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ABSTRACT

In recent years, with the use of electric drilling rig, electric fracturing pump, and other equipment, the harmonic resonance problem of oilfield power grid is becoming more and more serious. In view of the high time and space complexity and long calculation time of the traditional harmonic resonance analysis method, the improved power iteration method is combined with the traditional modal analysis method, and the harmonic resonance problem of the oilfield power grid is analyzed by the fast modal analysis method. At the same time, a new set of harmonic resonance amplification index is derived and verified, and the harmonic content amplification times in the resonant influence region and different busbars are revealed. And then a passive filter is used to suppress harmonic resonance, and the effectiveness of the scheme is verified by field tests. The results show that, in the frequency range of 0–1000 Hz, the resonant frequency points in the oil field are mainly related to the rectifier pulse number of the drilling rig and the frequency conversion device for fracturing. The proposed fast modal analysis method has the advantages of fast convergence speed and memory saving, which is helpful to accurately detect the harmonic resonance region caused by the multi-pulse frequency conversion device, and the harmonic resonance can be effectively suppressed by installing a filter at the main excitation bus of the resonant frequency.

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I. INTRODUCTION

In recent years, with the use of a large number of electronic power equipment and the continuous expansion of distribution network, the harmonic resonance problem of oil distribution network is becoming more and more serious. In view of these harmonic resonance problems, domestic and foreign experts and scholars have carried out a series of research. In Ref. 9, modal analysis method is used to obtain various information of resonance when wind power plants are connected to the grid, which proves that the harmonic resonance modal analysis method is also applicable in distributed power grid. In Ref. 10, the harmonic resonance problem of multi-inverter system was analyzed. It was found by modal analysis that only some components had a great influence on the resonant mode. In literature, modal analysis method and virtual branch method are applied to combine circuit impedance matrix, virtual branch method and modal analysis method, and then the series harmonic resonance is analyzed, and a complete analysis result on harmonic resonance is obtained.

Under the condition of certain calculation accuracy, the rapid analysis method of harmonic resonant mode based on improved power iteration can effectively reduce the number of iterations required by adopting a new iteration starting vector selection method and iteration termination condition. Based on the harmonic electric distance, the harmonic transmission area and the corresponding amplification index are established. Compared with the existing harmonic resonance analysis methods, the main advantage of this index is that it can quantify the influence area and severity of harmonic resonance, and can carry out more types of sensitivity analysis. All of these have a broad application prospect in harmonic resonance monitoring and suppression of oil power grid.
II. COMPONENT LOAD MODELING FOR DISTRIBUTION NETWORK OF OIL FIELD

In order to analyze the harmonic resonance of oil grid, it is necessary to establish the internal component model of oil grid. The main components in the distribution network of oil field include transmission lines, transformers, fracturing pumps, etc.

A. Transmission line modeling

For the distribution network of oil field, the transmission line adopts π-type equivalent circuit, as shown in Fig. 1.

The harmonic reactance and susceptance corresponding to the line can be expressed as

\[
\begin{align*}
X_{lh} &= hX_L = \omega_0 hL, \\
B_{lh} &= hB_L = \omega_0 hC,
\end{align*}
\]

where, \(X_{lh}\) is the harmonic reactance value of the transmission line, \(L\) is the inductance value of the transmission line, \(B_{lh}\) is the harmonic susceptance value of the transmission line, \(C\) is the equivalent capacitance value of the transmission line to ground, and \(h\) is the number of different harmonics.

B. Transformer modeling

The double-winding transformer also uses π-type equivalent circuit to equivalent, and its equivalent circuit is shown in Fig. 2.

In Fig. 2, \(R_T + jX_T\) is the fundamental wave impedance of the transformer, and \(R_T\) and \(X_T\) are calculated as follows:

\[
\begin{align*}
R_T &= \frac{\Delta P_S}{1000} \frac{U_{SN}^2}{S_N}, \\
X_T &= \frac{U_i}{100} \frac{U_{SN}^2}{S_N},
\end{align*}
\]

where \(\Delta P_S\) is the short-circuit loss value of the distribution network transformer in oil field, \(U_{SN}\) is the rated voltage value of the distribution network transformer in oil field, \(S_N\) is the rated capacity value of the distribution network transformer in oil field, and \(U_i\) is the percentage of short-circuit voltage of the distribution network transformer in oil field.

The resistance and inductance of the transformer remain unchanged without skin effect, and its harmonic impedance is shown as follows:

\[
Z_{Th} = R_T + jhX_T,
\]

where \(Z_{Th}\) is the harmonic impedance of the transformer, and \(h\) is the harmonic frequency.

C. Modeling of electric fracturing pump

Compared with the first-order model, the third-order motor model considers the electromagnetic transient process, which is closely related to the change of electromagnetic power and can accurately reflect the change of load power. The third-order fracturing mathematical model in the \(d\theta\) coordinate system is shown in Eqs. (4)–(17),

\[
\begin{align*}
\dot{v}_{ds} &= R_s i_{ds} - \omega_0 \psi_{qr} + \frac{d\psi_{ds}}{dt}, \quad (4) \\
\dot{v}_{qs} &= R_s i_{qs} + \omega_0 \psi_{ds} + \frac{d\psi_{qs}}{dt}, \quad (5) \\
\dot{v}_{dr} &= R_r i_{dr} - (\omega_s - \omega_r) \psi_{qr} + \frac{d\psi_{dr}}{dt}, \quad (6) \\
\dot{v}_{qr} &= R_r i_{qr} + (\omega_s - \omega_r) \psi_{dr} + \frac{d\psi_{qr}}{dt}, \quad (7) \\
\psi_{ds} &= L_s i_{ds} + L_m i_{dr}, \quad (8) \\
\psi_{qs} &= L_s i_{qs} + L_m i_{dr}, \quad (9) \\
\psi_{dr} &= L_m i_{dr} + L_r i_{dr}, \quad (10) \\
\psi_{qr} &= L_m i_{qr} + L_r i_{qr}, \quad (11) \\
T_e &= 1.5 p (\psi_{ds} i_{ds} - \psi_{qs} i_{ds}), \quad (12) \\
\frac{d\omega_s}{dt} &= \frac{p}{2H} (T_e - T_L), \quad (13) \\
\frac{d\psi_{ds}}{dt} &= 0, \quad (14) \\
\frac{d\psi_{qs}}{dt} &= 0. \quad (15)
\end{align*}
\]
where \( R_s \) is the stator resistance; \( L_s \) is the stator inductance; and \( v_{qs} \) and \( i_{qs} \) are Q-axis stator voltage and current, respectively. \( v_{dr} \) and \( i_{dr} \) are the voltage and current of D-axis rotor, respectively. \( v_{qr} \) and \( i_{qr} \) are Q-axis rotor voltage and current, respectively. \( L_r \) is rotor inductance; \( R_r \) is rotor resistance; \( L_d \) is rotor inductance; \( \Psi_{qr} \) and \( \Psi_{dr} \) are the magnetic fluxes of stator \( q \) and \( d \) axis, respectively; and \( \Psi_{qr} \) and \( \Psi_{dr} \) are the magnetic fluxes of rotor \( q \) and \( d \) axis, respectively. \( \omega_s \) is rotor angular velocity; \( \omega_e \) is the stator angular velocity; \( p \) is polar logarithm; \( T_e \) is electromagnetic torque; \( T_m \) is mechanical torque; and \( H \) is the inertia constant.

