The load characteristic of PL is shown in Fig. 1. Typical PL includes pulse laser, electromagnetic launcher, modern electronic radar, etc. Such load characteristics will have a great impact on the stability of the power system. The impact of PL on the power quality of AC and DC nodes in the ship's integrated power system is analysed in [3]. Reference [4] analysed the power quality of AC/DC hybrid microgrid containing PL from the perspective of harmonic analysis. However, the pulse period of this type of load is generally above the second level. The energy balance of PL systems from the perspective of energy supply and demand and the system transient problems caused by PL are analysed in [5,6].

![Fig.1 The load characteristic of PL.](image-url)
At present, it is generally believed that the nonlinear load is the main cause of the power quality deterioration of the system. Nonlinear loads include two categories: one is the load that changes suddenly, such as when the motor starts; and the other type of nonlinear load will generate a periodic non-sinusoidal current. It is typified by power electronics equipment and it injects a lot of harmonics into the system [7]. The pulse period of the PL represented by modern radar is 10ms-100ms, and contains a variety of power electronic equipment. It is a complex nonlinear load that has the characteristics of both types of loads. The PL mentioned later also refers specifically to this type of PL. Only by analyzing the harmonic generation mechanism of the PL can we explain the influence of the load on the system, and guide the harmonic compensation and filter design. There have been many studies on the harmonic source models of non-linear loads in detail. The main models are constant-current source model [8], Norton equivalent model [9], crossed frequency admittance matrix [10-11], harmonic coupling admittance matrix model [12], Matrix Model of Nonlinear Single-port Network [13]. The sensitivities of some models are evaluated for the system in [14]. The harmonic characteristics and effects of rectifier loads have been analyzed in detail by many scholars [15-16]. Harmonic coupling admittance matrix model is a modeling method for rectifier-type loads. However, it does not consider the existence and influence of inter-harmonic. The Matrix Model of Nonlinear Single-port Network is only applicable when the parameter change frequency is an integer multiple of the power frequency. A power flow calculation model with PL is established by the method of power equivalence in [17], but the loading process and the unloading process are processed separately, so the influence of inter-harmonic and sub-harmonic is ignored. At present, there is no introduction of harmonic analysis for millisecond PL.

In order to verify the correctness of the analysis method, experiments were carried out on diesel generator sets (DGS) with PL and on public power grids with PL. In the following sections, the working principle and equivalent circuit model of PL are described first. Following the system description, the switching function model of PL is given. Also, the harmonic analysis of AC and DC currents is presented in section IV. Section V proves the correctness of mathematical models and analysis methods through simulation and experimental data. The influence of PL mode on harmonic characteristics be analyzed in section VI.

2. Pulse Load Working Principle and Equivalent Circuit Model

2.1. The Working Principle of Pulse Load
PL belongs to DC load. The structure of PL is shown in Fig. 2. We can see the transmission process of electric energy from the three-phase power supply to the dc load when PL works.

![Fig.2 The structure of PL.](image)

2.2. The Equivalent Circuit Model of Pulse Load
The equivalent circuit structure of the PL is shown in Fig. 3. According to PL working principle and working characteristics, we simplify its circuit structure. First, the loading and unloading process of the
PL is simulated by the on-off of VL. T and D of the PL are controlled by VL. Second, the variable resistor RL is used to represent the P of the PL [17].

![Equivalent Circuit Model of PL](image)

The equivalent circuit includes three parts: the rectifier part, the DC/DC part and the DC switch load part. The role of the DC/DC part is to maintain the stability of u0.

3. The Switching Function of Pulse Load

Switching function is a common method to describe the working process of switching devices. The main switching devices have been marked in Fig. 3. There is a detailed derivation process of the switching function in [18]. Only the corresponding functions are given below.

3.1. The switching function of three-phase uncontrolled rectifier

When the three-phase power supply is the ideal power supply, and phase commutation of the rectifier is ignored, the Fourier series of the A-phase switching function can be expressed as:

$$S_a(t) = \frac{2\sqrt{3}}{\pi} \sum_{n=0}^{\infty} \frac{1}{6n+1} \cos \left( \frac{(6n+1)\omega t}{\pi} \right) - \frac{2\sqrt{3}}{\pi} \sum_{n=0}^{\infty} \frac{1}{6n-1} \cos \left( \frac{(6n-1)\omega t}{\pi} \right)$$  \hfill (1)

Where ω=2πf50, f50 is the frequency of power supply. Similarly, the switching functions of phase B and phase C can be obtained. Sb(t) and Sc(t) lag behind Sa(t) 120 ° and 240 °, respectively.

