Research on harmonic suppression ability of active power filter

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Abstract. The system control model of double resonance injection hybrid active power filter (DIHAPF) and mathematical model of voltage source inverter with controller was established based on the structure and operating principle of DIHAPF. The injection branch features were analyzed including the static reactive power compensation capability and dividing capability of harmonic voltages. Stability and harmonic suppression capacity of DIHAPF was analyzed simultaneously. The influence of the parallel resonant circuit resonant frequency to system performance was discussed in detail. Furthermore, the method of designing the resonant frequency of parallel resonant circuit was proposed. The simulation model of DIHAPF was established and simulated on PSIM 6.0 taking nonlinear loads as harmonic current sources. A 6kV DIHAPF experiment prototype controlled by TMS320F28335 was built. Simulation and experimental results prove the validity of the analysis in this paper.

1. Introduction

With the development of power electronics technology, the proportion of non-linear load in the power grid is increasing day by day, and the harmonic pollution in the power grid is getting more and more serious [1-4]. This brings direct and indirect losses to power grid enterprises and power users, and also causes energy waste. In order to ensure the safe and stable operation of the power grid, protect the users’ electrical equipment and save power and energy, it is imminent to control the harmonic of the power grid [5-7]. The active power filter is an important method of harmonic control. Among them, the injection hybrid active power filter (IHAPF) has the ability of harmonic suppression and large-capacity reactive power static compensation, taking into account the passive filter and the advantages of active filters [8-10]. In order to improve the application range of the hybrid active power filter and improve the compensation performance, a new double resonance injection branch is proposed in paper [11]. The characteristics of the double resonance injection hybrid active power filter (DIHAPF) and its application in power grid are discussed in paper [12]. DIHAPF has become the new harmonic control device for medium and high voltage power systems.

In the existing literature of DIHAPF characteristic analysis, the inverter is regarded as the voltage source or the current source for controlling the current control, and the output voltage or current is proportional to the control current. Based on this, the model is established and analyzed [13-14]. This model simplifies the influence of control links and inverters on the characteristics of the model and...
can not fully reflect the influence of the controller on the system characteristics. Therefore, the detailed DIHAPF model of the controller and its characteristics need further study.

Based on the analysis of structure and working principle of DIHAPF, a mathematical model of voltage source inverter containing controller is established, and then a DIHAPF mathematical model is established. The injection branch characteristics, system stability and harmonic compensation characteristics of DIHAPF are analyzed. The influence of resonant frequency of parallel resonant branch on the system performance is emphatically discussed, and the design method of resonant frequency is put forward. The results of simulation and experiment prove the correctness of this analysis.

2. DIHAPF model and working principle

Double resonance active power filter DIHAPF topology shown in Figure 1. In the figure, C1, L1, C2, L2 constitute the injection branch. C1 and L1 form a series resonant branch, resonating at the fundamental frequency. C2, L2 constitute a parallel resonant branch.

By simplifying the DIHAPF, treating the non-linear load as a harmonic current source and controlling the active part of the DIHAPF as a voltage source, the single-phase equivalent circuit of the double resonance injection hybrid system in the harmonic domain is shown in Figure 2. Ush is the harmonic voltage of the power grid, ZS is the harmonic impedance of the power grid, ILh is the harmonic current of the load, Zc is the injection impedance, Zf is the impedance of the fundamental resonance branch, and ZO is the impedance of the smoothing reactor.

According to the equivalent circuit diagram, the following equations can be obtained from Kirchhoff’s voltage and current law.

\[ U_{sh} = Z_sh I_{sh} + Z_c I_c + Z_f I_f \]  

(1)
Solve the simultaneous equations above, eliminating $I_c$, $I_1$, $I_2$ and $I_p$. According to load harmonic current control mode, the active part output voltage is controlled to $K$ times of load harmonic voltage, and then

$$I_{sh} = \frac{(n^2Z_o + Z_t)U_{sh} + k_t I_{th}}{n^2Z_o(Z_c + Z_t) + Z_t(Z_c + Z_t + n^2Z_o)}$$  \hspace{1cm} (5)

Where $k_t = n^2Z_oZ_t + n^2Z_oZ_c + Z_tZ_c - nKZ_t$

When the DIHAPF active part output voltage is considered only, the system equivalent circuit is shown in Figure 3.