### III. HARMONIC RESONANCE ANALYSIS OF DISTRIBUTION NETWORK OF OIL FIELD

#### A. Resonant fast modal analysis based on improved power iteration

1. **Modal analysis method**

Frequency scanning method is a common harmonic resonance analysis method in power system, but its scanning of resonant frequency points is not complete, and it cannot effectively analyze the resonant circuit and its key influencing factors, so it has certain limitations. In 2005, Xu proposed the modal analysis method, which uses the participation factor and other indicators to locate the resonant center, making up for the deficiency of the frequency scanning method and laying the foundation for the adoption of targeted suppression measures.\(^{10}\)

Write the node admittance matrix according to the topology of oil field power grid

\[
I_f = Y_f U_f. \tag{18}
\]

\( I_f \) is the column vector of the injected current at the node with frequency \( f \); \( Y_f \) is the node admittance matrix with frequency \( f \); and \( U_f \) is the node voltage column vector with frequency \( f \).

The eigenvalues of the node admittance matrix are obtained, and the node admittance matrix can be expressed as

\[
Y_f = RAR^{-1}. \tag{19}
\]

\( R \) is the right eigenvector matrix of \( Y_f \); and \( A \) is a diagonal matrix of eigenvalues.

The product of the left and right eigenvectors of the eigenvalue \( \lambda_i \) of the admittance matrix \( Y_f \) of the distribution network node is the participation factor of \( \lambda_i \),

\[
P = R_i L_i. \tag{20}
\]

\( P \) is the participation factor matrix, which reflects the influence of nodal injection current on nodal voltage under modal impedance.

2. **Fast power iteration method**

The eigenvalues of the node admittance matrix at the turning point between the two peaks of the key mode curve are relatively close, so the iterative convergence speed is slow and many iterations are required, which greatly increases the unnecessary computation.\(^{7}\)

These turning points are usually not frequency resonant points, so the termination iteration criterion of the traditional power iteration method can be improved to reduce the number of iterations. The selection of a reasonable starting vector also plays a crucial role in the iterative process. The improper selection of the initial vector may cause the slow convergence speed of the iteration and the large error of the calculation result, so the selection of the initial vector of the traditional power iteration method can also be improved.

- **a. Starting vector** In modal analysis, the step size is usually selected very small, so the admittance matrix of system nodes with two adjacent frequencies is very close. In this case, the maximum eigenvalue vector corresponding to the previous frequency can be set as the starting vector of the next frequency to avoid repeated similar calculation.

Due to the following equations:

\[
x^{(0)} = \sum_{i=1}^{n} a_i v_i, \tag{21}
\]

\[
x^{(k)} = A^k x^{(0)} = \sum_{i=1}^{n} a_i A^k v_i = \sum_{i=1}^{n} a_i A^k v_i = \lambda_1 a_1 v_1 + \sum_{i=1}^{n} \left( \frac{1}{\lambda_1} \right)^k a_i v_i. \tag{22}
\]

If the starting vector \( x^{(0)} \) is nearly orthogonal to \( v_1 \), the iteration result may be close to the eigenvalues and eigenvectors of the second or even higher order, and the threshold error can be estimated only when the threshold is very small. Therefore, the starting vector \( x^{(0)} \) and \( v_1 \) should be far away from the orthogonal state. At this time, the eigenvalues converge quickly, the threshold is small, and the error is small. Therefore, the iteration starting vector \( x^{(0)} \) of the initial frequency point is chosen as

\[
x^{(0)} = \frac{\sum_{j=1}^{n} Y_{i,j}}{\sum_{i=1}^{n} Y_{i,j}}. \tag{23}
\]

The elements in the starting vector \( x^{(0)} \) can be evenly distributed, so as to achieve the purpose of keeping the starting vector \( x^{(0)} \) away from the orthogonal state of \( v_1 \).

- **b. Terminates the iteration criterion.** In the iteration process, there needs to be a criterion to terminate the iteration; otherwise, the iteration process will go on indefinitely. Usually, there are two ways to stop the iteration. One is to set the threshold, and the calculation will stop when the number of iterations reaches the threshold. Because the number of iterations required for different frequency points varies greatly, if this method is applied, a very small threshold will lead to a large error in the calculation results, and a very large threshold will cause a lot of unnecessary calculations. Therefore, it is difficult to choose a reasonable threshold, and it is not suitable for large-scale applications.

The other method is to set a criterion for the accuracy of calculation results, and the calculation stops when the accuracy of
Because when the adjacent eigenvalues of the node admittance matrix are close in size, the corresponding frequencies are usually not resonant frequency points, it is not necessary to continue the iteration, and the local convergence rate is slow at this time. Therefore, the convergence speed $V(k)$ and convergence acceleration $a(k)$ are both termination iteration criteria, i.e.,

$$V(k) = \| y^{(k)} \|_{\infty} - \| y^{(k-1)} \|_{\infty} < \varepsilon,$$  

(24)

$$a(k) = V(k) - V^{(k-1)} < \delta.$$

(25)

When $V(k) < \varepsilon$, the convergence rate is small, or when $a(k) < \delta$, the convergence acceleration is small. In these cases, it is considered...
unnecessary to continue the iterative calculation, then the iteration is terminated.

3. Rapid analysis of resonant modes based on improved power iteration method

Based on the above analysis, the basic flow of rapid analysis of harmonic resonance modes of power system based on improved power iteration method is developed, as shown in Fig. 3.

Step 1: Starting from the first frequency point in the frequency range to be analyzed, the admittance matrix \( Y_f \) of the system node corresponding to the frequency point is calculated.

Step 2: Select the iteration starting vector \( x^{(0)} \). For the first frequency point, the initial iteration vector \( x^{(0)} \) was calculated according to Eq. (23), and the iteration count \( k = 1 \) was set.

Step 3: Calculate \( y^{(k)} = Y_f^{-1} x^{(k-1)} \);

Step 4: Calculate \( x^{(k)} = y^{(k)}/\|y^{(k)}\|_\infty \), including \( \|y^{(k)}\|_\infty \) is \( y^{(k)} \) largest element in the vector;

Step 5: \( V^{(k)} \) and \( a^{(k)} \) are calculated according to Eqs. (24) and (25), respectively;

Step 6: If \( V^{(k)} < \varepsilon \) or \( a^{(k)} < \delta \), terminate the iteration process and go to Step 5; otherwise, set \( k = k + 1 \) and go to Step 3;

Step 7: System at the frequency point maximum characteristic value of the node admittance matrix inverse matrix \( Y_f^{-1} |A_1| = \|y^{(k)}\|_\infty \), the corresponding eigenvectors is \( x^{(k)} \);

Step 8: Select the appropriate frequency interval, calculate the admittance matrix of the system node corresponding to the next frequency point, and select the feature vector corresponding to the maximum eigenvalue at the previous frequency point as the iteration starting vector \( x^{(0)} \), reset the iteration count \( k = 1 \), and repeat Steps 3–7.