3.2. The switching function of DC/DC converter

The switching function of DC/DC converter can be expressed as:

$$S_{VT}(t) = \begin{cases} 1 & 0 \leq t < D_{VT} \cdot T_{VT} \\ 0 & D_{VT} \cdot T_{VT} \leq t < T_{VT} \end{cases} \hfill (2)$$

Where TVT and DVT are period and duty of VT. The Fourier series of (2) is:

$$S_{VT}(t) = a_{0,VT} + \sum_{n=1} a_{n,VT} \cos n\omega_{VT}t + b_{n,VT} \sin n\omega_{VT}t$$ \hfill (3)

Where:

$$\omega_{VT} = \frac{2\pi}{T_{VT}}$$
3.3. The switching function of DC switching load

The T and D of the PL are both determined by the switch VL. When PL works in a fixed working mode, the switching function of the DC switching load can be expressed as:

\[
S_{VL}(t) = \begin{cases} 
1 & 0 \leq t < D_{VL} \cdot T_{VL} \\
0 & D_{VL} \cdot T_{VL} \leq t < T_{VL}
\end{cases}
\]

The Fourier series of the switching function \( S_{VL}(t) \) be expressed as:

\[
S_{VL}(t) = a_{0,VL} + \sum_{n=1}^{\infty} A_{n,VL} \cos(n\omega_{VL}t + \phi_{n,VL})
\]

Where

\[
A_{n,VL} = \sqrt{a_{n,VL}^2 + b_{n,VL}^2}
\]

\[
\phi_{n,VL} = -\arccos\left(\frac{a_{n,VL}}{A_{n,VL}}\right)
\]

The meaning of the symbol is the same as (3), just the subscript corresponds to VL.

4. Analysis of Harmonic Characteristics of Pulse Load Based on Switching Function

4.1. DC Current Harmonic Analysis

Consider the DC/DC converter and DC switch load as the DC part of PL. Because it contains two switching elements, each switch contains two states. DC/DC converter has continuous conduction mode and discontinuous conduction mode, so there are 6 operating states in DC part during operation. Fig. 4 shows the current path. Where the three-phase power supply and the rectifier are equivalent to the constant voltage DC source \( u_{dc} \), \( u_0 \) is the voltage of Cf.

![Fig. 4 The current path of DC part](image)

According to Fig. 4. The DC current can be written as:

\[
i_{dc}(t) = S_{VT}(t) \cdot C_f \frac{du_0(t)}{dt} + S_{VT}(t) \cdot S_{VL}(t) \cdot u_0(t) \cdot \frac{1}{R_L}
\]

Because the DC/DC converter uses feedback control, the capacitor voltage \( u_0 \) is a certain value, so the first term of (6) can be ignored. The DC current can be rewritten as:
\( i_{dc}(t) = S_{VT}(t) \cdot S_{VL}(t) \cdot \frac{u_a}{R_L} \)  \( (7) \)

Using (3), (5), (7) to obtain:

\[
\begin{align*}
    i_{dc}(t) &= \left( a_{0,VT} \cdot a_{1,VL} + i_{dc,n,m} + i_{dc,n,m} \right) \frac{u_a}{R_L} \\
    &= \left( a_{0,VT} \cos n\omega_{VT}t + b_{0,VL} \sin n\omega_{VT}t \right) + \\
    &\quad \sum_{n=1}^{\infty} \left( a_{n,VT} \cos n\omega_{VT}t + b_{n,VL} \sin n\omega_{VT}t \right) + \\
    &\quad \sum_{n=m=1}^{\infty} \left( a_{m,n,m} \cos (m\omega_{VT}+n\omega_{VL})t \right) + \\
    &\quad \sum_{n=m=1}^{\infty} \left( b_{m,n,m} \sin (m\omega_{VT}+n\omega_{VL})t \right)
\end{align*}
\]

