CUSTOMIZED POWER QUALITY CONTROL SCHEMES AND COMPREHENSIVE EVALUATION METHOD FOR AN OFFSHORE OIL PLATFORM

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Aiming at the power quality problems existing in offshore oil platforms, this paper analyzes three typical power quality problems on a platform through actual measurement, such as high harmonic content, low power factor and voltage sag. Then multiple customized power quality control schemes were proposed, and by considering energy-saving, reliability, and economy, the weight of indicators was determined by AHP-EWM method, and different schemes were compared by the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Finally, the optimal scheme which balances management effectiveness, reliability, and economy was obtained, and its effectiveness was verified through electromagnetic transient simulation.

Keywords: offshore oil platform, power quality, AHP, EWM, TOPSIS

1. Introduction

Traditional offshore oil platforms mostly use self-powered power supply technology, which consumes high energy and pollutes a lot. The platform using electricity from the onshore substation through submarine cables is a new way to effectively reduce the space and emissions and improve efficiency. However, due to the small capacity of the distribution network and complex working conditions, the power quality problems of the platform are obvious [1]. The loads on the platform are mainly induction motors, which lead to a lower power factor of the system. The change of loads may also cause the voltage sag and harmonics, thereby increasing power losses and affecting the normal operation of important equipment.

For improving the power quality of offshore oil platforms, some solutions have been studied. In Reference [2], tuned filters were installed on the low-voltage bus of the Qinhuangdao 32-6WHPA platform to compensate for reactive power, resulting in an overall voltage improvement. Similar methods were also used in the ship power supply system, where special parameter design can achieve a certain

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effect [3]. But the passive compensation device has poor flexibility and a slow response, it cannot realize dynamic compensation. Active power filters (APF) are flexible with a fast response, and its compensation effect is little affected by voltage. Therefore, APF is mostly used on the platform [4]. The relevant scholars have compared the functions of passive power filters, static var compensators (SVC), and APF, and better effects have been achieved by adopting APF or SVC [5,6]. New types of power electronic devices also have been proposed to protect the loads from voltage sag, regulate voltage imbalances, and reduce harmonics [7]. As can be seen, the power quality issues for oil platforms generally consider reactive power or harmonics in some areas, with corresponding equipment installed near the equipment. However, this approach is not well-targeted and lacks a comprehensive and systematic solution to the power quality problems for the platforms.

Also, when there are several control schemes, a comprehensive evaluation method taking into account the various benefits is required in order to select the best one. For example, a cost-benefit method to assess the transboundary power quality indicators and their alternative schemes were studied in [7]. And a loss calculation method for regional power grids in coastal areas was studied in [8], and the economic benefits of reactive power compensation were evaluated. Existing researches only evaluate the control schemes from effects or economy [9-11], and the evaluation is mostly used in reliability assessment [12,13]. In addition, the treatment schemes proposed for oil platforms only emphasize the effects, and there is no relevant study on the evaluation in terms of energy savings and reliability.

To address the above issues, this paper proposes specified power quality control solutions based on the load characteristics. Then a comprehensive evaluation system is established to evaluate different schemes in terms of energy saving, reliability and economy. Finally, the optimal scheme is obtained and also verified through simulation.

2. Power quality of the oil platform and its control scheme

2.1 Introduction of the oil platform

The topology of a typical offshore oil platform is shown in Fig. 1. The 10kV onshore substation is connected to the platform through 5km submarine cables.

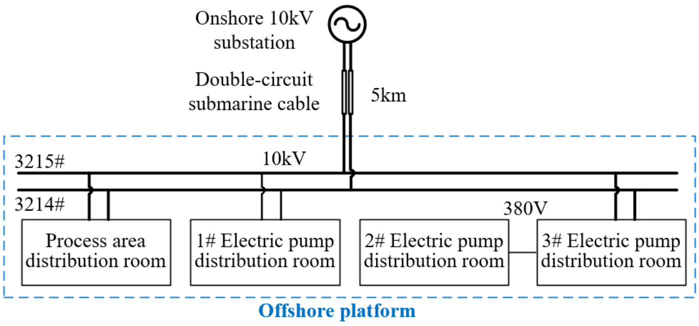


Fig. 1. Topology of an offshore oil platform

The incoming line of the 2# electric pump distribution room comes from 3# room, and two rooms are connected in series. The equipment in each room are mainly induction motors, and their capacity ranges from 37kW to 315kW. the topologies of each room are shown in Fig. 2.

