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An Advanced Current Control Strategy Using $\mathbf{I}_d - \mathbf{I}_q$ Controlled Technique for Three-Phase Shunt Active Filters

S. Vignesh,
PG Scholar,
Dept of Electrical & Electronics Engineering,
Sri Ramakrishna Engineering College,
Coimbatore,

K. Sebasthirani,
Assistant Professor (SL.G),
Dept of Electrical & Electronics Engineering,
Sri Ramakrishna Engineering College,
Coimbatore,

Abstract

This paper presents detailed analysis to compare and promote the performance of two control schemes for extracting reference currents of shunt active power filter under unbalanced voltage condition by using PI controller. An instantaneous active and reactive current component (id-iq) method and an instantaneous active and reactive power (p-q) method are two control schemes which are widely used in active filters. A shunt active power filter based on the instantaneous active and reactive current component method is proposed. This method purposes to compensate harmonic and first harmonic unbalance. Two methods are completely frequency independent. The simulations are carried out with PI controller for the control strategies for different voltage condition. Under unbalanced voltage condition it is found that the instantaneous active and reactive current component has a better harmonic compensation performance

Index Terms*—Shunt Active power filter, id-iq control method, p-q control method and PI controller*

1. Introduction

The presence of harmonics in the power system cause greater power loss in distribution, interference problem in communication system and, sometimes results in operation failure of electronic equipment's which are more and more sensitive because it contains microelectronic controller systems, which work with very low energy levels. It is noted that non-sinusoidal current results in many problems for the utility power supply company, such as low energy efficiency, low power factor, electromagnetic interference (EMI), distortion of line voltage etc. Active filters have been extensively studied and a large number of the works have been published. Shunt active power filters compensate load current harmonics by injecting equal-but opposite harmonic compensating current. The series active filter injects a voltage component in series with the supply voltage and therefore can be regarded as a controlled voltage source, compensating voltage sag and swell on the load side. Till now many control strategies have been developed but instantaneous active and reactive current (*id-iq*) component method and instantaneous active and reactive power (*p-q*) method are more popular methods. This paper mainly concentrates on these two control strategies (*id-iq* and *p-q*) with PI controller. Both methods are compared under distorted main voltage condition and it is found that *id-iq* control method achieve superior harmonic compensation performance. The *id-iq* control is based on a synchronous rotating frame derived from the mains voltages without the use of a phase-locked loop(PLL).By the id-iq control method many synchronization problems are avoided and a truly frequency-independent filter is achieved.

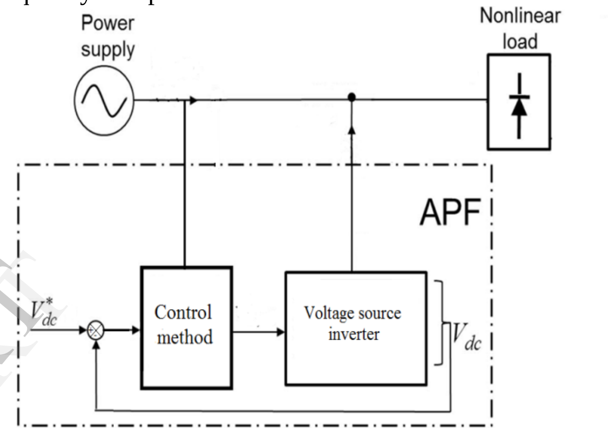

Figure 1.Shunt active power filter block diagram

2. An Instantaneous Active and Reactive Power (P-Q) Method

The p-q theory, or was developed by *Akagi et al* in 1983, with the objective of applying it to the control of active power filters Akagi et al proposed a theory based on instantaneous values in three phase power system with or without neutral wire, and is valid for steady-state or transient operations, as well as for generic voltage and current waveforms called as Instantaneous Power Theory or Active-Reactive (*p-q*) theory which consists of a Clarke transformation of the three-phase voltages in the *a-b-c* coordinates to the *α-β-0* coordinates. The theory is based on a transformation from the phase reference system 1-2-3 to the 0-α-β system.