Where:

\[
\begin{align*}
    i_{dc,n,m} &= a_{0,VT} \sum_{n=1}^{\infty} \left( a_{n,VL} \cos n\omega_{VT}t + b_{n,VL} \sin n\omega_{VT}t \right) + \\
    &\quad a_{0,VL} \sum_{n=1}^{\infty} \left( a_{n,VT} \cos n\omega_{VT}t + b_{n,VT} \sin n\omega_{VT}t \right) + \\
    i_{dc,n,m} &= \sum_{m,n=1}^{\infty} \left( a_{m,n,m} \cos (m\omega_{VT}+n\omega_{VL})t \right) + \\
    &\quad \sum_{m,n=1}^{\infty} \left( b_{m,n,m} \sin (m\omega_{VT}+n\omega_{VL})t \right)
\end{align*}
\]

Record the switching frequency of VT and VL as fVT, fVL. It can be known from (8) that the direct current idc(t) can be divided into three components. The first component is the DC component; the second component is the nth harmonic with the PWM carrier frequency as the fundamental frequency and mth order with the PL frequency as the fundamental frequency harmonics; the third component is the harmonics whose frequency is nfVT±mfVL. Because the carrier frequency of PWM is much higher than the pulse frequency of the PL, it belongs to higher harmonics and is easy to filter out, and its amplitude is getting smaller and smaller as the number of harmonics increases. Therefore, the harmonics in the low frequency band are mainly the low order harmonics with the PL frequency as the fundamental frequency, and the influence of the DC/DC converter on the harmonics in the low frequency band can be ignored.

4.2. Ac Current Harmonic Analysis

For a three-phase rectifier, the relationship between the voltage and current on the AC and DC sides can be expressed as:

\[
\begin{align*}
    u_{dc}(t) &= u_a(t) \cdot S_a(t) + u_b(t) \cdot S_b(t) + u_c(t) \cdot S_c(t) \\
    i_a(t) &= i_{dc}(t) \cdot S_a(t) \\
    i_b(t) &= i_{dc}(t) \cdot S_b(t) \\
    i_c(t) &= i_{dc}(t) \cdot S_c(t)
\end{align*}
\]

In low frequency band, DC current idc(t) can be expressed as:

\[
\begin{align*}
    i_{dc}(t) &= I_{dc,0} + \sum_{n=1}^{\infty} I_{dc,n,VL} \cos(n\omega_{VL}t - \varphi_{n,VL})
\end{align*}
\]

Where:
\[
\begin{align*}
I_{dc,0} &= a_{0,VT} \cdot a_{0,VL} \cdot \frac{u_0}{R_L} \\
I_{dc,nVL} &= a_{0,VL} \cdot \frac{u_n}{R_L} \sqrt{a^2_{n,VT} + b^2_{n,VT}} \\
\phi_{n,VL} &= \arctan \left( \frac{b_{n,VT}}{a_{n,VT}} \right)
\end{align*}
\]

Taking the A-phase current as an example, using (1), (10), (11) to obtain:
\[
i_a(t) = i_{a,6n+1}(t) + i_{a,6n+1+m}(t) \quad (12)
\]

Where:
\[
i_{a,6n+1}(t) = \frac{2\sqrt{3}U_D D_{VT} D_{VL}}{\pi R_L} \left( \sum_{n=0}^{\infty} \frac{1}{6n+1} \cos \left( (6n+1)\omega t \right) - \sum_{n=1}^{\infty} \frac{1}{6n-1} \cos \left( (6n-1)\omega t \right) \right)
\]

According to the analysis of (12), the AC current can also be divided into three parts in the low frequency band. The first part is the fundamental frequency components; the second part is the \((6n\pm1)\)th harmonic caused by the rectifier; The third part is the harmonics with frequency of \((6n\pm1)f_{50}\pm m f_{VL}\), where \(m\) is the multiple of the pulse frequency \((m \geq 1)\). The existence of the third part shows that the PL will inject inter-harmonic and sub-harmonic, and even DC components into the power system. Such harmonic characteristics will bring new challenges to the power quality and stability of the power system.

5. Experimental Validation

5.1. Influence of DC/DC Converter on Harmonic Characteristics
According to (6), the DC/DC converter is equivalent to another DC switch before the VL. In theory, the system will inject harmonics corresponding to its switching frequency. In order to verify the correctness of the theoretical analysis, a simulation model is set up in MATLAB / Simulink. Fig. 5 is the simulation model of the first group of experiments. Another DC switch \(VT\) is added in place of the DC/DC converter before the DC switch VL. The switching function model of this current is formally consistent with the (6). Table 1 is the system simulation parameters. The simulation time is 10s, and the Fourier analysis results of the collected DC current \(i_{dc}\) and A-phase current \(i_a\) data are shown in Fig. 6.
The frequency marked by red dot is the result of theoretical analysis, and the main components of the corresponding frequency are also marked in Fig. 6. It is found from the results that the distribution of harmonics in simulation results is completely consistent with the theoretical analysis.