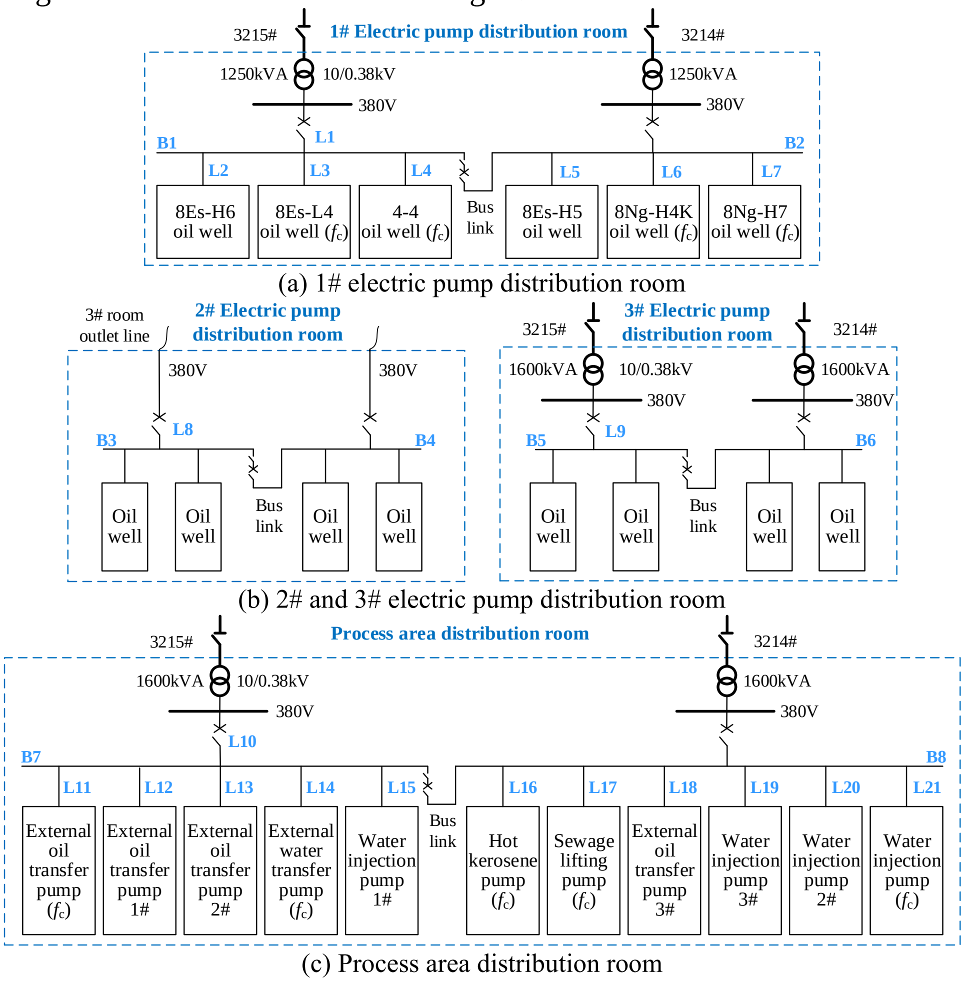


Fig. 2. The topologies of each room (f_c represents the motor is driven by a frequency converter)

2.2 Power quality measurement and control scheme

The power data of typical loads on the oil platform were obtained through measurement. Since 2# and 3# rooms are not accessible for measurement, and they are connected in series, only the data of 3# room were collected to represent the total power of two rooms. The measurement shows that frequency and voltage deviation, voltage fluctuation and current unbalance in each room is within 0.035Hz, 5%, 0.7%, and 2.3%, respectively, and they are in the normal range. But the power factor (PF) which is defined as the ratio of the active power to the complex power is low and the current harmonic is high, as shown in Fig. 3.