The transformation matrix associated as follows:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} \quad (2)$$

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$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

Where v_1 v_2 v_3 and i_1 i_2 i_3 are phase voltage and currents. From equation (1) and (2) it can be deduced that

$$i_N = i_1 + i_2 + i_3 = i_0\sqrt{3} \quad (4)$$

The power terms are defined as follows:

$$\begin{bmatrix} p_0 \\ p_{\alpha\beta} \\ q_{\alpha\beta} \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (5)$$

Where p_0 is the zero sequence real instantaneous power
$p_{\alpha\beta}$- is the α-β instantaneous real power
$q_{\alpha\beta}$- is the α-β instantaneous imaginary power

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_0 v_{\alpha\beta}^2} \begin{bmatrix} v_{\alpha\beta} & 0 & 0 \\ 0 & v_0 v_\alpha & -v_0 v_\beta \\ 0 & v_0 v_\beta & v_0 v_\alpha \end{bmatrix} \begin{bmatrix} p_0 \\ p_{\alpha\beta} \\ q_{\alpha\beta} \end{bmatrix} (6)$$

Where $v_{\alpha\beta}^{\ 2} = v_\alpha^{\ 2} + v_\beta^{\ 2}$

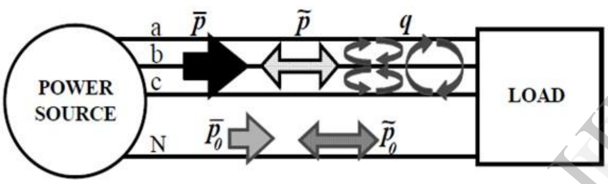

Figure 2.Power components of the p-q theory in a-b-c coordinate

The active filter currents ic_i are obtained from the instantaneous active and reactive powers p_l and q_l of the nonlinear load. This is achieved by calculation of the main voltages v_i and the nonlinear load currents il_i in a stationary reference frame, that is in α-β component by (1) and (2).A null value is assumed for the zero component voltage . Due to the absence of neutral wire a null value is considered for the zero current components. So as a result equation will be:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} il_1 \\ il_2 \\ il_3 \end{bmatrix} \quad (8)$$

Power compensated by active filter is given in figure 2.

The instantaneous active and reactive load powers *pl* and *ql* are given by eq. (5)

$$\begin{bmatrix} p_l \\ q_l \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix} \quad (9)$$

This equation can be decomposed into oscillatory and average terms

$$p_l = \tilde{p}_l + P_l \ \text{ and } \ q_l = \tilde{q}_l + Q_l$$

$\tilde{p}_l$ and $\tilde{q}_l$ are oscillatory terms and P_l *and* Q_l are average terms

- Under balanced and sinusoidal condition the average power component can be related to the first harmonic current of the positive sequence$il_{1h}^{\ +}$.
- The oscillatory components represent all higher order harmonics including negative sequence of the first harmonic current,$il_{nh}^{\ +} + il_{1h}^{\ -}$.
- Thus, the oscillatory power should be compensated by active power filter so that the average power components remain in the mains and by this way rating of the active filter can be minimized.

The average power component will be eliminated by using high pass filter (HPF). The power to be compensated which is given as follows:

$$p_c = -\tilde{p}_l \ \text{ and } \ q_c = \tilde{q}_l$$

The compensation current can be found by the matrix equation (9) as follows:

$$\begin{bmatrix} ic_\alpha \\ ic_\beta \end{bmatrix} = \frac{1}{v_{\alpha\beta}^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p_c \\ q_c \end{bmatrix} \quad (10)$$

Where $v_{\alpha\beta}^{\ 2} = v_\alpha^{\ 2} + v_\beta^{\ 2}$

By transforming α-β component into three phase component i1 i2 i3 by Clarke transformation by equation (3) we get

$$\begin{bmatrix} ic_1 \\ ic_2 \\ ic_3 \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} ic_\alpha \\ ic_\beta \end{bmatrix} \quad (11)$$