In order to further analyse the impact of DC/DC link on the harmonic characteristics of PL, two sets of simulation experiments are set up. One set of experiments considers DC/DC converters, and one set of experiments does not consider DC/DC converters (DVT=1). The working mode of the PL is set to P30-T100-D50. The other parameters in the simulation are consistent with Table 1. The spectrum analysis result of ia is shown in Fig. 7.
As can be seen from Fig. 7, in the low frequency band, the harmonic distribution of the two sets of experiments is completely consistent, and the relative magnitude of the amplitude can basically reflect the original harmonic amplitude. Therefore, in the analysis of harmonic distribution of the low frequency band, the DC/DC can be ignored, and the precondition of (7) is true.

5.2. Effect of Power Supply on Harmonic Distribution of Pulse Load

With the increase of PL types, more and more PL will appear in the microgrid, and power supply capacity of the independent microgrid system is small. In order to verify the applicability of the theoretical analysis under different power supply conditions, the public power grid and DGS are used as the power supply for PL. The public power grid can be used as an ideal power source for infinity, and the DGS is used as a limited capacity power source. Fig. 8 shows the experimental setup. The working mode of the PL is set to P30-T56-D50. The spectrum analysis result of ia is shown in Fig. 9.

![Fig. 8 The experimental test setup.](image1)

![Fig. 9 Harmonic analysis of $i_a$ under two cases.](image2)

It can be seen from Fig. 9 that whether the power source is public power grid or DGS, the harmonic distribution generated by the PL is the same. The result is completely consistent with the theoretical analysis. The amplitude of the harmonics on the left and right sides of the fundamental frequency even exceeds the fifth harmonic. They have become the dominant harmonic. However, under different power supply conditions, the harmonic amplitudes of the two groups of experiments are significantly different, which indicates that different power sources will not affect the harmonic distribution, but will affect the harmonic amplitude.

6. Influence of Pulse Load’s Working Mode on Harmonic Characteristics

It can be seen from the theoretical analysis that the working mode of the PL is the decisive factor affecting the harmonic characteristics. In order to verify the correctness of the theoretical analysis, a series of experiments were carried out to explore the influence of PL mode on harmonic characteristics.

6.1. Effect of peak power on harmonic current

The PL working mode is set to PX-T56-D50, changing P from 5kW to 50kW. The variation results of each harmonic current in phase A with P are shown in Table 2:

| Peak Power (kW) | $I_{33}(A)$ | $I_{50}(A)$ | $I_{67}(A)$ | $I_{233}(A)$ | $I_{250}(A)$ | $I_{267}(A)$ |
|-----------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 5               | 1.83        | 3.68        | 1.88        | 0.54        | 1.57        | 0.51        |
| 10              | 4.23        | 6.52        | 4.06        | 1.12        | 2.02        | 0.89        |
| 15              | 5.94        | 9.91        | 6.05        | 1.56        | 3.05        | 1.37        |
| 20              | 7.61        | 12.9        | 4.478       | 1.821       | 3.435       | 1.487       |
| 25              | 10.81       | 15.85       | 10.16       | 2.196       | 3.92        | 1.837       |
If D and T are fixed and P is increased, the amplitude of the harmonic current will increase. According to the experimental and theoretical analysis results, P only affects the amplitude of the harmonic current and does not change the distribution of the harmonic. Therefore, the larger P of the PL is, the more the content of harmonic current is, which is not conducive to the system stability.