**Figure 3.** Single-phase equivalent circuit taking the output voltage of active part as the only source

From Figure 3, the following equation is obtained.

$$I_c = \frac{nZ_t}{(Z_c + Z_t)Z_t + n^2Z_c(Z_c + Z_t + Z_t)} U_c$$  \hspace{1cm} (6)

Considering the voltage source inverter, and in accordance with the load harmonic current control mode, DIHAPF system control model shown in Figure 4.

**Figure 4.** Control mode of DIHAPF

Assuming that the transfer function of the inverter output voltage $U_c$ and the harmonic current $I_c$ injected into the power grid by the active filter is $G_{out}$, and then

$$G_{out} = \frac{nZ_t}{(Z_c + Z_t)Z_t + n^2Z_c(Z_c + Z_t + Z_t)}$$  \hspace{1cm} (7)

As seen in Figure 4.

$$U_c = G_{out}(s)G_c(s)(-I_{th} - I_{sh})$$  \hspace{1cm} (8)

$$I_{sh} = G_{out}(s)U_c$$  \hspace{1cm} (9)

The mathematical model of the voltage-source inverter is derived from Eqs. (8) and (9).
3. Analysis of DIHAPF characteristics

3.1. Injection branch characteristics
The injection branch consists of an injection section and a fundamental series resonance circuit (FSRC). The active part of the active filter is connected in parallel with the fundamental series resonant branch via the coupling transformer. Therefore, the capacity of the active part is determined by the voltage division capacity of the fundamental series resonant branch and the output current capacity of the inverter. The partial pressure of the fundamental series resonant branch is mainly composed of two parts, which are the partial pressure of the power grid on the FSRC and the harmonic voltage of the injection branch near the tuning frequency.

The impedance of the IHAPF injection branch can be expressed as

\[ Z_1 = R_{11} + j(\omega L_{11} - \frac{1}{\omega C_{11}} - \frac{1}{\omega C_{12}}) \]  
\[ \text{(11)} \]

\[ Z_2 = [R_{21} + \frac{R_{22}}{k_2}] + j(\omega L_{21} - \frac{1}{\omega C_{21}} + k_3) \]  
\[ \text{(12)} \]

Where \( k_2 = (1 - \omega^2 L_{22} C_{22})^2 - \omega^2 C_{22}^2 R_{22}^2 \) and \( k_3 = \frac{1 - \omega^2 L_{22} C_{22}}{(1 - \omega^2 L_{22} C_{22})^2 - \omega^2 C_{22}^2 R_{22}^2} \).

The Matlab7.0 simulation software is used to simulate the IHAPF injection structure and the DIHAPF injection structure. The system simulation parameters are shown in Table 1.

| Parameter                                | IHAPF  | DIHAPF |
|------------------------------------------|--------|--------|
| Reactance of fundamental series resonant branch | 14.58 mH | 14.58 mH |
| Capacitance of the fundamental series resonant branch | 690 uF  | 690 uF  |
| Internal resistance of reactance of fundamental series resonant branch | 0.1 ohm | 0.1 ohm |
| Capacitance of the injection part         | 36 uF  | 50 uF  |
| Reactance of the injection part           | --     | 167.47 mH |
| Internal resistance of reactance of injection part | --     | 0.1 ohm |

The impedance characteristics of the two structures and the frequency amplification of the series resonant branch voltage are analyzed respectively. The simulation results are shown in Figure 5.

3.2. Analysis of reactive power and static power
It can be seen from Figure 5(a) that the impedance of the IHAPF injection branch is capacitive and gradually decreases until it reaches zero when the frequency is less than the resonance frequency. When the frequency is greater than the resonance frequency, the impedance of the injection branch is inductive and gradually increasing. The impedance of DIHAPF injection branch changes suddenly at the resonance point. When the frequency is lower than the resonance frequency, the impedance is capacitive and gradually increasing. When the frequency is greater than the resonance frequency, the impedance is inductive and gradually decreasing. At the fundamental frequency, the injection branch impedances of IHAPF and DIHAPF are both capacitive and have reactive static compensation capability. At each frequency point after the resonance point, the DIHAPF injection branch impedance is greater than that of IHAPF. Because the impedance characteristics of the fundamental series
resonant branch are the same, the partial pressure characteristic of the DIHAPF fundamental series resonant branch is better, which effectively reduces the withstand voltage of the active part. At the same time, due to the existence of the parallel inductance, which can control the reactive power of the parallel branch injection system and avoid the reactive power compensation of the system.