In Table I, three harmonic resonance analyses determine the resonant frequency, the highest excited nodes, and observation nodes. The corresponding participation factor difference is very small, which based on the technology of adaptive frequency sweep resonance modal analysis, the simulation time is 2781.5 s, the simulation time the shortest, fully shows the adaptive frequency sweep algorithm to determine the resonant frequency efficiency.

### IV. HARMONIC RESONANCE AMPLIFICATION INDEX

#### A. Harmonic electrical distance

Electrical distance, usually used as a measure of electrical connectivity (or vice versa), has been applied to many problems in power systems, such as voltage control and structural network analysis. For a power system, there are many different ways to measure the electrical distance, the simplest of which is to take the absolute value of the elements of the inverse matrix of the admittance matrix of the power system nodes, as shown in the following equation:

\[
Z = |Y^{-1}| = |Z_{bus}|
\]  

where \( Y_{bus} \) is the admittance matrix of system nodes; \( Z_{bus} \) is the impedance matrix of system nodes; and \( |\cdot| \) refers to taking the absolute value of the matrix elements.

Considering the node admittance matrix of \( h \) order system, the harmonic electrical distance matrix obtained from the admittance matrix can be used to analyze the transmission law of harmonics in the power system. Suppose that unit \( h \) harmonic current \( I_h \) is injected into bus \( j \), and the harmonic voltage at each bus in the system is shown as follows:

\[
\begin{bmatrix}
U^1_n \\
\vdots \\
U^n_n
\end{bmatrix}
= \begin{bmatrix}
Z^1_{11} & \cdots & Z^1_{1j} & \cdots & Z^1_{1n} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
Z^n_{j1} & \cdots & Z^n_{jj} & \cdots & Z^n_{jn} \\
\vdots & \cdots & \cdots & \cdots & \cdots \\
Z^n_{nj} & \cdots & Z^n_{nn}
\end{bmatrix}
\begin{bmatrix}
I^1_i \\
\vdots \\
I^n_i
\end{bmatrix}
\]  

Thus, each element \( Z_{jj} \) in the harmonic electrical distance matrix \( Z \) reflects how sensitively the voltage at bus \( i \) changes with the current injection at bus \( j \) for a given bus pair.

#### B. Local resonant amplification index

In this subsection, two quantization indices are given for the local resonant state of the bus where the harmonic current source is located and the local resonant state of the bus where the harmonic voltage source is located.

For the bus \( j \) where the harmonic current source is located, after injecting the maximum allowable value of the \( h \) subharmonic

| TABLE I. Modal analysis results and simulation time of distribution network in an oil region. |
|-------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Harmonic resonance analysis method | Maximum impedance/Ω | Corresponding node | Resonant frequency f/Hz | Highest excited node | Highest observation node | Participation factor | Simulation time/s |
| Modal analysis method based on fixed step size sweep frequency | 140.4568 | 62 | 906.2 | 63 | 63 | 0.2044 | 9264.7 |
| Modal analysis method based on the golden section method | 140.4553 | 66 | 906.3 | 63 | 63 | 0.2045 | 3508.2 |
| Modal analysis method based on improved power iteration | 140.4568 | 62 | 906.2 | 63 | 63 | 0.2044 | 2781.5 |
current, the $h$ subharmonic voltage content can be calculated as follows:

$$HRU^h_{j} = \frac{\sqrt{3} \cdot Z^h_{jj} \cdot I^h_i}{10 \cdot U_N} = \frac{\sqrt{3} \cdot Z^h_{jj} \cdot I^h_i \cdot RI^h_{j \text{max}}}{10 \cdot U_N} \%,$$  \hspace{1cm} (28)

where $RI^h_{j \text{max}}$ is the maximum allowable injection content of harmonic current at bus $j \%$, $I_i$ is the maximum load demand current (A), and $U_N$ is the rated voltage at bus $j$ (kV). If $HRU^h_{j} > 1$, the harmonic voltage content at the harmonic source bus, or comparing the actual admittance at bus $j$ can be determined, respectively.

For the harmonic voltage source bus $j$, after applying the maximum allowable value of $h$ subharmonic voltage, the $h$ subharmonic current content can be calculated as follows:

$$HRI^h_{j} = \frac{10 \cdot U_N \cdot RU^h_{j \text{max}}}{\sqrt{3} \cdot I_L \cdot RI^h_{j \text{max}}} \%,$$  \hspace{1cm} (29)

where $RU^h_{j \text{max}}$ is the maximum allowable value of harmonic voltage content at bus $j$.

In fact, for the harmonic current source bus, according to Eq. (29), the maximum allowable value of the driving point $h$ harmonic impedance at bus $j$ can be calculated as follows:

$$Z^h_{j \text{max}} = \frac{10 \cdot U_N \cdot RU^h_{j \text{max}}}{\sqrt{3} \cdot I_L \cdot RI^h_{j \text{max}}}.$$  \hspace{1cm} (30)

Similarly, for the harmonic voltage source bus, according to Eq. (30), the maximum allowable value of $h$ harmonic admittance at the driving point of bus $j$ can be calculated as follows:

$$Y^h_{j \text{max}} = \frac{\sqrt{3} \cdot I_L \cdot RI^h_{j \text{max}}}{10 \cdot U_N \cdot RU^h_{j \text{max}}}.$$  \hspace{1cm} (31)

Using Eqs. (30) and (31), by comparing the actual driver point admittance and its maximum allowable value at the harmonic current source bus or comparing the actual driver point admittance and its maximum allowable value at the harmonic voltage source bus, the potential parallel resonance risk or series resonance risk at the bus $j$ can be determined, respectively.

C. Non-local resonant amplification index

1. Non-local parallel resonant amplification index

A method based on the harmonic electrical distance is used to predict the non-local harmonic resonance; however, this method can only give a qualitative judgment for the harmonic amplification region. This section will derive metrics that can specifically quantify the harmonic resonance amplification.

