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# DC-BUS VOLTAGE STABILIZATION OF HYBRID ACTIVE POWER FILTER

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Abstract. *This paper presents a new DC-bus voltage stabilization method of the Hybrid Active Power Filter (HAPF). First, the cause of DC-bus voltage change on HAPF system was analysed. On this basis, a method of stabilizing the DC-bus voltage using a Boost converter has been proposed. Compared to the DC-bus control method using a release circuit for the Hybrid Active Power Filters, the simulation results demonstrate that the proposed method has better results in reducing voltage ripple on the DC-bus, compensation error and total harmonic distortion of the supply current in steady-state. Especially, this method is able to stabilize the DC bus voltage when the load changes.*

**Keywords:** Hybrid active power filter, Boost converter, DC-bus voltage, Harmonic voltage

## 1. Introduction.

Hybrid Active Power Filter (HAPF) shows great promise in reducing hermonics and improving the power factor with a relatively low capacity active power filter [1,2]. In particular, DC-bus voltage stability is one of the factors that directly affect the performance and stability of the HAPF system. Therefore, the study DC-bus voltage stability is an important factor contributing to improving the efficiency of HAPF. There are currently a number of research papers on DC-bus voltage stabilization, but mainly on traditional Active Power Filter (APF) rather than on HAPF and may be listed as follows.

The first is to use a Proportional Integral Derivative (PID) controller to stabilize the DC-bus voltage for the APF. However, the overvoltage of the DC-bus is quite large [3]. Studies [4-9] provide a method of stabilizing the DC-bus voltage using a Proportional Integral (PI)-fuzzy controller applied in a three-phase four-wire shunt active filter; simulation results show that the PI-fuzzy controller produces better results when using the traditional PI controller in cancelling harmonics and improving power factor. However, the transient time is still great. A new DC-bus voltage stabilization study for APF has been proposed using the Pole-Zero placement method, which has the advantage of a smaller DC-bus voltage ripple and a shorter transient time when using the PI controller [10,11]. Another method used to stabilize the DC-bus voltage for a shunt three-phase four-wire APF is the adaptive control method [12]; the floating point of this method is parameters vary according to the error between the reference DC-bus and the actual DC-bus voltages. Research [13] provides an algorithm for adjusting the DC-bus voltage for a three-phase four-wire shunt active filter by dividing the DC capacitor into the same series capacitors. This algorithm mainly regulates the voltages on each capacitor based on the calculation of the phase current with the source voltage at the fundamental frequency to maintain

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the DC-bus voltage at the reference value. Studies [14,15] use hybrid fuzzy logic controllers to stabilize DC-bus voltage. This method has demonstrated superior advantages over traditional PI controllers under variable operating conditions, including the transient period as well as in the steady-state. A DC-bus voltage stabilization study for HAPF was proposed using a release circuit for very good results. However, the study did not consider the change of load [16].

In short, all these above studies focus only on DC-bus voltage stability for APF and review of case load has not changed. This paper presents a new method of stabilizing the DC-bus voltage for HAPF based on the Boost converter to maintain the DC-bus voltage for the APF. Compared to the DC-bus voltage stabilization method using a release circuit [16], simulation results demonstrate that the proposed method is also effective in reducing the DC-bus voltage ripple, Total Harmonic Distortion (THD) and compensation error in steady-state and the ability to stabilize the DC-bus voltage whenever there is a load change.

The structure of this paper is divided into 5 parts: Part 1 is an introduction to the research topic, Part 2 is to analyse the cause of changing the DC-bus voltage in HAPF system, the DC-bus voltage stabilization method is given in Part 3, Part 4 shows simulation results and the conclusions are given in Part 5.

2. **Causes of Changing the DC-Bus Voltage in HAPF System.** The structure of HAPF is expressed as in Figure 1. $U_s$ and $Z_s$ are the source voltage and impedance of the source. $C_1$ and $L_1$ are capacitance and inductance at the fundamental frequency. $C_F$ is the added capacitance to filter harmonics and reactive power compensation, $L_0$, $C_0$ is the output filter of the voltage source inverter.