![Image](image_url)

**Figure 5.** Impedance characteristics of injection branch: (a) injection branch impedance and (b) partial pressure ratio of fundamental wave resonance branch

3.3. Analysis of harmonic partial pressure characteristics

The voltage division capability of the fundamental series resonant branch affects the active capacity of the hybrid active power filter. The harmonic partial pressure characteristics of the FRSC are analyzed by the ratio of the impedance of the fundamental series resonant branch and the total impedance of the injected branch. The fundamental and harmonic partial pressure data of the two kinds of implanted structural fundamental wave series resonant branches are shown in Table 2.

|        | IHAPF | DIHAPF |
|--------|-------|--------|
| Fundamental | 0.20  | 0.04   |
| 3th    | 200.16 | 31.84  |
| 5th    | 120.01 | 61.68  |
| 7th    | 109.09 | 76.93  |
| 11th   | 103.45 | 89.48  |
| 13th   | 102.44 | 92.28  |

Table 2. The voltage ratio of fundamental series resonance branch(%)
From Figure 1(b) and Table 2, it is known that the fundamental voltage of single implanted APF injection branch is 0.2%, however, the harmonic voltage of the second order and above is amplified and larger than the corresponding harmonic voltage of the power grid. The fundamental voltage of double resonance injection APF series resonant branch is 0.04%, and the harmonic voltages are lower than the corresponding harmonic voltage of the power grid, the operating voltage of the active part is reduced, and then the active capacity of the DIHAPF is reduced.

3.4. DIHAPF stability and harmonic rejection characteristics

Ignoring the harmonic voltage of the power grid, only considering the influence of the load harmonic current, the harmonic suppression function of DIHAPF can be obtained as

\[
G_h = \frac{l_{bh}}{l_{ab}} = \frac{n^2 Z_{f1} + n^2 Z_{r1} + Z_{r2} - nKZ_{p}}{n^2 Z_{f1}(Z_{f1} + Z_r) + Z_{f1}(Z_{f1} + Z_r + n^2Z_{p})}
\]

For convenience of discussion, the effect of system delay on stability is not considered, the open-loop transfer function of DIHAPF system is

\[
G_o = \frac{[n^2 Z_{f1}(Z_{f1} + Z_r) - Z_{f1} - nKZ_{p}]Z_p}{n^2 Z_{f1}k - Z_{r1}(Z_{f1} + Z_{p})}
\]

Where \( k = (Z_{f1} + Z_p)Z_{r1} + (Z_{f1} + Z_r + Z_{r1})Z_{p} \)

Suppose the system characteristic equation is

\[
[b_1 \ b_2 \ ... \ b_n] [s^7 \ s^6 \ ... \ s^0]^T = 0
\]

The simplified DIHAPF system is a linear, stationary system. The necessary and sufficient condition for the stability of a linear stationary system is that the eigenvalues of the system lie in the left half of the complex plane. Therefore, whether the DIHAPF system is stable or not is judged according to whether the eigenvalues of the open-loop transfer function of the DIHAPF system are all located in the left half plane of the s domain. DIHAPF described in this article is a high-level system, the stability of the system can be based on the symbols of the first row of the Routh-table parameter to determine system stability.

When the resonant frequency of parallel branch is 42 Hz, 44 Hz and 48 Hz respectively, the value of the first column of the Routh table of the characteristic equation of the DIHAPF system is shown in Table 3.

According to the Routh criterion, it is known that the DIHAPF system is stable at the three resonant frequencies.

When the frequency is less than the resonant frequency, the total impedance of the parallel resonant circuit is inductive; greater than the resonant frequency, was capacitive. DIHAPF has a certain capacity of capacitive reactive power static compensation, and the resonant frequency of the parallel resonant branch should be less than the fundamental frequency.