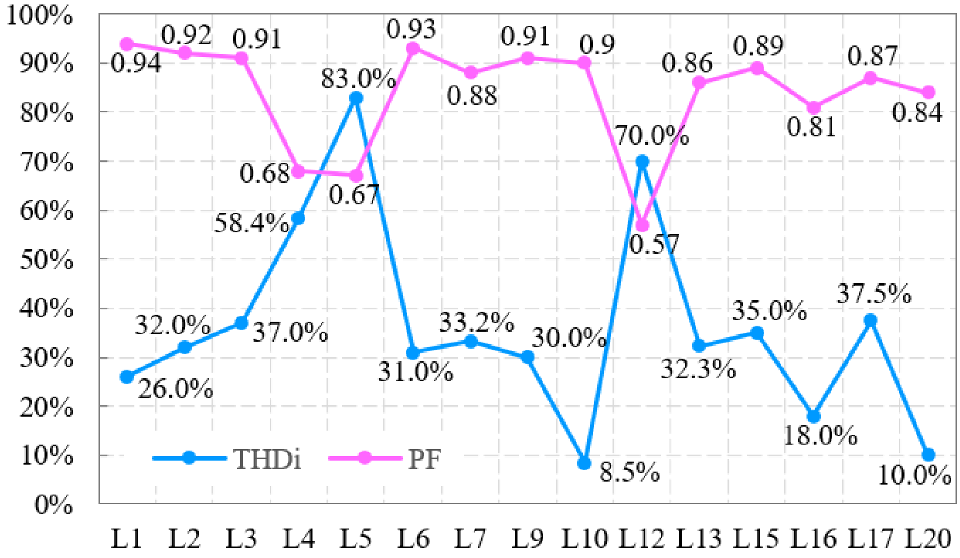


Fig. 3. The main power quality issues of the platform

The PF of the process area distribution room is smaller than 0.9, and the total harmonic current distortion (THDi) of the pump rooms generally exceeds 30%. The electrical equipment with very low PF should be focused on, such as oil pump 1#, 4-4 and 8Es-H5 oil pumps. As the high current harmonic on the platform, harmonic control devices should be installed. Though the voltage sag is not obvious, considering the voltage drop during faults or startup, it is possible to configure voltage compensation devices for equipment that is sensitive to voltage. Consequently, five power quality control schemes are proposed.

(1) Scheme 1

Economy priority. The shunt capacitor bank (SCB) and APF are selected for reactive power compensation and harmonic control. To reduce the equipment cost, only SCB is used to compensate the reactive power, and the APF is configured on the incoming line to reduce the harmonics.

(2) Scheme 2

Control effect priority. In order to achieve better effect, the combination of decentralized compensation and in-situ compensation is adopted. The capacity of 2# room is small, and the static var generator (SVG) which can achieve a better performance than the traditional SVC is configured at the incoming line; the capacity of process area distribution room is larger, and SVGs are configured to compensate reactive power for equipment with low PF.

(3) Scheme 3

Economy and control effect. Using SCB+SVG for reactive power compensation can meet the requirements with less cost. Therefore, SVG is configured in 2# room with small capacity, and SCB+SVG is configured in process area distribution room with large capacity. And the APF is installed locally for the equipment with a large THDi in each room.

(4) Scheme 4

Economy, energy saving and control effect. Since in-situ compensation is only for a single electrical equipment, the investment is high, and the operation and maintenance are inconvenient. Therefore, scheme 3 is improved by decentralizing the installation of APF.

(5) Scheme 5

Considering voltage sag. Due to the voltage sag of 2# and 3# rooms, sewage lifting pump, and water injection pump (f_C) in the process area distribution room has a larger capacity and higher importance, dynamic voltage restorer (DVR) can be chosen to configure for the above equipment. Overall, detailed configurations of the five schemes are shown in Table 1.

Table 1

Customized power quality control schemes proposed

Scheme	Equipment	Configuration
Scheme1	APF	B1, B3, B5, B6, B7, B8
	SCB	B3, B4, B7, B8
Scheme2	APF	B1, B3, B5, B6, B7, B8
	SVG	B3, B4, L11, L16, L20
Scheme3	APF	L3, L4, L5, L11, L14, L17, L21
	SVG	B3, B4
	SVG+SCB	B7, B8
Scheme4	APF	B1, B3, B5, B6, B7, B8
	SVG	B3, B4
	SVG+SCB	B7, B8
Scheme5	DVR	L8, L17, L21
	APF	B1, B3, B5, B6, B7, B8
	SVG	B3, B4
	SVG+SCB	B7, B8

3. Evaluation indicators and evaluation method

The essential requirement to control the power quality is to increase production, save electricity, and improve the economy. Therefore, there must be differences in the energy-saving, reliability or cost of the above schemes.

The technical, reliability and economy of different schemes were evaluated in this paper by establishing a comprehensive evaluation system shown in Fig. 4. Since power electronics is usually used by control equipment, there is little difference in their lifetime, so the it is not included in the evaluation system.