The unit $h$ harmonic current is injected at bus $j$, and the harmonic voltage of each node is shown in the following equation:

$$[U^h_i, \ldots, U^h_i, \ldots, U^h_i] \cdot [Z^h_{ij}, \ldots, Z^h_{ij}, \ldots, Z^h_{ij}]'.$$  \hspace{1cm} (32)

Indeed, the absolute value of $Z_{ij}$ is an effective way of measuring the electrical distance between two bus lines and can be used to reveal the sensitivity of the harmonic voltage on bus $i$ to the change of the injected harmonic current at bus $j$. According to Eq. (32), the amplification multiples of the voltage amplitude of the $h$ subharmonic at the bus $i$ of the anharmonic source to the voltage amplitude of the $h$ subharmonic at the bus $j$ of the harmonic source can be calculated as follows:

$$ARHV^h_{ij} = \frac{|U^h_{i}|}{|U^h_{j}|} = \frac{|Z^h_{ij}|}{|Z^h_{jj}|}.$$  \hspace{1cm} (33)

Here, $U^h_{i}$ and $U^h_{j}$ are the per-unit value of the $h$-subharmonic voltage at bus $i$ and bus $j$, respectively, $Z^h_{ij}$ is the per-unit value of the impedance between bus $i$ and bus $j$, and $Z^h_{jj}$ is the per-unit value of the impedance of the driving point at bus $j$.

At the same time, under the per-unit system, the amplification of the $h$-subharmonic voltage content at anharmonic source bus $i$ to the $h$-subharmonic voltage content at harmonic source bus $j$ can be calculated as follows:

$$ARV^h_{ij} = \frac{HVVD^h_{i}}{HVVD^h_{j}} = \left[ \frac{U^h_{i}}{U^h_{j}} \right] \left[ \frac{U^h_{j}}{U^h_{j}} \right] \left[ \frac{Z^h_{ij}}{Z^h_{jj}} \right].$$  \hspace{1cm} (34)

Among them, $ARV^h_{ij}$ is the amplification factor of the voltage content of the $h$ subharmonic at the bus $i$ of the non-harmonic source to the voltage content of the $h$ subharmonic at the bus $j$ of the harmonic source. $HVVD^h_{i}$ and $HVVD^h_{j}$ are, respectively, the harmonic voltage content at the harmonic source bus $j$ and the harmonic source bus $i$. $U^h_{i}$ and $U^h_{j}$ are the standard per-unit values of the fundamental voltage at bus $i$ and bus $j$, respectively. Since both $U^h_{i}$ and $U^h_{j}$ are approximately equal to 1, substituting Eq. (33) into Eq. (34), $ARV^h_{ij}$ can be further expressed as follows:

$$ARV^h_{ij} = \left[ \frac{U^h_{i}}{U^h_{j}} \right] \left[ \frac{U^h_{j}}{U^h_{j}} \right] \left[ \frac{Z^h_{ij}}{Z^h_{jj}} \right].$$  \hspace{1cm} (35)

The $ARV$ in Eq. (35) is defined in this paper as a non-local parallel resonant amplification index. If $ARV^h_{ij} > 1$, the harmonic voltage content at the anharmonic source bus $i$ is greater than the harmonic voltage content at the harmonic source bus $j$. If one or more anharmonic source buses satisfy this resonance condition, it means that a nonlocal parallel resonance has occurred.

2. Non-local series resonant amplification index

For harmonic voltage sources, such as background harmonic voltage, DC side capacitor filter rectifier, etc., consider the unit $h$ harmonic voltage applied to the harmonic voltage source bus $s$, resulting in harmonic current

$$I^h_{s} = 1/Z^h_{s}.$$  \hspace{1cm} (36)

Considering the branch $L_{ab}$ between bus $a$ and bus $b$, the $h$ harmonic voltages caused by this harmonic voltage source on bus $a$ and bus $b$ are, respectively,

$$U^h_{a} = Z^h_{ab} I^h_{s},$$  \hspace{1cm} (37)

$$U^h_{b} = Z^h_{bs} I^h_{s},$$  \hspace{1cm} (38)
Obviously, in the standard per-unit system, $U_a^h$ and $U_b^h$ can also be equated to the amplification of the H-subharmonic voltage content at bus $a$ and bus $b$ to the H-subharmonic voltage content at bus $s$ of the harmonic source.

In this way, the harmonic current in branch $L_{ab}$ can be expressed as follows:

$$I_{ab}^h = \frac{|U_a^h - U_b^h|}{Z_{ab}^h} = \frac{|Z_{ah}^h - Z_{bh}^h|}{Z_{ab}^h}.$$  \hspace{1cm} (39)

Then, the harmonic current in the branch $L_{ab}$ amplifies the current generated by the harmonic voltage source as follows:

$$ARC_{ab}^h = \frac{I_{ab}^h}{I_{ah}^h} = \frac{|Z_{ah}^h - Z_{bh}^h|}{Z_{ab}^h}.$$  \hspace{1cm} (40)

Therefore, in the standard per-unit system, similar to Eqs. (39) and (40), the harmonic current content in the branch $L_{ab}$ amplifies the harmonic current content generated by the harmonic voltage source by

$$ARC_{ab}^h = \frac{IHCD_{ab}^h}{IHCD_i} = \frac{|Z_{ah}^h - Z_{bh}^h|}{Z_{ab}^h}.$$  \hspace{1cm} (41)

Here, $IHCD_{ab}^h$ and $IHCD_i^h$ are the $h$ subharmonic current content on branch $L_{ab}$ and harmonic voltage source branches, respectively.

For the ground-to-ground $o$ parallel branch $L_{ao}$ at bus $a$, such as a parallel capacitor, its branch impedance is $Z_{o}^a$, and Eq. (41) can be re-expressed as

$$ARC_{ao}^h = \frac{IHCD_{ao}^h}{IHCD_i} = \frac{|Z_{o}^a - Z_{ah}^h|}{Z_{ab}^h}.$$  \hspace{1cm} (42)

where $IHCD_{ao}^h$ is the $h$ harmonic current content on the branch $L_{ao}$. At this point, the influence region and corresponding severity of harmonic voltage sources can be revealed by Eqs. (41) and (42). If $AVR_{ab}^h > 1$ or $AVR_{ao}^h > 1$, the harmonic current content on the branch $L_{ab}$ or branch $L_{ao}$ is greater than the harmonic current content at the busbar $s$ where the harmonic voltage source is injected. If one or more branches satisfy this resonance condition, it means that non-local series resonance has occurred.

V. SUPPRESSION OF HARMONIC RESONANCE EFFECT IN DISTRIBUTION NETWORK OF OIL FIELD

A. Passive filtering suppression

Considering the high voltage level of the on-load bus of the hydraulic fracturing pump platform, a monotone filter is selected to filter the inverter part of the hydraulic fracturing pump from the perspective of economy. The filtering principle is as follows: the passive filter is incorporated into the power grid. When the resonant frequency of the filter is the same as the harmonic frequency in the system, the impedance of the filter reaches the minimum value, and then almost all the harmonic current flows through the filter, thus achieving the filtering effect. The specific parameters of the filter can be adjusted as follows.

