Non-intrusive load monitoring and power quality optimization technology of major power customer basing on RFID

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Abstract. The upgrading of industry and manufacturing industry has put forward higher requirements on the economy and reliability of electricity consumption, this situation urges the major power customers to pay more attention to optimize their power quality. For this purpose, this paper proposed Non-intrusive load monitoring and power quality optimization technology of large power customer basing on RFID, from the viewpoint of the comprehensiveness and integrity of power quality optimization, realized non-interve monitoring of main electrical equipment and transformer, further researched optimization method of power quality on major power customers, and formulated detailed implementation strategy. The correctness and validity of the proposed results were verified via field tests.

1. Introduction
Along with the rapid development of big data analysis, artificial intelligence, cloud computing and Internet of things technology, modern manufacturing industry is marching towards the direction of intelligence, lean and modernization, furthermore, the continuous implementation and promotion of electric energy replacement exacerbated the trend, on the other hand, the shortage of fossil energy and the demand of environmental protection urgently require the scientific and rational utilization of electric energy. Under the demand of situations mentioned above, major power customers are promoted to pay more attention on the use and distribution of electric energy.

As an important evaluation standard of quality of goods acquired by energy trading, power quality is of great practical significance and reference value to both power enterprises and users. To power enterprises, power quality is necessary to provide more stable and better power supply while ensure the operational safe of power grid; and for major power customers, more acknowledge of power quality would enable themselves to optimize distribution of energy, operation of equipment and doing better schedule on production, improve the usage level of energy and decrease electric charge. Take the facts above and trends appearing into consideration, taking proper methods to realize non-intrusive load monitoring and optimization of power quality has been the focus of recent research.

2. Definition and key characterization parameters of power quality
Generally, power quality refers to the quality of electric energy in the power system, that is, the consistency of electric energy waveform and ideal power frequency sine wave in amplitude, phase and period, from the view of forming mechanism and characteristic factors, it can be divided into voltage, frequency and waveform. 7 national standards has been formulated and promulgated to standardize the
calculation, monitoring, demand and governing methods on power system frequency deviation, supply voltage deviation, three-phase voltage unbalance, network harmonics, inter-network harmonics, voltage fluctuation and flicker, voltage sag and short interruption. As for major power customers, common parameters used to reflect power quality mainly contains three-phase unbalance, harmonic wave and power factor, the calculation formulas of them are as shown:

2.1. Three-phase unbalance

\[
\begin{align*}
&\varepsilon_{u_2} = \frac{U_2}{U_1} \times 100\% \\
&\varepsilon_{u_0} = \frac{U_0}{U_1} \times 100\%
\end{align*}
\]

\(U_1, U_2, U_0\) refers to positive, negative and zero sequence components of three-phase voltage, and the formula can also be used to acquire unbalance of three-phase current by taking \(I_1, I_2, I_0\) instead of \(U_1, U_2, U_0\).

2.2. Harmonic wave
The main inflecting parameters of harmonic waves is harmonic ratio, whose calculation formula are:

\[
\begin{align*}
&HRU_h = \frac{U_h}{U_1} \times 100\% \\
&HRI_h = \frac{I_h}{I_1} \times 100\%
\end{align*}
\]

\(U_h, I_h, U_1, I_1\) refers to the \(h\) time harmonic wave’s voltage and current(Rms value), \(U_1, I_1\) stands for fundamental wave’s voltage and current(Rms value).

2.3. Power factor

\[
\cos \varphi = \frac{P}{\sqrt{P^2 + Q^2}}
\]

\(P\) refers to active power, \(Q\) refers to reactive power of power grid.

3. Research status and main problems
At present, considering the existence of reactive power assessment clause and the increasing number of intelligent and automated precision equipment, major power customers have had sufficient motivation to pay attention to and take necessary measures to improve their power quality, existing technologies are shown as below:

3.1. Three-phase unbalance
At present, there is no effective online governing method for three-phase unbalance, main measurement taken is to distribute different loads reasonably among three phases according to the expected equipment operation plan and production and business plan, so that the loads of three phases will be balanced. However, due to the fact that major power customers have not enough ability to conduct necessary analysis and prediction of their equipment operating characteristics and make reasonable running schedule. To make matters worse, for major power customers in operation, even they found that there are serious imbalance problem, they would be unable to reset the distribution strategy of power.
3.2. Harmonic wave
Recently, the main measurement of harmonic wave is to install filters, which can be divided into active filter and passive filter according to their structural characteristics.

The principle of active power filter is to collect and analyze the current waveform of the monitoring point and obtain the specific content of each harmonic through spectrum analysis, and give out current signals whose amplitude is equal to load current while phase is different from load current by 180°, so that the harmonic waves are eliminated. This measurement has advantage of high harmonic wave elimination effect, but taking this method must configure current source according to harmonic status, which will increase the operation complexity and governance cost.

The main mechanism of passive filter is to construct a low impedance path for a specific frequency band through reasonable configuration of components and parameters such as capacitance and inductance, so that harmonic waves could be separated from power grid, this method takes lower cost and strong capacity able to expanse but the control frequency band is narrow, and the harmonic wave elimination is relatively poor.