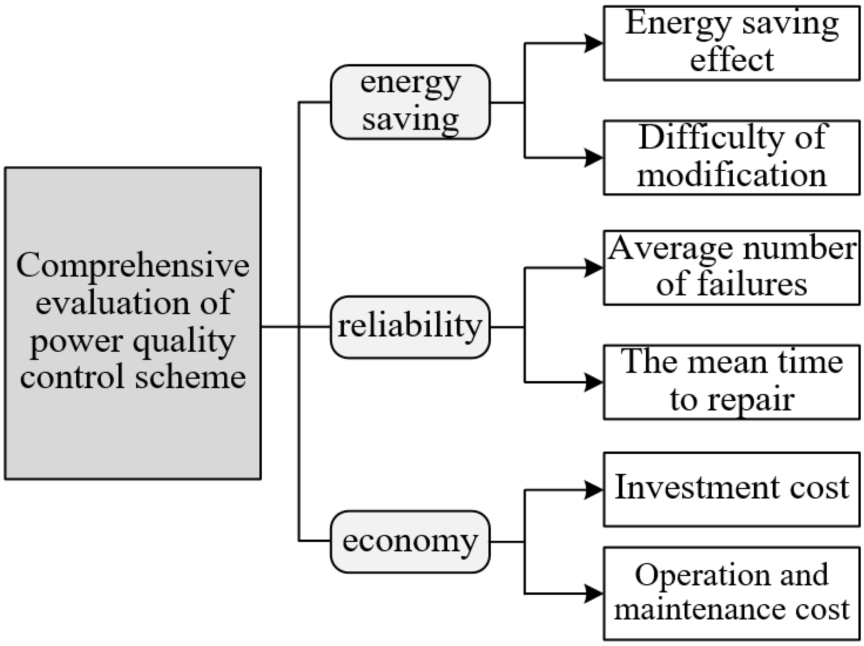


Fig. 4. Comprehensive evaluation system for power quality control schemes

3.1 Calculation of the energy saving indicators

(1) Energy saving due to lower harmonics

Because harmonics consume energy but do not produce active power, the harmonics in the platform will directly increase power losses. The calculation methods of power ΔP_1 and electricity ΔE_1 saved by reducing harmonics are shown in (1) and (2) [12].

$$\Delta P_1 \approx \sqrt{3}U \cdot \Delta I \cdot \mathrm{PF1} = \sqrt{3}U\left(\sqrt{I_\mathrm{h}^2 + I_1^2} - I_1\right)\mathrm{PF1} \tag{1}$$

$$\Delta E_1 = \Delta P_1 \cdot T \tag{2}$$

where I_h is the total harmonic current component; I_1 is the fundamental current component; PF1 is the true power factor of each room, and it’s the ratio of active power to the complex power which can be easily get from the power analyzer; T is the annual working time of each room.

(2) Energy saving due to higher power factors

The improvement of PF can ensure that the equipment works within the rated range and reduce the power loss, and the energy saving ΔE_2 is calculated as in (3) with reactive power compensation. Since the voltage waveform is much better than current and the equipment consumes little active power, then effects of efficiency of the equipment on energy saving is not considered.

$$\Delta E_2 = \Delta P \cdot T = (P_{21} - P_{22}) \cdot T \tag{3}$$

where P_{21} is the line loss before treatment; P_{22} is the line loss after treatment.

(3) The difficulty of modification

Considering the aspects of safety, environmental protection, energy consumption, floor space and resource utilization, the difficulty of implementing different schemes can be qualitatively evaluated. The difficulty of modification (DOM) can be evaluated by the project implementer into four levels:

$$DOM \in \{A,\ B,\ C,\ D\} \tag{4}$$

where A represents simple; B represents normal; C represents difficult; D represents very difficult.

3.2 Calculation of the reliability indicators

The platform may fail during normal operation, and the installation of different equipment may also affect the normal operation of loads. The mean time to repair (MTTR) is the average time required to repair the system, including the repair time and any test time until the system is fully restored.

$$\mathrm{MTTR} = \sum_{i=1}^{N} T_i / N \tag{5}$$

where T_{i} is the ith fault repair time; N is the number of faults.

3.3 Calculation of the economic indicators

3.3.1 Compensation capacity

(1) The capacity of the required reactive power is:

$$Q_{\mathrm{C}} = \beta P_{\max}\left(\tan\left(\arccos \mathrm{PF1}\right) - \tan\left(\arccos \mathrm{PF2}\right)\right) \tag{6}$$

where Q_{C} is the reactive power provided by the equipment; β is the average load factor, $P_{\max}$ is the maximum active power of the load; PF1 has the same definition as in (1) and it represents the power factor before the compensation, and PF2 is the power factor after compensation.

(2) The harmonic current to be compensated by the APF is:

$$I_{\mathrm{thd}} = I_{\mathrm{rms}} \frac{THD_{\mathrm{i}}}{\sqrt{1 + THD_{\mathrm{i}}^2}} \tag{7}$$

where I_{thd} is the RMS value of harmonic current; I_{rms} is the rms value of load current; THD_{i} is the total harmonic distortion rate of current.