The reactive power compensation capacity of the single tuned filter is determined, then the capacitor capacity is

$$Q_C = \frac{h^2 - 1}{h^2} \cdot Q_F.$$  \hspace{1cm} (43)

The capacitive fundamental wave reactive reactance is

$$X_C = \frac{U^2}{Q_C}.$$  \hspace{1cm} (44)

The inductance base wave reactance is

$$X_L = \frac{X_C}{h^2}.$$  \hspace{1cm} (45)

The series resistance is

$$R = \frac{hX_L}{Q}.$$  \hspace{1cm} (46)

The configuration of passive filter to suppress harmonics in the power grid changes the topology of the network in essence, making the resonant frequency of the system deviate from the harmonic source frequency. Under certain conditions, when the passive filter and system parameters cooperate to produce a new parallel resonance, electrical equipment damage, and harm the safety of the grid. Therefore, it is necessary to obtain the admittance matrix of network nodes after the passive filter is configured and carry out modal analysis to optimize the parameters of the filter.

In practice, the passive filter is connected in parallel with the nodes in the network to filter out harmonics. Therefore, the admittance matrix of the network nodes after the filter is configured does not need to be re-formed. Only modification on the original network admittance matrix is needed to reduce the repetitive work.

For the $N$-node network, assuming that $M$ passive filters with different filtering frequencies are configured at node $i$, the equivalent admittance of the $m$th filter under the $h$ harmonic wave is

$$Y_{mh} = \frac{1}{R_{LM} + j(hX_L)_{m} - \frac{X_m}{h}}.$$  \hspace{1cm} (47)

where $R_{LM}$ is the fundamental wave resistance of the $m$th filter, and $X_L$ and $X_m$ are the fundamental wave induced reactance and capacitive reactance of the filter, respectively.

After the passive filter device is connected to the power grid, the admittance of nodes configured with the passive filter only needs to be modified on the original network admittance matrix. The node admittance matrix of the network changes from the original node admittance matrix $Y$ to $Y + \Delta Y$, wherein $\Delta Y$ is shown in the following equation:

$$\Delta Y = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ R_{LC1} + j(hX_L - \frac{X_m}{h}) & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ R_{LCM} + j(hX_L - \frac{X_m}{h}) & \cdots & 0 & 0 \end{bmatrix}.$$  \hspace{1cm} (48)

The position of the non-zero element in Eq. (48) is $\Delta Y_{ii}$. The proposed harmonic resonance node analysis method is used to analyze the distribution network of oil field, and the parallel
harmonic resonance frequency and the highest resonant excitation node are determined. A passive filter is configured at the node with the highest resonance excitation, and the improved mode analysis method of harmonic resonance in the distribution network is used to analyze the system configured with the passive filter, and the parameters of the passive filter are optimized. The configuration of passive filter can effectively inhibit the occurrence of harmonic resonance without harmonic amplification to achieve the purpose of harmonic resonance management in the distribution network.

The parameter optimization steps of the passive filter are as follows:

1. The improved mode analysis method of harmonic resonance of distribution network based on the adaptive frequency sweep technology is applied to analyze the power network, and the shunt harmonic resonant frequency and the highest resonant excitation node are determined, namely, the node where the passive filter needs to be installed.
2. Set initial filter capacity value \( Q_{L0} = 10 \text{ kvar} \) and capacity step size \( \Delta Q = 10 \text{ kvar} \).
3. Set the parameters of the filter, configure the passive filter at the highest resonant excitation node, and obtain the admittance matrix of the network node after configuring the passive filter.
4. The admittance matrix of the network nodes configured with passive filters is analyzed by the improved modal analysis method based on the adaptive frequency sweep technology, and the shunt harmonic resonant frequency and the highest resonant excitation node are determined.
5. When the harmonic source frequency is close to the resonant frequency of the system configured with passive filter, new harmonic harmonics will be triggered, causing harmonic resonance amplification. At this time, the parameter design of the filter is unreasonable and needs to be redesigned.
6. Increase the capacity of the filter, redesign the parameters of the filter, and repeat the above steps until the harmonic source frequency is no longer close to the resonant frequency of the system configured with passive filter.

The flow chart of parameter optimization design of passive filter is shown in Fig. 4.

**FIG. 4.** Design flow chart of passive filter parameter optimization.
B. Hybrid active power filter suppression

The injection branch of the Hybrid Active Power Filter (HAPF) shown in Fig. 5 effectively reduces the capacity of the DC capacitor and can be used as a new harmonic control device for the electric fracturing pump. However, the harmonic injection capacity depends on the injection capacitance. However, larger injection capacitors will not be compensated. There is no impedance in the improved injection branch of the parallel HAPF to compensate the harmonic current injection into the grid, which effectively improves its compensation ability and improves the attenuation effect of the injection branch on the harmonic current injection. Double resonance injection HAPF adds the double resonance injection branch, effectively reduces the voltage of the active part, and the active capacity is smaller, which is suitable for higher voltage levels and improves the application range of injection mixed APF.

VI. ANALYSIS OF EXAMPLES

The grid structure of an oil field is shown in Fig. 6. The 220 kV substation has two main transformers, all of which are three-winding transformers with a voltage class of 220/35/10 kV. The neutral point of the 35 kV side system is not grounded, that is, the medium voltage winding of the main transformer adopts the Yn type connection mode, and the main connection adopts the single busbar section mode. Two voltage transformers are connected to the two busbars of the 35 kV side system. One is a double-winding voltage transformer, which adopts star-grounded and open-triangle connection mode. The other one is a three-winding voltage transformer, which adopts star-star-open triangle connection mode. Each busbar has 5 cable outlets, and all of them are laid with double cables. The bus is also connected with shunt capacitors for reactive power compensation when the operating voltage of the system is low, shunt reactor for voltage stability, lightning arrester for protection against lightning overvoltage of the system and so on. The 35 kV II busbar side is also connected with a low-voltage double-winding transformer for the power plant.

The structure of the test system is shown in Fig. 7. The main circuit of the test system consists of the main circuit breaker, step-down transformer, cascaded H-bridge module, etc. The main circuit breaker connects the test system to the distribution network bus, and...
FIG. 7. The structure diagram of the impedance measurement system.

the relay protection device ensures that the circuit breaker can be disconnected when the system fails, so that the test system can be disconnected from the distribution network and the normal operation of the distribution network is not affected. Step-down transformer cascade H-bridge module is the key part of the test system, through the voltage control loop, AC current control loop, and harmonic control loop. The converter converts part of the fundamental power absorbed from the distribution network into harmonic power and instill harmonic current with adjustable frequency (100–5000 Hz) and amplitude (effective value of harmonic current <5 A) into the distribution network.