Table 3. Rolls table under different resonance frequencies

| Fr=42Hz | Fr=44Hz | Fr=48Hz |
|---------|---------|---------|
| s^7     | 8.262e-23 | 8.262e-23 | 8.262e-23 |
| s^6     | 8.265e-18 | 8.265e-18 | 8.265e-18 |
| s^5     | 2.715e-16 | 2.724e-16 | 2.715e-16 |
| s^4     | 1.108e-11 | 8.113e-11 | 2.594e-11 |
| s^3     | 1.146e-9  | 8.421e-10 | 2.782e-10 |
| s^2     | 1.348e-5  | 9.814e-6  | 3.006e-6  |
| s^1     | 2.1e-6    | 2.1e-6    | 2.1e-6    |
| s^0     | 2.1e-6    | 2.1e-6    | 2.1e-6    |
The static reactive power compensation ability of the injected branch is guaranteed, and simultaneously, the influence of the resonant frequency of the parallel resonant branch on the system stability is analyzed. The parallel branch parameters are calculated at the resonant frequency of 42Hz, 44Hz and 48Hz respectively. The open loop transfer function of the system is analyzed by Matlab, and the Potter diagram is shown in Figure 6.

![Bode plot of DIHAPF](image)

**Figure 6.** Open-loop Bode plot of DIHAPF as fr=42 Hz, 44 Hz, 48 Hz

It can be seen from Figure 6 that the phase angle curve of the DIHAPF system has three points of abrupt change. The first point of abrupt change is caused by the parallel resonant branch, the frequency is 299 rad / sec, the second point of abrupt change is caused by the fundamental series resonance branch. The third mutation frequency is the resonant frequency of the injection branch. When the resonant frequency of the parallel branch is 42 Hz, 44 Hz and 48 Hz respectively, the resonant frequency of the injected branch is 4 260 rad/sec, 3 680 rad/sec and 2 070 rad/sec. After the phase angle is stable, the phase-frequency curve gradually increases and gradually approaches -180°. Maintaining the other parameters unchanged and guaranteeing the static reactive power compensation ability of the fundamental, simultaneously, when the resonance frequency of parallel branch is 42Hz, 44Hz and 48Hz, respectively, the phase margin of open-loop transfer function of DIHAPF system is 107.93°, 106.21° and 103.44°, respectively. As a result, when the resonant frequency is larger, the stability of DIHAPF is poor. With the decrease of the resonant frequency of the parallel branch, the system angle margin increases and the stability is improved.

The influence of the resonant frequency of the parallel resonant branch on the harmonic suppression ability is analyzed. While keeping the other parameters unchanged, as well as guaranteeing the static reactive power compensation ability of the fundamental, the parameters of the parallel resonant branch are adjusted to resonate at 42Hz, 44Hz and 48Hz, respectively, and the influence on the harmonic suppression capability of DIHAPF is shown in Figure 7.

It can be seen from Figure 7 that the gain of DIHAPF in the main harmonic frequency band is approximately -58.4dB, -62.7dB and -73.3dB, respectively, when the resonance frequency of parallel resonant branch is 42Hz, 44Hz and 48Hz, respectively. It shows that the harmonic suppression ability of DIHAPF system is poor when the resonance frequency is small, and the harmonic suppression ability of DIHAPF system increases with the increase of resonance frequency.
3.5. Selection of resonant frequency of parallel branch
By analyzing the stability and harmonic filtering ability of DIHAPF, the resonant frequency of parallel branch must be less than the fundamental frequency to ensure the static reactive power compensation capability of DIHAPF system. When the harmonic frequency is less than the fundamental frequency, the resonant frequency is smaller. The better the system stability, the worse the harmonic suppression; the greater the resonance frequency, the better the system harmonic suppression, and the worse the system stability. Therefore, when designing the DIHAPF system parameters, the system stability and harmonic control effects need to be considered synthetically. The proper resonant frequency should be chosen so that the DIHAPF system can balance the stability and harmonic control effects.

In this paper, the resonant frequency of 44Hz is selected. Under this parameter, the phase margin of DIHAPF system is 106.21°, and the gain of the main harmonic frequency is about -62.7dB.