(3) The compensation capacity required for DVR is:

$$S_{\mathrm{DVR}} \approx |I_{\mathrm{L}}(\cos\theta + j\sin\theta)(U_{\mathrm{L}} - U_{\mathrm{sag}})| = I_{\mathrm{L}}(U_{\mathrm{L}} - U_{\mathrm{sag}}) \tag{8}$$

where S_{DVR} is the capacity of DVR; I_{L} and U_{L} are RMS load current and voltage before sag, respectively; U_{sag} is RMS load voltage after sag; θ is the phase angle between fundamental components of U_{L} and I_{L}.

3.3.2 Investment cost

Considering the initial investment cost of different equipment, the primary investment of different schemes can be calculated as (9).

$$C_{\mathrm{I}}(h) = \sum_{h=1}^{m} P_{\mathrm{R}}(h)S(h) \tag{9}$$

where $C_{\mathrm{I}}(h)$ is the primary investment, h is the type of equipment; m is the total number of equipment; $P_{\mathrm{R}}(h)$ is the investment cost per unit capacity of h-type equipment; $S(h)$ is the capacity of the h-type equipment to be installed.

When different equipment is installed, the annual operation and maintenance cost can be calculated by (10).

$$C_{\mathrm{tc}}(h) = \sum_{h=1}^{m} p(h)C_{\mathrm{I}}(h) \tag{10}$$

where C_{tc} is the total operation and maintenance cost; $p(h)$ is the proportion of the operation and maintenance cost of h-type equipment; $C_{\mathrm{I}}(h)$ is the initial investment cost.

The economic parameters of each equipment are shown in Fig. 5 based on (9)-(10) and references [9], [14]-[15].

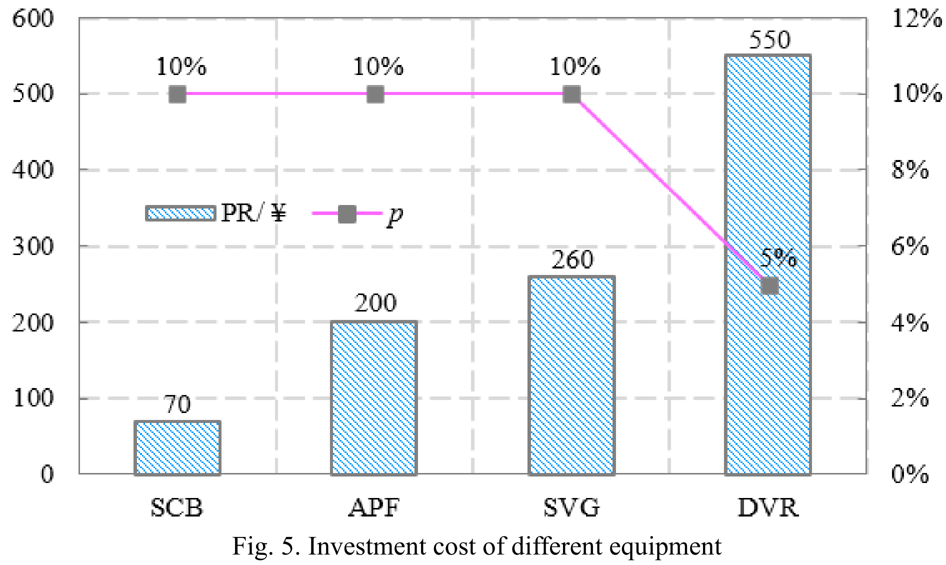


Fig. 5. Investment cost of different equipment

Finally, the evaluation values of the six level 2 indicators for different schemes can be obtained based on the power quality data on the platform as shown in Table 2.

Table 2

Evaluation indicators for different control schemes

Scheme	Energy saving		Reliability		Economy	
	ΔE/kW·h	*DOM*	N/time	MTTR/day	$C_I/10^4$ RMB	$C_{tc}/10^4$ RMB
Scheme1	6.14×105	B	7	2	11.41	1.14
Scheme2	6.94×105	C	4	3.5	14.27	1.43
Scheme3	5.31×105	C	5	3.5	9.53	0.95
Scheme4	6.89×105	B	3	3	12.93	1.29
Scheme5	7.02×105	C	0	5	23.93	1.84

4. Evaluation analysis of different control schemes

In order to evaluate different schemes, a combined evaluation method with analytic hierarchy process (AHP) and entropy weight method (EWM) was adopted to first calculate the weights of indicators in this study; then, the TOPSIS method was used to calculate the distance between different schemes and the ideal one. By solving the proximity to the ideal scheme and scoring, the ranking of the schemes was obtained.

4.1 The principle of AHP

The main analysis process of AHP is as follows:

(1) Establish a hierarchical structure model

Complex problems are decomposed into components of elements, and these elements form several levels according to their attributes and relationships.