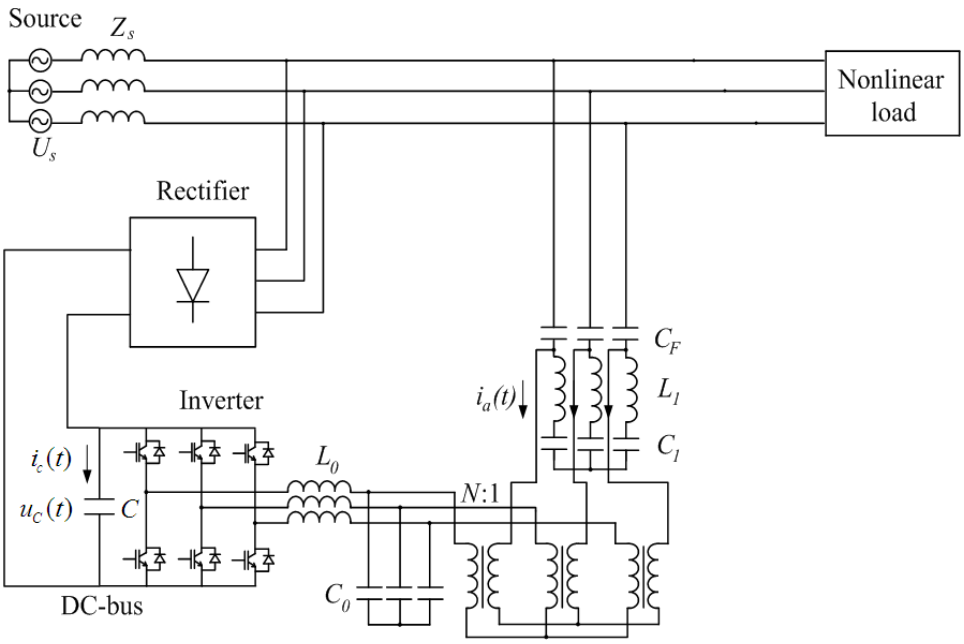


FIGURE 1. Structure of HAPF

According to Figure 1, we have that the power at the secondary side of the transformer is referred to as the primary side (power on the AC side of the voltage source inverter):

$$p_1(t) = \frac{R}{N^2}\left[i_a^2(t) + i_b^2(t) + i_c^2(t)\right] + \frac{1}{2N^2}L\frac{d}{dt}\left[i_a^2(t) + i_b^2(t) + i_c^2(t)\right] \tag{1}$$

where $i_a(t)$, $i_b(t)$ and $i_c(t)$ are the currents on the primary side of the transformer.

The power on the DC side of the voltage source inverter is

$$p_2(t) = u_C(t) \cdot i_C(t) \tag{2}$$

where $u_C(t)$ is the DC-bus voltage and $i_C(t)$ is the current through the DC-bus.

According to the principle of power balance, to make DC-bus voltage stable, the following condition must be ensured:

$$p_1(t) = p_2(t) \tag{3}$$

Based on the structure of HAPF, $p_1(t)$ is written as follows:

$$p_1(t) = \frac{R}{N^2}\left[i_{ah}^2(t) + i_{bh}^2(t) + i_{ch}^2(t)\right] + \frac{1}{2N^2}L\frac{d}{dt}\left[i_{ah}^2(t) + i_{bh}^2(t) + i_{ch}^2(t)\right] \tag{4}$$

where $i_{ah}(t)$, $i_{bh}(t)$ and $i_{ch}(t)$ are the harmonic current components of the $i_a(t)$, $i_b(t)$ and $i_c(t)$.