4. Simulation and experimental research
In order to verify the correctness of the above analysis and the comprehensive compensation effect of DIHAPF structure, according to the structure and principle of DIHAPF, the software PSIM6.0 is used for simulation. The harmonic is generated by the equivalent nonlinear load of the harmonic current source [15]. The DIHAPF system parameters are determined according to the harmonic control and reactive power compensation requirements of a steel plant. The simulation model is powered by three-phase AC power supply. The power grid model consists of voltage source, grid impedance, transformer and transmission line. The load consists of load impedance and random harmonic current sources. Among them, the grid parameters are as follows: the three-phase power line voltage is 35kV, the frequency is 50Hz, the equivalent impedance of the grid is 0.05mH and the internal resistance is 0.001Ω. The harmonic source parameters are as follows: the 5th harmonic current is 28A, the 7th harmonic current is 13.6A, the 11th harmonic current is 8.3A, the 13th harmonic current is 6A, and the 17th harmonic current is 3.7A. The DIHAPF parameters are as follows: output inductance 0.2mH, internal resistance 0.005Ω; fundamental series resonant branch inductance 14.58mH, internal resistance 0.1Ω, capacitance 690uF; parallel resonant branch inductance 109.03mH, internal resistance 0.1Ω, capacitance 120uF; coupling transformer voltage ratio of 2:1; inverter by the three-phase rectifier bridge power supply. Simulation results are shown in Figure 8, where IL is the
load current; $I_s$ is the grid current; $I_{ch}$ is the current injected into the grid by DIHAPF; $U_c$ is the inverter output voltage.

![Simulation result](image)

**Figure 8.** Simulation result: (a) simulation waveforms and (b) spectrum

| The order of harmonic current | Before put into operation/A | After put into operation/A |
|------------------------------|----------------------------|---------------------------|
| 5                            | 27.52                      | 1.21                      |
| 7                            | 13.51                      | 0.58                      |
| 11                           | 8.17                       | 0.48                      |
| 13                           | 5.95                       | 0.44                      |
| 17                           | 3.54                       | 0.34                      |
From the simulation Figure 8, it can be seen that the harmonic current of the load flows directly into the power grid before DIHAPF input, causing serious harmonic pollution. After the operation of DIHAPF, the harmonic currents in the power grid are greatly reduced, and the harmonic pollution is effectively controlled. Harmonic current data before and after system input is shown in Table 4.

In order to further verify the characteristics of the dual-resonant injection hybrid active power filter, an experimental prototype for 6kV distribution network was developed in the laboratory. The active part of DIHAPF selects Mitsubishi IGBT-IPM series module PM300CLA120 to form a three-phase inverter bridge. The DC side capacitor is composed of four 10000uF electrolytic capacitors by two in series and two in series. System controller using TMS320F28335 digital DSP control program. The output filter is installed to filter the high-frequency switching harmonics generated by the inverter, the inductance of 0.2mH is selected in this paper. The fundamental series resonant branch has an inductance of 14.57mH and a capacitance of 690uF. The parallel resonant branch inductance is 25.31mH with a capacitance of 400uF. The ratio of the coupling transformer is 2. The oscilloscope is used to obtain the current waveform before and after the DIHAPF prototype is put into operation, as shown in Figure 9.

**Figure 9.** Waveform of grid current before and after operating prototype: (a) the Phase A phase current waveform of the grid before the DIHAPF unit is put into operation, and (b) the Phase A phase current waveform of the grid after the DIHAPF unit is put into operation.
5. Conclusion
Through the analysis of DIHAPF characteristics and simulation experiments, we get the following conclusions:

(i) At the fundamental frequency, the impedance of DIHAPF injection branch is greater than the impedance of IHAPF injection branch. The fundamental voltage series resonant branch voltage dividing characteristics are good and the active part withstand voltage is reduced effectively, so that DIHAPF active capacity is smaller, and suitable for higher voltage levels. Moreover, shunt reactor can control the system into the reactive power to avoid reactive over-compensation.

(ii) When the resonant frequency of the parallel branch is determined, the stability of the given system and harmonic suppression become contradictory. In the design of DIHAPF system parameters, this paper presents a resonant frequency design method considering system stability and harmonic control effects.

(iii) Simulation and experimental results show that the DIHAPF system has good stability and harmonic governance ability, and verifies the correctness of the analysis.

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