The control strategy of the cascade H-bridge module is implemented in the dual DSP + FPGA main control system. Since the optical fiber communication has the advantages of anti-electromagnetic interference and good transmission quality, the H-bridge module communicates with the main control system through optical fiber. RS485 communication is carried out between the host computer and the main control system. The primary function of the host computer is to store the test data and calculate the harmonic impedance. The voltage \( u \) and current \( i \) on the high voltage side of the transformer are measured by the high voltage divider and the current sensor, and the data are collected by the acquisition card. Then the host computer performs Fourier decomposition of the data to obtain the harmonic voltage and current injected at the harmonic frequency, and calculates the impedance at this frequency

\[
Z(f) = \frac{u(f)}{i(f)}. \tag{49}
\]

In addition, the host computer also undertakes the task of monitoring the running state of the system and displays the electrical waveform of the test system. The upper computer has a human–computer...
interaction interface, through which the parameters and running state of the main control system can be adjusted. The specific working principle of the test system is shown in Fig. 8. The harmonic amplitude $u_h$ of the voltage $u_c$ of the converter module (called the bridge voltage) follows the given value $u_{h\text{ref}}$ of the harmonic voltage through the harmonic control loop, and the output of the harmonic control loop is superimposed on the modulation wave. Through the modulation process of the converter module, the harmonic voltage at a given frequency appears in the bridge voltage. Thus, the corresponding frequency harmonic current appears in the distribution network, and the harmonic impedance of the distribution system can be calculated by the traction network $h$ harmonic voltage and $h$ harmonic current. The harmonic voltage given value is superimposed on the modulation wave, and the harmonic current given value is not directly superimposed on the current given value, which avoids the attenuation of the high-frequency signal by the current loop. By changing the frequency and amplitude of the given harmonic voltage, the frequency sweep process is completed, and the harmonic impedance of the distribution system in the frequency range of 100–5000 Hz is measured.

A. Example analysis of harmonic resonance in distribution network of oil field

Considering that the distribution network of oil field is in the frequency range of 0–1000 Hz, the mode analysis method is used to analyze the harmonic resonance problem inside the grid of oil field. At this time, HP31, HP36, and other fracturing systems are in normal operation, and the internal mode impedance scanning results are shown in Fig. 9.

Figure 9 shows that there are five resonant frequency points in the distribution network of this oil field in the frequency range of 0–1000 Hz, excluding the 54 Hz near the fundamental wave, which are 158, 246, 425, 532, and 573 Hz, respectively.

Due to the high harmonic content of the third, fifth, seventh, ninth, eleventh and thirteenth times, it is easy to cause serious harmonic distortion. According to the measured data of the harmonic source in oil field, at the 573 Hz resonant frequency point, the results of the eigenvectors (vector value greater than 0.1) of the main observation bus and the main excitation bus are shown in Table II, and the results of the participation factor (factor value greater than 0.09) are shown in Table III.

### Table II. Feature vectors of each bus at 573 Hz (the vector values are greater than 0.1).

<table>
<thead>
<tr>
<th>Bus bar</th>
<th>Voltage/kV</th>
<th>Eigenvector</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP36</td>
<td>35</td>
<td>0.3018 $\angle -178.95^\circ$</td>
</tr>
<tr>
<td>HP31</td>
<td>35</td>
<td>0.318 $\angle -178.95^\circ$</td>
</tr>
<tr>
<td>HP20</td>
<td>35</td>
<td>0.2981 $\angle -178.24^\circ$</td>
</tr>
<tr>
<td>HP12</td>
<td>35</td>
<td>0.2974 $\angle -178.45^\circ$</td>
</tr>
<tr>
<td>HP13</td>
<td>35</td>
<td>0.2974 $\angle -178.45^\circ$</td>
</tr>
<tr>
<td>HP19</td>
<td>35</td>
<td>0.2974 $\angle -178.45^\circ$</td>
</tr>
<tr>
<td>HP23</td>
<td>35</td>
<td>0.2974 $\angle -178.45^\circ$</td>
</tr>
<tr>
<td>205</td>
<td>10</td>
<td>0.2531 $\angle -177.29^\circ$</td>
</tr>
<tr>
<td>197</td>
<td>10</td>
<td>0.2528 $\angle -177.28^\circ$</td>
</tr>
<tr>
<td>194</td>
<td>10</td>
<td>0.2496 $\angle -177.78^\circ$</td>
</tr>
<tr>
<td>207</td>
<td>10</td>
<td>0.2495 $\angle -177.78^\circ$</td>
</tr>
<tr>
<td>195</td>
<td>10</td>
<td>0.2494 $\angle -177.78^\circ$</td>
</tr>
<tr>
<td>200</td>
<td>10</td>
<td>0.2492 $\angle -177.78^\circ$</td>
</tr>
</tbody>
</table>

### Table III. The main observation bus and excitation bus participation factors under 573 Hz (factor values are greater than 0.09).

<table>
<thead>
<tr>
<th>Observation of bus</th>
<th>Bus voltage observation value/kV</th>
<th>Incentive bus</th>
<th>Bus voltage excitation value/kV</th>
<th>Participation factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP36</td>
<td>35</td>
<td>HP36</td>
<td>35</td>
<td>0.0911 $\angle -2.10^\circ$</td>
</tr>
<tr>
<td>HP36</td>
<td>35</td>
<td>HP31</td>
<td>35</td>
<td>0.0911 $\angle -2.10^\circ$</td>
</tr>
<tr>
<td>HP20</td>
<td>35</td>
<td>HP31</td>
<td>35</td>
<td>0.0911 $\angle -2.10^\circ$</td>
</tr>
<tr>
<td>HP12</td>
<td>35</td>
<td>HP36</td>
<td>35</td>
<td>0.0911 $\angle -2.10^\circ$</td>
</tr>
<tr>
<td>HP9</td>
<td>35</td>
<td>HP31</td>
<td>35</td>
<td>0.0911 $\angle -2.10^\circ$</td>
</tr>
</tbody>
</table>

It can be seen from Table II that, in this resonant mode, the characteristic vector values of HP36 and HP31 are the largest, so the main observation bus is HP36 and HP31, and the dominant mode voltage at 573 Hz has the greatest influence on the resonant voltage. As can be seen from Table III, when the observed bus is HP36, HP31, HP20, and HP9, bus HP36 and bus HP31 are the main excitation bus at this resonant frequency point, and the harmonic current of their nodes is most likely to cause the resonance problem at this frequency.

In order to further avoid the occurrence of harmonic resonance, the resonant frequency points of different platforms in the distribution network of oil fields under the fracturing operation conditions were scanned.
The HP36 fracture was removed

The mode analysis method is used to analyze the harmonic resonance of the distribution network of the oil field after the removal of HP36 due to fault, and the frequency impedance characteristic curve is shown in Fig. 10.

As can be seen from Fig. 10, when the HP36 station fracturing is excised, there are three resonant frequency points in the frequency range of 0–1000 Hz, which are 158, 518, and 719 Hz, respectively. By comparing Figs. 4 and 5, it can be seen that the HP36 platform has a great influence on the 246, 425, 532, and 573 Hz resonant frequency points, and the above resonant frequency points disappear after the removal of HP36. Among the three resonant frequency points, new 518 and 719 Hz resonant frequency points appear in the remaining part of the distribution network of the oil field. The participating factors under the resonant frequency are analyzed, and the results are shown in Tables IV and V, respectively.