When the harmonic components $i_{ah}(t)$, $i_{bh}(t)$ and $i_{ch}(t)$ change, it will put on the AC-side of the inverter through the transformer, resulting in the voltage on the DC-bus changing. According to [16], there are two main reasons for the change in the DC-bus voltage, which is due to sag voltage and non-linear load. In this paper, we consider the source is ideal. Nonlinear loads will produce harmonic voltages put on the APF. Suppose the voltage applied to the fundamental resonant circuit is $u_{shn}$ and the AC-side output voltage of the inverter is $u_{ahn}$. If the transformation ratio of matching transformer is 1:1, we can replace the circuit from the output of the fundamental resonant circuit to the output of the inverter by an inductance $L_\Sigma$.

We have

$$u_{shn} = U_{shn}\sin(n\omega t) \tag{5}$$

and

$$u_{ahn} = U_{ahn}\sin(n\omega t - \theta_n) \tag{6}$$

where $\theta_n$ is phase angle between $u_{shn}$ and $u_{ahn}$.

The equivalent voltage of the output inductor includes the output loop inductor and the transformer equivalent leakage inductor:

$$U_{L_\Sigma} = n\omega L_\Sigma \cdot i_{L_\Sigma} \tag{7}$$

or

$$L_\Sigma \frac{di_{L_\Sigma}}{dt} = u_{shn} - u_{ahn} \tag{8}$$

From (5) to (8), we can deduce

$$i_{L_\Sigma} = \frac{1}{n\omega L_\Sigma}\left[U_{shn}\sin(n\omega t) - U_{ahn}\sin(n\omega t - \theta_n)\right] \tag{9}$$

So, the average harmonic active power flowing into APF can be expressed as

$$P_{hn} = \frac{1}{T}\int_0^T u_{shn} \cdot i_{L_\Sigma} dt \tag{10}$$

Substituting (5) and (9) into (10), we have

$$P_{hn} = \frac{U_{shn}.U_{ahn}.\sin\theta_n}{2n\omega L_\Sigma} \tag{11}$$

From (11), we can see that: if $0^\circ < \theta_n < 180^\circ$ then $P_{hn} > 0$, and the active power of the $n^{\text{th}}$ harmonic transmits to the AC-side from DC-side of the inverter, and as a result, the DC bus voltage will increase. If $-180^\circ < \theta_n < 0^\circ$ then $P_{hn} < 0$, and the active power of the $n^{\text{th}}$ harmonic transmits to the DC-side from AC-side of the inverter and as a result, the DC bus voltage will drop.

**3. Proposed DC-Bus Voltage Stabilization Method.** According to these above analyses, the DC-bus voltage is unstable when working with nonlinear loads. This paper presents a new method of stabilizing the DC-bus voltage using a Boost converter. The structure of the proposed method is shown in Figure 2.