(2) Construct all judgment matrices in each level

Two indicators x_i and x_j are taken each time, and a_{ij} is used to represent the ratio of the influence of x_i and x_j on each criterion, and all comparison results are represented by matrix $A=(a_{ij})_{nxn}$, which is called the comparison judgment matrix (judgment matrix for short).

(3) Hierarchical single sorting and consistency check

Firstly, the consistency test of the judgment matrix should be performed, and the consistency index *CI* should be calculated as shown in (11).

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{11}$$

where n represents the order of judgment matrix, and usually n is smaller than 9.

Then we can find the average random consistency index *RI* according to the standard AHP method, and the consistency ratio *CR* can be calculated:

$$CR = \frac{CI}{RI} \tag{12}$$

When $CR<0.10$, the consistency of the judgment matrix is acceptable; otherwise, the judgment matrix A should be reconstructed, and then judged again.

After the consistency check is passed, the weight of each indicator relative to the target can be obtained after normalizing the judgment matrix by the maximum eigenvalue.

(4) Hierarchical total sorting and consistency check

The total sorting weight is to synthesize the weights under the single criterion from top to bottom. Assume that the upper level (layer *A*) contains a total of *m* factors $A_1, A_2, ..., A_m$, and their total ranking weights are $a_1, a_2, ..., a_m$, and then the next level (layer *B*) contains *n* factors $B_1, B_2, ..., B_n$, and their hierarchical single ranking weights on A_j are $b_{1j}, ..., b_{nj}$, respectively (when B_j is not related to A_j, $b_{ij}=0$). Now calculate the weight of each factor in layer *B* with respect to the overall goal, as shown in (13).

$$w_i^{AHP} = \sum_{j=1}^{m} b_{ij} a_j \quad (i = 1, \cdots, n) \tag{13}$$

The consistency check is also required here, assume that *CI*(*j*) and *RI*(*j*) has been obtained in single-level sorting, the random consistency ratio of the total sorting of layer *B* is shown in (14). And the principle of consistency check is the same as (12).

$$CR = \frac{\sum_{j=1}^{m} CI(j) a_j}{\sum_{j=1}^{m} RI(j) a_j} \tag{14}$$

4.2 The principle of EWM

The main steps of EWM are as follows:

Assume that the original data matrix of *m* evaluation indicators and *n* evaluation objects is $A=(a_{ij})_{m\times n}$, and $R=(r_{ij})_{m\times n}$ is obtained after normalization as in (15):

$$r_{ij} = \frac{a_{ij} - \min_j \{a_{ij}\}}{\max_j \{a_{ij}\} - \min_j \{a_{ij}\}} \tag{15}$$

For the index whose small value is superior, the normalization formula is:

$$r_{ij} = \frac{\max_j \{a_{ij}\} - a_{ij}}{\max_j \{a_{ij}\} - \min_j \{a_{ij}\}} \tag{16}$$

The entropy h_i of the *i*-th evaluation index is:

$$h_i = -\frac{1}{\ln n} \sum_{j=1}^{n} f_{ij} \ln f_{ij} \quad (f_{ij} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}}) \tag{17}$$

In particular, when $f_{ii}=0$, set $lnf_{ii}=0.1$. Then the entropy weight w_i^{EWM} of the *i*-th indicator can be obtained as shown in (18).

$$w_i^{EWM} = \frac{1-h_i}{m-\sum_{i=1}^{m} h_i}\left(0 \le w_i \le 1, \sum_{i}^{m} w_i = 1\right) \tag{18}$$

4.3 The principle of TOPSIS method

The TOPSIS method is a method of sorting the alternatives by means of the "positive ideal solution" and "negative ideal solution" of the multi-objective decision-making problem. First, we can get the comprehensive weight w_i^T as in (19).

$$w_j^T = \alpha w_j^{AHP} + (1-\alpha) w_j^{EWM} \tag{19}$$

where, α is the subjective coefficient, 1-α is the objective coefficient, usually α=0.7.

Then standardize the evaluation matrix in a process similar to (15) and (16), and obtain the standardized evaluation result v_{ij}^T, and the weighted judgment matrix r_{ij}^T can be obtained as shown in (20).

$$r_{ij}^T = w_j^T \cdot v_{ij}^T \quad (i = 1, 2, \ldots, m,\ j = 1, 2, \ldots, n) \tag{20}$$

Then calculate the Euclidean distance between each scheme and the positive and negative ideal solutions according to the elements of the weighted judgment matrix:

$$\begin{cases} S_i^+ = \sqrt{\sum_{j=1}^{n} (\max_{1\le i\le m}\{r_{ij}\} - r_{ij})^2} \\ S_i^- = \sqrt{\sum_{j=1}^{n} (\min_{1\le i\le m}\{r_{ij}\} - r_{ij})^2} \end{cases} \tag{21}$$

Finally, according to the fitting degree obtained in (22), the schemes are sorted from large to small, and the one with the highest results is the optimal scheme.

$$h_i^+ = \frac{S_{di}^-}{S_{di}^- + S_{di}^+} \quad (i = 1, 2, \ldots, m) \tag{22}$$

5. Comprehensive evaluation and verification of control schemes

In this section, the AHP-EWM combination method is used to solve the weights of indicators, and the optimal scheme with good energy saving, reliability and economy is selected. Then the effectiveness of the scheme is verified.