It can be seen from Table IV that the main excitation bus at the 518 Hz resonant frequency point is HP31, HP20, HP19, HP1, and HP23. The bus HP31 is the inlet bus of the fracturing station, and the bus HP20, HP19, and HP1 are the inlet bus of the drilling rig.

### Table IV. The main observation bus and excitation bus participation factors under 518 Hz (factor values are greater than 0.12).

<table>
<thead>
<tr>
<th>Observation bus</th>
<th>Bus voltage observation value/kV</th>
<th>Incentive bus</th>
<th>Bus voltage excitation value/kV</th>
<th>Participation factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP31</td>
<td>35</td>
<td>HP31</td>
<td>35</td>
<td>0.1293 &lt; -2.75°</td>
</tr>
<tr>
<td>HP20</td>
<td>35</td>
<td>HP31</td>
<td>35</td>
<td>0.1293 &lt; -2.75°</td>
</tr>
<tr>
<td>HP20</td>
<td>35</td>
<td>HP20</td>
<td>35</td>
<td>0.1293 &lt; -2.75°</td>
</tr>
<tr>
<td>HP31</td>
<td>35</td>
<td>HP19</td>
<td>35</td>
<td>0.1293 &lt; -2.75°</td>
</tr>
<tr>
<td>HP20</td>
<td>35</td>
<td>HP19</td>
<td>35</td>
<td>0.1293 &lt; -2.75°</td>
</tr>
<tr>
<td>HP20</td>
<td>35</td>
<td>HP1</td>
<td>35</td>
<td>0.1293 &lt; -2.75°</td>
</tr>
<tr>
<td>HP23</td>
<td>35</td>
<td>HP20</td>
<td>35</td>
<td>0.1293 &lt; -4.04°</td>
</tr>
<tr>
<td>HP23</td>
<td>35</td>
<td>HP31</td>
<td>35</td>
<td>0.1293 &lt; -4.04°</td>
</tr>
<tr>
<td>HP23</td>
<td>35</td>
<td>HP19</td>
<td>35</td>
<td>0.1293 &lt; -4.04°</td>
</tr>
<tr>
<td>HP23</td>
<td>35</td>
<td>HP1</td>
<td>35</td>
<td>0.1293 &lt; -4.04°</td>
</tr>
<tr>
<td>HP23</td>
<td>35</td>
<td>HP23</td>
<td>35</td>
<td>0.1293 &lt; -4.32°</td>
</tr>
</tbody>
</table>

### Table V. The main observation bus and excitation bus participation factors under 719 Hz (factor values are greater than 0.11).

<table>
<thead>
<tr>
<th>Observation bus</th>
<th>Bus voltage observation value/kV</th>
<th>Incentive bus</th>
<th>Bus voltage excitation value/kV</th>
<th>Participation factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP31</td>
<td>35</td>
<td>HP31</td>
<td>35</td>
<td>0.1183 &lt; -2.75°</td>
</tr>
<tr>
<td>HP18</td>
<td>35</td>
<td>HP18</td>
<td>35</td>
<td>0.1183 &lt; -2.75°</td>
</tr>
<tr>
<td>HP18</td>
<td>35</td>
<td>HP19</td>
<td>35</td>
<td>0.1183 &lt; -2.75°</td>
</tr>
<tr>
<td>HP31</td>
<td>35</td>
<td>HP19</td>
<td>35</td>
<td>0.1183 &lt; -2.75°</td>
</tr>
<tr>
<td>HP18</td>
<td>35</td>
<td>HP1</td>
<td>35</td>
<td>0.1183 &lt; -2.75°</td>
</tr>
<tr>
<td>HP18</td>
<td>35</td>
<td>HP19</td>
<td>35</td>
<td>0.1183 &lt; -2.75°</td>
</tr>
<tr>
<td>HP19</td>
<td>35</td>
<td>HP1</td>
<td>35</td>
<td>0.1183 &lt; -2.75°</td>
</tr>
<tr>
<td>HP19</td>
<td>35</td>
<td>HP19</td>
<td>35</td>
<td>0.1183 &lt; -2.75°</td>
</tr>
<tr>
<td>HP19</td>
<td>35</td>
<td>HP1</td>
<td>35</td>
<td>0.1183 &lt; -2.75°</td>
</tr>
<tr>
<td>HP9</td>
<td>35</td>
<td>HP18</td>
<td>35</td>
<td>0.1183 &lt; -3.04°</td>
</tr>
<tr>
<td>HP9</td>
<td>35</td>
<td>HP31</td>
<td>35</td>
<td>0.1183 &lt; -3.04°</td>
</tr>
<tr>
<td>HP9</td>
<td>35</td>
<td>HP19</td>
<td>35</td>
<td>0.1183 &lt; -3.04°</td>
</tr>
<tr>
<td>HP9</td>
<td>35</td>
<td>HP1</td>
<td>35</td>
<td>0.1183 &lt; -3.04°</td>
</tr>
<tr>
<td>HP9</td>
<td>35</td>
<td>HP9</td>
<td>35</td>
<td>0.1183 &lt; -3.32°</td>
</tr>
</tbody>
</table>
They are all connected to the platform HP23 through the transmission line, indicating that the resonant frequency point has an impact on the HP31 fracturing station and the HP20, HP19, HP1, and HP23 drilling stations.

It can be seen from Table V that the main excitation bus at the 719 Hz resonant frequency point is HP31, HP18, HP19, HP1, and HP9, which indicates that the influence area of this resonant frequency point is involved in the HP31 fracturing station and the HP18, HP19, HP1, and HP9 drilling stations.

2. Removal of HP31 fracturing

The HP31 platform fracturing pump was removed due to the fault, and the harmonic resonance analysis was carried out on the distribution network of the oil field. The frequency impedance characteristic curve is shown in Fig. 11.

As can be seen from Fig. 11, when the fracturing of HP31 station is removed, there are still five resonant frequency points of 158, 246, 425, 532 and 573 Hz in the frequency range of 0–1000 Hz in the remaining part of the distribution network of the oil field. Compared with the time when the fracture was not removed, the resonant frequency point changed little, which was less affected by the HP31 platform fracturing pump.

B. Harmonic amplification severity evaluation

1. Only harmonic sources at busbar HP3 are considered

The electrical distance between the harmonic source busbar HP3 and other busbars is shown in Fig. 12(a). The resonant amplification index ARV of all other busbars relative to the harmonic source busbar 3 is shown in Fig. 12(b). In frequency bands with ARV greater than 1, non-local parallel resonance amplification occurs. For example, for the 11th harmonic at busbar HP3, non-local harmonic amplification occurs at busbar HP1, HP2, HP4, HP5, HP7, and HP9, while the 25th harmonic will be amplified at busbar HP1, HP2, and HP5, thus leading to a higher voltage content of single harmonic than that at busbar 3 of the harmonic source and conforming to the corresponding amplification factor. The calculation results of harmonic power flow are shown in Fig. 13, and the amplification factor of each harmonic voltage content is consistent with the corresponding index in Fig. 12(b).