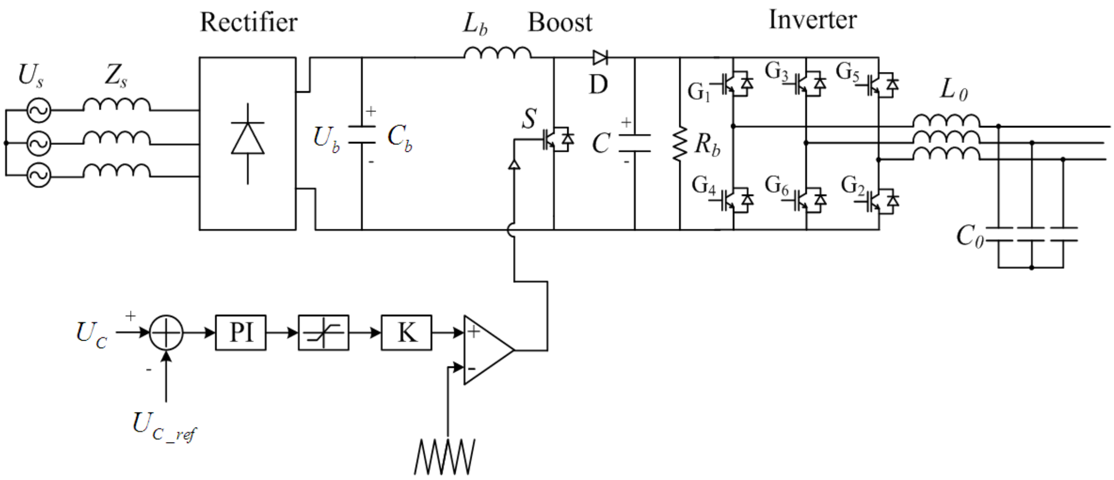


FIGURE 2. Proposed DC-bus voltage stabilization method

Three-phase balanced power supply through the three-phase unbalanced bridge rectifier to generate the DC voltage $U_b$, this voltage oscillates from 1.5 to 1.73 times the amplitude of the source voltage. To reduce the voltage and current variations, we add a capacitor $C_b$ and inductance $L_b$ at the output of rectifier. The voltage across the capacitor $C_b$ is the input voltage of the Boost converter. After passing the Boost converter, a DC voltage will be generated (voltage on the $C$ capacitor). It is greater than the voltage on the $C_b$ capacitor and with an output voltage ripple very small. In order to stabilize the voltage on the $C$ capacitor, we must control the $S$ switch to always keep a fixed voltage at the DC-bus. According to the analysis in Part 2, if $0° < \theta_n < 180°$ then the power is transferred from the AC-side to the DC-side of the inverter, the voltage across the DC-bus is greater than the reference value, then the $S$ switch will close, the energy on the capacitor will be discharged through $R_b$ and the voltage on capacitor $C$ is reduced. If the voltage on the capacitor $C$ is less than the reference value, then switch $S$ will open. At this point, the capacitor $C$ will be charged from the Boost circuit.

The parameters calculation of the control diagram in Figure 2 is based on the Boost converter theory. The relationship between the input voltage and the output voltage of the Boost converter is

$$U_C = \frac{U_{C_b}}{1-D} \tag{12}$$

where $D$ is duty ratio ($0 < D < 1$).

The value of $L_b$ is calculated by the following formula

$$L_{b\_\min} = \frac{D(1-D)^2 R}{2f} \tag{13}$$

where $f$ is switching frequency (Hz).

In practice, $L_b$ is usually chosen as: $L_b = (1.1 \div 1.3)L_{b\_\min}$.

The value of DC-bus capacitor is

$$C \geq \frac{D}{Rf\frac{\Delta U_C}{U_C}} \tag{14}$$

where $\frac{\Delta U_C}{U_C}$ is the output voltage ripple (voltage ripple on DC-bus), and this value is usually less than or equal to 1%.

4. **Simulation Results and Discussion.** To demonstrate the effectiveness of the proposed method with the release circuit method in [16], simulation results were performed on a HAPF model with parameters as shown in Table 1.

Table 1. Parameters of HAPF

| $U_s$ (V) | $f$ (Hz) | $C_F$ ($\mu$F) | $C_1$ ($\mu$F) | $L_1$ (mH) | $C_0$ ($\mu$F) | $L_0$ (mH) | $C$ ($\mu$F) |
|---|---|---|---|---|---|---|---|
| 220 | 50 | 120 | 349.2 | 29.77 | 690 | 0.2 | 10000 |

Research [16] uses a three-phase uncontrolled bridge rectifier coupled with a release circuit through a resistor $R = 1.5\Omega$. Parameters of the PI controller are $K_p = 10$ and $K_i = 0.1$. The simulation results of the method in the study [16] are shown in Figure 3. $i_L$, $i_s$, *error* and $U_C$ are the load current, supply current, compensation error and DC-bus voltage, respectively.