5.1 Evaluation of different schemes

Based on the basic data in Table 2, the AHP is used to calculate the weights of the three first-level indicators, they are 0.40, 0.20 and 0.40; and then weights of the second-level indicators under each first-level can be calculated as in Table 3.

Table 3

The weight of the second-level indicators

Weight	Energy saving	Difficulty of modification	Average number of failures	Average time of repairing	Investment cost	Operation and maintenance cost
AHP	0.75	0.25	0.75	0.25	0.50	0.50
EWM	0.22	0.78	0.55	0.45	0.47	0.53
AHP+ EWM	0.59	0.41	0.69	0.31	0.49	0.51

Then the distance between each scheme and the ideal scheme is calculated with (22), and the radar charts of the scores of different schemes on each indicator is shown in Fig. 6.

It can be seen from Fig. 6 that scheme 4 has the largest area, which means that the scheme is best with good scores in three aspects; scheme 3 and scheme 5 are the worst two schemes. The area of scheme 1 is close to that of scheme 4, and it is superior to scheme 4 in terms of economy, but not as good as scheme 4 in energy saving and reliability. Scheme 5 is economically poor due to the generally high cost of the equipment used, though it has a good reliability, it is poor in overall performance.

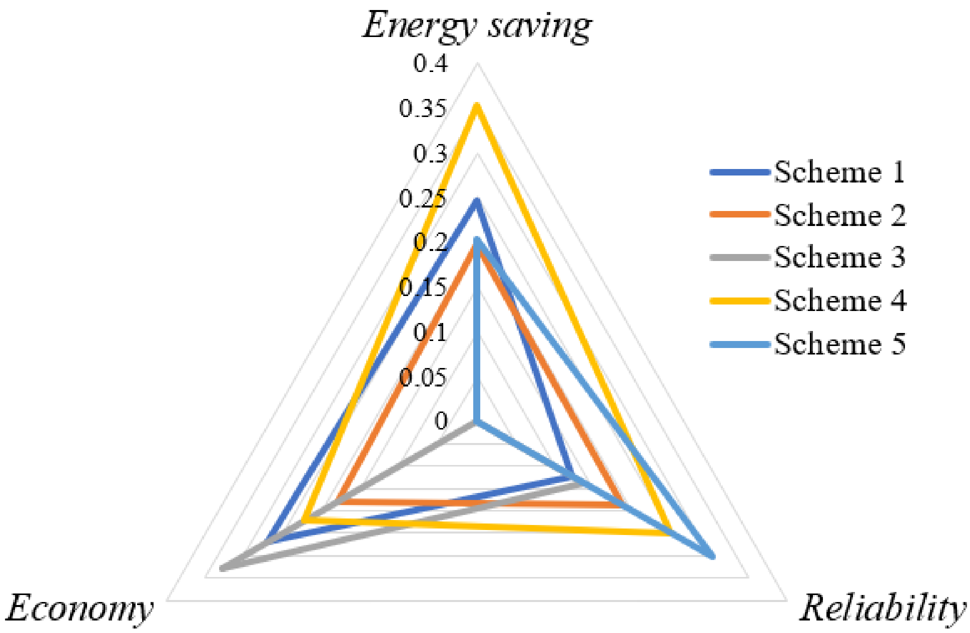


Fig. 6. The radar charts of the scores of different schemes on each indicator

Also, the scores of five schemes are 0.22, 0.19, 0.17, 0.26 and 0.16 respectively. Based on the above analysis, some conclusions can be drawn as follows:

1) Although the SCB with the lowest investment cost is used for reactive power compensation in scheme 1, it is relatively convenient and the energy-saving effect is acceptable, so it also can be used as a good choice;

2) Although scheme 4 uses SVG devices with higher investment, its reliability is higher than that of scheme 1, so it is better than scheme 1 when comprehensively considering the energy-saving effect and reliability;

3) Since scheme 2 uses SVGs to compensate for reactive power, and the cost of SVGs is higher than that of SCB, it is obviously inferior to scheme 4 in terms of economy;