3.3. Reactive power compensation
In terms of reactive power compensation, as for most large capacity electrical equipment is inductive. At present, the most commonly used reactive compensation are power capacitors or other equipment to provide capacitive reactive power to balance the inductive reactive power in power grid. Recent technologies mainly focus on control strategy and configuration of compensation device. This method can achieve the goal of improving power factor and power quality, but its effect depends on the rationality of the control strategy, otherwise, existing switching strategy hasn’t take the discharge time of power capacitor into consideration, it neither be able to deal with power quality risks in the future.

4. Non-intrusive load monitoring method for major power customers basing on RFID
RFID is a short name for radio frequency identification, is a non-contact two-way data communication through radio frequency signals, a common RFID system includes reader, electronic tag and application software system.

Combined with the application demand and actual situation of major power customers, this paper proposes a non-intrusive load monitoring method for dedicated customers basing on RFID, the main idea of which is to reasonably configure and install RFID tags on all main electrical equipment, so that the tags could accurately reflect the real-time operation status of the associated electrical equipment, and then feed back the running status to data processing center through the reader module to complete running state evaluation and prediction of device.

![Figure 1. Function chart of RFID communication system.](image-url)
To realize the non-intensive load monitoring method, it is necessary to configure the main components of the power system, the specific configuration method and implementation scheme are as below:

**4.1. RFID tags**

The function of RFID tag is to monitor and feed back the running state of related device in real time, among which, active and passive tags can be configured according to the characteristics of the running state of electrical equipment, active tags can be used to monitor equipment with complex running conditions and obvious time variability, while passive tags are used to monitor devices with stable running state and do not change over time.

The configuration of passive tags are relatively simple, which only needs to be aware of the electrical equipment’s switching state and feedback the serial number and switching state the corresponding electrical equipment. Therefore, the passive label is generally adopted, and the electrical equipment code and the running state variable are stored in RFID tags, so that the reader is able to check the running state of electrical equipment at any time.

The configuration of the active tag should be based on the specific operating characteristics of the electrical equipment, the configuration scheme of active RFID tags is shown as below:

![Figure 2 Module diagram of RFID tag control strategy for non-linear equipment](image2)

![Figure 3 Module diagram of RFID tag control strategy for linear equipment](image3)

As is shown in Fig.2, for non-linear equipment, the existing control or monitoring circuit structure of the equipment can be used to obtain the current running information of the equipment through wire/wireless sensor or other non-electrical sensors, and then charge relative active RFID tags so that the communication function was realized; for linear equipment, current monitoring and logic gate circuit may be combined to ensure that there will be only one correct active RFID tag was energized and communicated by shielding low-value switches with higher valued switch.

| Status       | State 1 | State 2 | State 3 |
|--------------|---------|---------|---------|
| Active tag 1 | ✓       |         |         |
| Active tag 2 |         | ✓       |         |
| Active tag 3 |         |         | ✓       |
| Passive tag  |         |         | ✓       |
4.2. Reader
The function of reader is to make use of the technical advantage of RFID to realize multiple point synchronous information interaction, collect and summarize the running status information of running equipment quickly and accurately, and then reader package it into data tables and send it to processing center.

4.3. Data processing center
After receiving the running information from reader, data processing center will complete the calculation of discrimination of equipment running status, power quality analysis, control strategy processing and other necessary computing, finally control appropriate governing equipment to take right action according to power quality optimization method and control strategy proposed in this paper.

5. Power quality optimization method and control strategy
The main calculation flow is as shown in Figure 4.

\[
V_f = \begin{bmatrix}
E_1 & q_1 & S_1 & HRI_1 \\
E_2 & q_2 & S_2 & HRI_2 \\
... & ... & ... & ...
\end{bmatrix}
\]

In the formula, \(E\) stands for equipment sequence number, \(q\) stands for the state factor of each equipment, while \(S\) stands for rated apparent power and \(HRI\) stands for a array of all harmonic wave ratios.

Secondly, for each electrical equipment to be analyzed, read or calculate the characteristic table to query or acquire current and short-term active power, reactive power, harmonic component and other
information of the electrical equipment, after which the power vectors and harmonic wave characteristic vectors of each phases were formed.

Then, according to the calculation or query of the data acquired through above steps, analysis and calculation will be carried out at reduction of three-phase unbalance, suppression of harmonic waves and compensation of reactive power, acquire detailed parameters of filters and power capacitors shall be switched.

Because of the fact that there are crosses among three governing equipment, and they may affect each other, it is necessary to arrange them in certain order. The relationship among three kinds of governing equipment is shown in Table 2.

| Table 2. Relationship among power quality optimization methods. |
|---------------------------------------------------------------|
| Harmonic suppression | Load balancing | Reactive power compensation |
| Filters | ✓ | ✓ |
| Phase-to-phase power capacitors | ✓ | ✓ |
| Phase-to phase power capacitors | ✓ | |

We can infer from the table that harmonic wave suppression should be taken first, and then an analysis be taken on active power and reactive power data of each phase, basing on which load would be balanced by switching power capacitors between different phases, and finally, calculate remaining reactive power in every phase, thus we can do well compensation with phase-to-ground power capacitors.