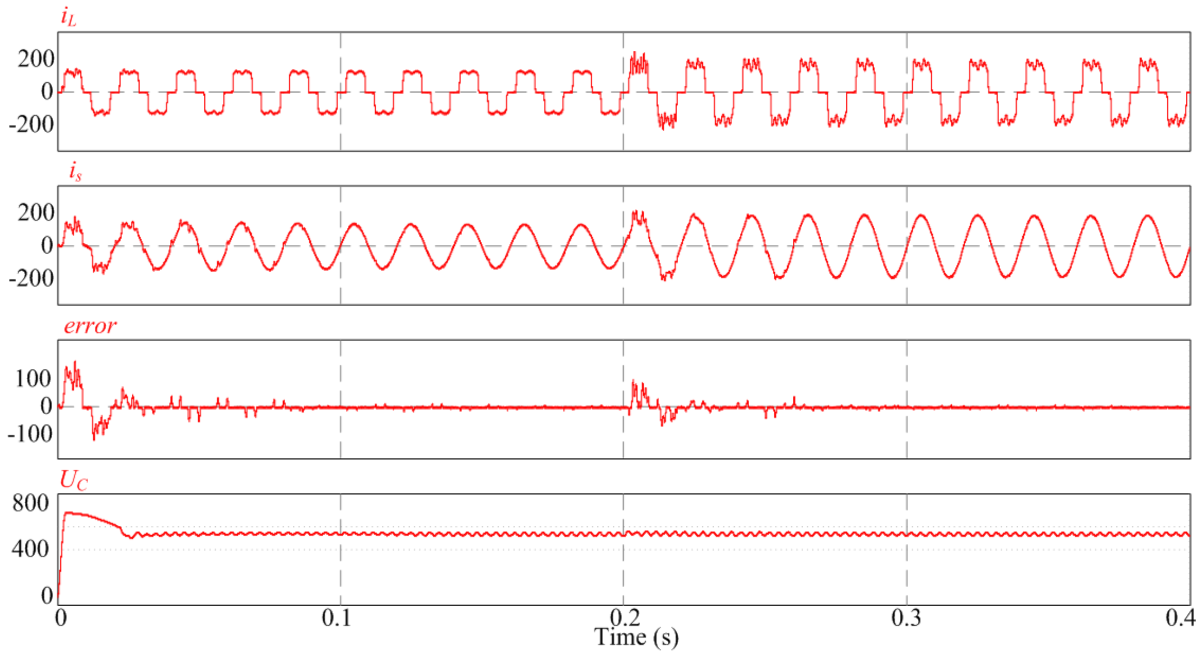


Figure 3. Simulation results with the method in study [16]

Simulation results with the proposed method are shown as in Figure 4. The parameters of the model are shown in Table 2. Parameters of the PI controller are $K_p = 10$ and $K_i = 0.1$.

From the simulation results shown in Figure 3 and Figure 4, we can see that: before the load is changed, the DC-bus voltage is kept constant at 535 volts. When the load is changed, the DC-bus voltage is also kept constant at 535 volts. However, with the method in the study [16], the voltage on DC-bus has a greater oscillation (from 1.5 to 1.73 times amplitude of supply voltage) whereas with the proposed method, the voltage ripple on DC-bus is very small leading to the compensaton error and THD$i_s$ also smaller. The summary table of the values: the voltage ripple on the DC-bus, the THD of the load current $i_L$, the THD of the source current $i_s$ and the compensation error of the two methods are described in Table 3.

From the results obtained in Table 3, we can see that the proposed method is more efficient than method in study [16] in reducing the voltage ripple on DC-bus, THD of the current source and compensation error.