4) The main difference between scheme 3 and scheme 4 is the installation of APF, and the evaluation results show that the comprehensive effects of decentralized compensation is better;

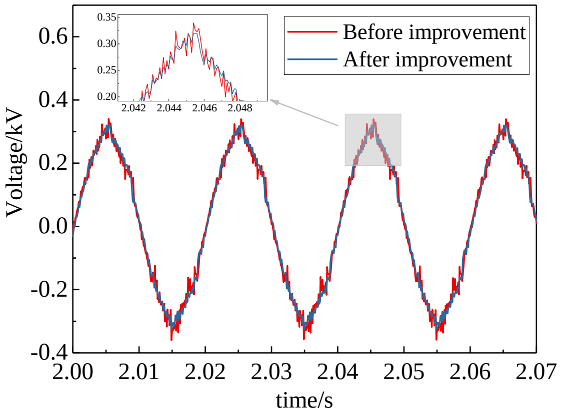
5) DVRs are adopted in scheme 5, and its investment is greatly increased so that the evaluation result is the worst. It is only necessary to adopt scheme 5 when the transient voltage sag may occur under special working conditions.

5.2 Verification of the control Effects

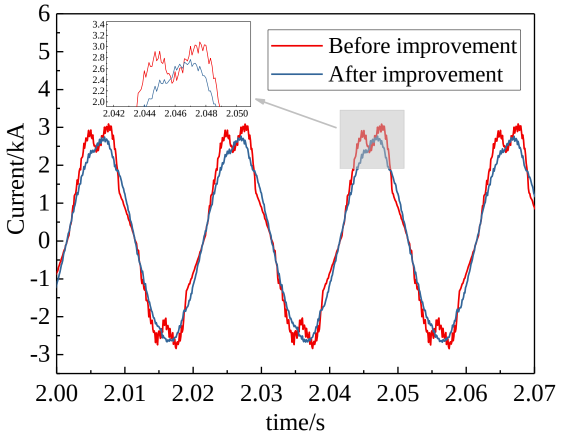
In order to verify the effects of the schemes, the electromagnetic transient model of the platform is built in PSCAD/EMTDC according to Fig. 1 and Fig. 2.

Scheme 4 is applied on the platform to analyze the power factor and harmonics. After improvement, the power factors of each room and the platform are higher than 0.95, which meets the standard of the onshore distribution grid. Taking the process area power distribution room as an example, the bus voltage and current before and after improvement are shown in Fig. 7. We can learn the voltage THD is about 5%, which meets the requirements for voltage harmonics; and the current THD is reduced from 13.6% to 6.9%, an improvement of about 50%.

In order to verify the effects of the DVRs in scheme 5, a single-phase short-circuit fault is applied at the incoming line of the process area power distribution room, and the results are shown in Fig. 8. Normally, the bus voltage can drop by 20% during the fault, but after using DVRs the voltage sag is less than 2%, and the instantaneous maximum voltage drop does not exceed 8%.



(a) Voltage waveform



(b) Current waveform

Fig. 7. Voltage and current waveform of the bus before and after improvement

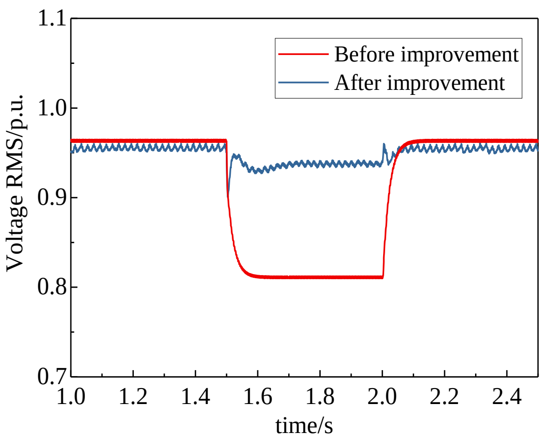


Fig. 8. The voltage sag of the bus before and after improvement

6. Conclusions

This paper takes an offshore oil platform in the Bohai Sea as an example to propose a targeted treatment scheme and comprehensively evaluate different programs. The main conclusions are as follows:

1) Power quality problems of the platform were analyzed through the measured data, then considering the hybrid reactive power compensation, decentralized and on-site compensation, five control schemes were proposed;

2) A comprehensive evaluation system for different schemes is established by considering the energy-saving, reliability, and economy. And the weights are calculated by the AHP-EWM method, then the optimal scheme is obtained with TOPSIS method;

3) The selected control schemes were verified through simulation; the results show that the power quality of the platform was effectively improved and can meet the requirements of the onshore substation.

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