Detailed calculating process is:

According to the harmonic characteristic vectors of each phase, do analysis to get harmonic components, and then form harmonic components spectrum vector:

\[
I_h = \begin{bmatrix}
I_{a1} & I_{a2} & I_{a3} & \cdots & I_{a_n} \\
I_{b1} & I_{b2} & I_{b3} & \cdots & I_{b_n} \\
I_{c1} & I_{c2} & I_{c3} & \cdots & I_{c_n}
\end{bmatrix}
\]  

(6)

Find major harmonic wave components among the vector, configure filter channels corresponding to the frequency of major harmonic waves, calculate reactive power compensation effect caused by filters, and form injecting reactive power vector:

\[
Q_H = [Q_{ha} \quad Q_{hb} \quad Q_{hc}]
\]  

(7)

In the filter, \( Q_{ha}, Q_{hb} \) and \( Q_{hc} \) refers to reactive power injected to power grid by filters.

Introduce injecting reactive power vector into power vector, analyze three-phase unbalance and configure the parameters of phase-to-phase power capacitors, calculate reactive compensation effect caused by the method.

Effective effect of unbalance regulation can be achieved by setting phase-to-phase power capacitors, the principle is as shown:
In the figure, $\mathbf{I}_{BC}^g$ represents the current flowing into phase B through phase-to-phase power capacitor, $\mathbf{I}_{BC(p)}^g$ and $\mathbf{I}_{BC(q)}^g$ refers to the active power and reactive power components, while $\mathbf{I}_{CB}^g$ reflects the effect this current caused to phase C.

By taking this method, active power transferred from phase B to phase C is:

$$P_{BC} = I_{BC(p)}^g \times U_C = \frac{\sqrt{3} C}{6}$$ (8)

Reactive power transferred is:

$$Q_{BC} = I_{BC(q)}^g \times U_C = \frac{C}{2}$$ (9)

Considering the effect of phase-to-phase capacitor, active powers and reactive powers injected into each phase are:

$$\begin{cases}
\Delta P_A = \frac{\sqrt{3} (C_{AB} - C_{CA})}{6} \\
\Delta P_B = \frac{\sqrt{3} (C_{BC} - C_{AB})}{6} \\
\Delta P_C = \frac{\sqrt{3} (C_{CA} - C_{BC})}{6} \\
\Delta Q_A = \frac{(C_{CA} + C_{AB})}{2} \\
\Delta Q_B = \frac{(C_{AB} + C_{BC})}{2} \\
\Delta Q_C = \frac{(C_{CA} + C_{BC})}{2}
\end{cases}$$ (10)

C refers to the capacity of phase-to-phase power capacitors.

Similarly take the reactive power compensation effect into power vector, thus we acquire final reactive power capacities need to be compensated of each phase, and then configure phase-to-ground electrical power capacitors, send out control signals and complete the switch with control circuit.
\[
\begin{align*}
Q_A' &= (Q_A - Q_{ha} - \Delta Q_A) \\
Q_B' &= (Q_B - Q_{bb} - \Delta Q_B) \\
Q_C' &= (Q_C - Q_{hc} - \Delta Q_C)
\end{align*}
\] (11)

\(Q\)' stands for ideal reactive capacitors shall be compensated of three phases.

6. Experimental verification and analysis

In order to verify the correctness and effectiveness of RFID based non-intrusive load monitoring and power quality optimization technology proposed in this paper, two major power customers in local industrial district were selected for experimental verification. Basic information of them is listed in Table 3.

| Customer | Main load          | Transformer capacity (kVA) | Gears of main load | Average charge (yuan) |
|----------|--------------------|--------------------------|--------------------|-----------------------|
| A        | Electric arc furnace | 630                      | 4                  | 80k                   |
| B        | Rectifying device  | 400                      | 2                  | 45k                   |

According to the monitoring system, power quality optimization technology and control strategy, RFID tags were attached to main electrical equipment of both customers, and data processing software was installed in controlling computer, and monitoring and control were realized by sensors and load switches, during the experiment, harmonic wave ratio, three phase unbalance and power factor were monitored or calculated before and after power quality governance, collected data was compared and the result was shown as Figure 6-8.

**Figure 6.** Contrast figure of harmonic wave suppression effect

**Figure 7.** Contrast figure of load balancing effect
Furthermore, according to current electrical charging strategy, customer A and B will save ¥7045 and ¥1861 as well.

7. Conclusion
This paper proposed a non-intrusive load monitoring and power quality optimization technology of major power customer basing on RFID, which designed non-intrusive load monitoring system and researched optimization method of power quality, configured realization scheme and control strategy, which was verified to be effective on major power customers.

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Figure 8. Contrast figure of reactive power compensation effect