6.2. Effect of pulse period on harmonic current

The PL working mode is set to P30-TX-D50, and the T is changed from 10ms to 100ms. The variation results of each harmonic current in phase A with the pulse period are shown in Table 3:

| Pulse Period (ms) | 20   | 40   | 60   | 80   | 100  |
|-------------------|------|------|------|------|------|
| Harmonic Current  |      |      |      |      |      |
| Frequency (Hz)    | 0    | 100  | 200  | 300  |      |
| Amplitude (A)     | 0.5  | 18.8 | 1.721| 1.411|      |
|                   | 25   | 75   | 225  | 275  |      |
|                   | 15.46| 15.19| 3.424| 3.424|      |
|                   | 33.3 | 66.7 | 233.3| 233.3|      |
|                   | 15.9 | 13.12| 3.61 | 3.61 |      |
|                   | 16.97| 62.5 | 237.5| 237.5|      |
|                   | 40   | 60   | 240  | 260  |      |
|                   | 15.65| 12.76| 4.002| 2.775|      |
| Frequency (Hz)    | 0    | 100  | 200  | 300  |      |
| Amplitude (A)     | 6.248| 9.32 | 21.17| 20.8 |      |
|                   | 9.32 | 11.05| 20.69| 20.03|      |
|                   | 11.05| 6.886| 266.7| 260  |      |
|                   | 6.886| 2.657| 2.338| 2.672|      |
|                   | 2.657| 4.183| 2.672|      |      |
|                   | 4.183| 5.417|      |      |      |
|                   | 5.417| 17.48|      |      |      |
|                   | 17.48| 18.82|      |      |      |
|                   | 18.82| 5.497|      |      |      |
|                   | 5.497| 4.85  |      |      |      |
|                   | 4.85 | 8.617 |      |      |      |
| Frequency (Hz)    | 0    | 100  | 200  | 300  |      |
| Amplitude (A)     | 21.17| 20.69| 20.8 | 20.8 |      |
|                   | 20.69| 4.937| 20.03| 20.03|      |
|                   | 4.937| 3.156| 3.935| 3.935|      |
|                   | 3.156| 2.958| 3.11 | 3.11 |      |
|                   | 2.958| 6.692 |      |      |      |
|                   | 6.692 | 4.718| 3.11 | 3.11 |      |
|                   | 4.718| 3.11 | 7.963|      |      |
| Frequency (Hz)    | 0    | 100  | 200  | 300  |      |
| Amplitude (A)     | 7.019| 15.15| 11.86| 11.86|      |
|                   | 15.15| 11.86| 6.725| 6.725|      |
|                   | 11.86| 3.786| 12.64| 12.64|      |
|                   | 3.786| 4.684| 8.242| 8.242|      |
|                   | 4.684| 8.085| 8.242| 8.242|      |
|                   | 8.085| 1.597| 8.242| 8.242|      |
|                   | 1.597| 11.88 | 8.242| 8.242|      |

When P and D are fixed and only the T is changed, the average power of the PL is basically unchanged, so changing the pulse period will only change the distribution of harmonics.

6.3. Effect of duty cycle on harmonic current

The PL working mode is set to P50-T56-DX, and the D is changed from 10% to 90%. The results of each harmonic current in phase A with D are shown in Table IV. In order to highlight the influence of duty cycle load harmonic characteristics, only 5th harmonic is marked in the Table 4.

| Duty Cycle (%) | 20   | 40   |
|----------------|------|------|
| Harmonic Current | Frequency (Hz) | 16 | 16 |
|                 | Amplitude (A)  | 6.248 | 6.248 |
|                 | Frequency (Hz) | 33 | 33 |
|                 | Amplitude (A)  | 21.17 | 21.17 |
|                 | Frequency (Hz) | 16 | 16 |
|                 | Amplitude (A)  | 7.019 | 7.019 |

According to Table IV and (3), the influence of D on harmonic characteristics of load at fixed P and T is relatively complex. Duty cycle not only affects the amplitude of harmonic current, but also affects the distribution of harmonic. It can be seen from (3) that when D is 50%, the switching function of the DC switching load and DC/DC converter contains only odd harmonics. So, the phase A current does not include even harmonics related to the pulse frequency. When the D is near 50%, the amplitude of
the harmonic current is the largest, and the amplitude of the integer harmonic increases with the increase of the duty cycle, because the increase of D is equivalent to increasing the average power.

7. Conclusion

Compared with ordinary rectifier load, PL will inject integer-harmonics and inter-harmonics into the system at the same time. In the low frequency band, inter-harmonic currents are symmetrically distributed around 6n±1 harmonic and DC/DC does not affect the harmonic distribution. Theoretical analysis and experiments show that the working mode of PL is the main factor affecting the harmonic distribution, and the power supply hardly affects the harmonic current distribution of PL.

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