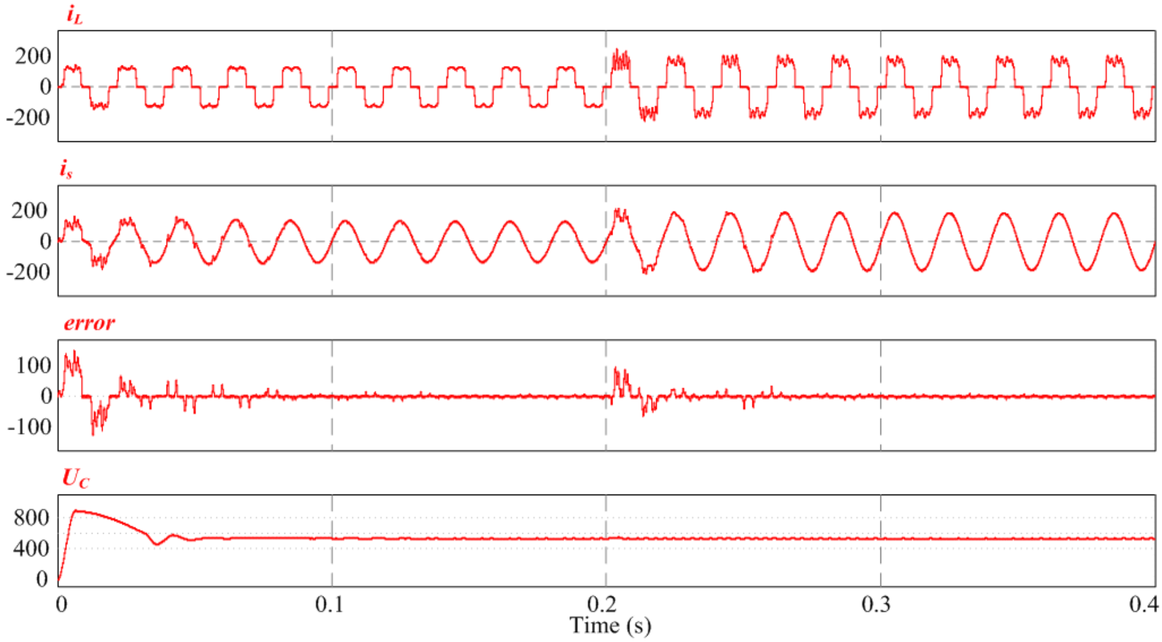


FIGURE 4. Simulation results with the proposed method

TABLE 2. Parameters of HAPF with the proposed method

| $U_s$ (V) | $f$ (Hz) | $C_F$ ($\mu$F) | $C_1$ ($\mu$F) | $L_1$ (mH) | $C_0$ ($\mu$F) | $L_0$ (mH) | $C$ ($\mu$F) | $C_b$ ($\mu$F) | $L_b$ (mH) | $R_b$ ($\Omega$) |
|---|---|---|---|---|---|---|---|---|---|---|
| 220 | 50 | 120 | 349.2 | 29.77 | 690 | 0.2 | 10000 | 3 | 4 | 1.5 |

TABLE 3. Summary table of the values of the proposed method and method in [16]

| Methods | Before the load is changed | | | | After the load is changed | | | |
|---|---|---|---|---|---|---|---|---|
| | $\Delta U_C/U_C$ | THD$i_L$ | THD$i_s$ | *Error* | $\Delta U_c/U_c$ | THD$i_L$ | THD$i_s$ | *Error* |
| [16] | 5% | 28.06% | 1.31% | ±10 A | 5.49% | 30% | 1.69% | ±10 A |
| Proposed | 1.0% | 28.06% | 1.08% | ±5 A | 1.01% | 30% | 1.26% | ±5 A |

5. **Conclusion.** This paper proposed a new DC-bus voltage stabilization method for HAPF. This method is a combination of a three-phase uncontrolled rectifier and a Boost converter. The advantage of this new method over the release circuit method is the ability to stabilize the DC-bus voltage with an output voltage ripply very small even when the load changes. This leads to the compensation error and THD$i_s$ are also very small. However, when the load changes with a large range, the parameters of the Boost converter is no longer accurate, resulting in low efficiency. Thus the future research trend of the paper is to use a three-phase pulse-width modulation rectifier to replace the three-phase uncontrolled rectifier and the DC-DC Boost converter.

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