Therefore, the index proposed in this chapter can effectively and intuitively reveal the influence region of harmonic resonance in power system and the corresponding amplification times, and can get quantitative results.

2. Only harmonic sources at bus HP8 are considered

The electrical distance between harmonic source busbar HP8 and other busbars is shown in Fig. 14(a). The resonance amplification index ARV of other busbars relative to the harmonic source busbar HP8 is shown in Fig. 14(b). Since ARVs in the 5–30 pu frequency band are all less than 1, non-local resonant amplification will not occur. Therefore, the single harmonic voltage content in the 5–30 pu frequency band at the busbar HP8 caused by this harmonic source is higher than that at other busbars, as shown in Fig. 15.

![FIG. 13. Harmonic voltage distortion on all busbars caused by harmonic sources at busbar HP3.](image-url)

![FIG. 12. The electrical distance (a) and the harmonic resonance amplification index ARV (b) between the harmonic source busbar HP3 and all busbars.](image-url)
Therefore, the proposed index can predict whether non-local resonance will occur, which is very helpful for finding harmonic suppression schemes, such as efficient configuration of filters. For the harmonic source busbar HP8, because there is no non-local amplification, so only need to install a suitable filter at the busbar HP8. However, for the harmonic source bus HP3, because the harmonic transmission is not limited to the local area, not only the bus HP3 but also other busbars that may have resonance amplification may need filters. In theory, harmonic filters can provide a low-impedance transmission path for specific harmonics. However, in practical applications, for many reasons, no filter can achieve 100% filtering performance, such as (1) due to manufacturing errors and material characteristics affected by temperature, aging, harmonic filter R, L, and C components of the parameter error; (2) impedance and frequency changes of the power supply system, and (3) load fluctuations of each system bus. Therefore, in addition to the filter on the harmonic source bus, additional evaluation is needed to install the filter on the bus where there is a load sensitive to harmonic pollution. It is worth noting that harmonic filter planning is a system-level problem, not a bus-level problem. In addition to achieving maximum harmonic suppression in the system, harmonic filter optimization strategies also need to consider optimizing the size and/or cost of the filter, or reducing the degree of harmonic distortion on the busbars that are sensitive to harmonic pollution. Therefore, although the method in this chapter can be used to analyze the bus-level resonant amplification and provide a preliminary arrangement of harmonic filters based on the results, in specific applications, further analysis at the system level is needed to effectively arrange the filters according to the desired objectives.

C. Example analysis of harmonic resonance suppression in distribution network of oil field

In view of the high voltage level of the loaded bus of the fracturing pump platform, the monotone filter is selected to filter the frequency converter part of the fracturing pump from the perspective of economy. A single tuning filter is installed on the nodes of the resonant excitation bus platform determined in the harmonic resonance analysis method. The optimal configuration method of passive filter is used to suppress the harmonic resonance of the distribution network of oil field including the electric fracturing pump. The optimal configuration parameters of the single tuning filter are shown in Table VI.

FIG. 15. The harmonic voltage distortion on all bus lines caused by the harmonic source at bus HP8.

**FIG. 14.** The electrical distance (a) and the harmonic resonance amplification index ARV (b) between the harmonic source busbar HP8 and all busbars.

**TABLE VI.** Single tuned filter optimization configuration parameters.

<table>
<thead>
<tr>
<th>Node</th>
<th>Filter frequency/Hz</th>
<th>Capacity of filter/kvar</th>
<th>Quality factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP36</td>
<td>573</td>
<td>550</td>
<td>30</td>
</tr>
<tr>
<td>Nominal voltage/kV</td>
<td>0.005891</td>
<td>10.90413</td>
<td>0.032076</td>
</tr>
</tbody>
</table>
The bus current spectrum analysis results after adding the configured single tuning filter are shown in Fig. 17.

After testing and analysis, it can be seen from the comparison of Figs. 16 and 17 that the distortion rate of the 5th, 7th, 9th, 11th, and 13th harmonics in the platform bus current decreases by 7.5%, 4.8%, 5.7%, 4.9%, and 3.8%, respectively. The HP36 platform of the distribution network of this oil field is configured with a single tuned filter as shown in Table VI. The impedance frequency characteristic curve of this node before and after adding the optimized configured filter is shown in Fig. 18.

The solid line in Fig. 18 represents the impedance frequency characteristic curve of HP36 nodes without filter, and the dotted line represents the impedance frequency characteristic curve of nodes with filter added. The abscissa represents the frequency and the ordinate represents the amplitude of the harmonic impedance. It can be seen from the figure that after adding the optimized configuration...
filter, the node impedance value decreases significantly at the resonant frequency without causing harmonic amplification. The specific harmonic resonance analysis results before and after adding the optimized configuration filter are shown in Table VII.

Table VII shows that the impedance of this node at 573 Hz, 423.225 Ω, is small compared to the impedance of this node before filtering, which is 4720 Ω, after adding the optimally configured filter. It indicates that the filter configuration scheme in Table V can effectively suppress the occurrence of harmonic resonance in the distribution network of oil field with fracturing pump.

VII. CONCLUSION

In this paper, the mathematical model of the internal components of the oilfield distribution network considering the characteristics of the electric fracturing pump is established, and the main methods of harmonic resonance analysis are introduced. According to the different operating conditions of an oilfield in China, the fast mode analysis method is used to analyze the problem, and the conclusions are as follows:

(a) Under the condition of certain calculation accuracy, the rapid analysis method of harmonic resonant mode based on improved power iteration can effectively reduce the number of iterations required by adopting a new iteration starting vector selection method and iteration termination condition. By improving the calculation step selection method, the unnecessary calculation amount was further reduced, and the calculation time was reduced by 15.6%.

(b) Based on the harmonic electric distance, the harmonic transmission area and the corresponding amplification index are established. Compared with the existing harmonic resonance analysis methods, the main advantage of this index is that it can quantify the influence area and severity of harmonic resonance, and can carry out more types of sensitivity analysis.

(c) The field test shows that the resonant high-frequency frequency points of the oilfield distribution network are mainly generated by the frequency conversion device. The resonant frequency points are suppressed by adding filters at the main excitation bus of the resonant frequency, and the corresponding node impedance is reduced by 91%, without changing the control mode of power electronic equipment.

TABLE VII. Harmonic resonance analysis results of node DP36 before and after adding the filter.

<table>
<thead>
<tr>
<th>Frequency/Hz</th>
<th>Node</th>
<th>Node impedance/Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before filtering</td>
<td>573</td>
<td>DP36</td>
</tr>
<tr>
<td>After filtering</td>
<td>573</td>
<td>DP36</td>
</tr>
</tbody>
</table>

![FIG. 18. Impedance frequency characteristic curve of node HP36 before and after adding the filter in oil distribution network considering electric fracturing pumps.](image)

REFERENCES


AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Na Liu: Conceptualization (equal); Data curation (equal); Formal analysis (equal). Bin Zhang: Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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