3. An Instantaneous Active and Reactive Current Component (I_d-I_q) Method

In this method the active filter currents ic_i can be obtained from the instantaneous active and reactive current components il_d and il_q of the nonlinear load. By using Park transformation on two phase α-β (by Clarke transformation) we will get (*d-q*) components. In Park transformation two phase α-β are fed to vector rotation block where it will be rotated over an angle θ to follow the frame *d-q* .The calculation to obtain these components (il_d ,il_q) follows the same method to the instantaneous active and reactive power(*p-q*) theory. In a same manner the mains voltages v_i and the polluted currents il_i in α-β components will be calculated as same way calculated. However, the *d-q* load currents components are derived from a synchronous frame based on the Park transformation.

$$\begin{bmatrix} il_d \\ il_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix} \quad (12)$$

Where $\Theta = tan^{-1}\left(\frac{\mu\beta}{\mu\alpha}\right)$ (13)

Where θ is a transformation angle
Under balanced and sinusoidal mains voltage condition θ is a uniformly increasing function of a time. The transformation angle 'θ' is sensible to all voltage harmonics and unbalanced voltages therefore, dθ/dt may not be constant over a mains period. Figure 5 shows the voltage and current space vectors in the stationary *(α-β)* and rotating frames (d-q)

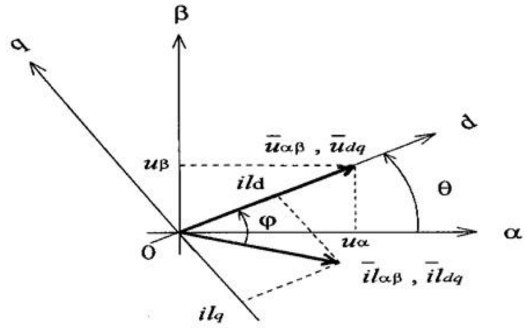

Figure 3.Space vectors representation of voltage and current

By transformation (13) the direct voltage component is given as follows:

$v_d = |v_{\alpha\beta}| = |v_{dq}| = \sqrt{{v_\alpha}^2 + {v_\beta}^2}$ and the quadrature voltage component will be always null, uq=0.So from the geometric relation equation (12) can be written as:

$$\begin{bmatrix} il_d \\ il_q \end{bmatrix} = \frac{1}{\sqrt{{v_\alpha}^2+{v_\beta}^2}} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix} \quad (14)$$

An instantaneous active and reactive load currents il_d and il_q can be decomposed into oscillatory and average terms as follows:

$$il_d = \widetilde{il_d} + Il_d \text{ and } il_q = \widetilde{il_q} + Il_q$$

The first harmonic current of the positive sequence will be transformed to dc quantities,$il_{d1h}{}^{+}$, $il_{q1h}{}^{+}$,.This components contain the average current components. And all the higher order harmonic current with the first harmonic of negative sequence of current are transformed to non dc quantities which will undergo frequency shift in the spectra which constitute the oscillatory components $(il_{dnh}{}^{+-} + il_{d1h}{}^{-})$, $(il_{qnh}{}^{+-} + il_{q1h}{}^{-})$. This assumption is valid for balanced and sinusoidal mains voltage conditions. The average current term will be eliminated by high pass filters (HPF).The currents which will be compensated can be obtained as $ic_d = -\widetilde{il_d}$ and $ic_q = -\widetilde{il_q}$.

Finally the compensation currents can be calculated as:

$$\begin{bmatrix} ic_\alpha \\ ic_\beta \end{bmatrix} = \frac{1}{\sqrt{{v_\alpha}^2+{v_\beta}^2}} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} ic_d \\ ic_q \end{bmatrix} \quad (15)$$

The main advantage of this method is that angle 'θ′ can be directly calculated from the mains voltages and thus make this frequency independent by avoiding the phase locked loop (PLL). Furthermore, under unbalance and non-sinusoidal mains voltage conditions, a large number of synchronization problems can be avoided. Thus i_d-i_q achieves large frequency operating limit essentially by the cut-off frequency of voltage source inverter.

4. Simulation and Performance

Simulation is carried out for both instantaneous direct and quadrature (i_d- i_q) method instantaneous active and reactive power method (p-q).

The performance of shunt active power filter under sinusoidal condition, as load is highly inductive; current drawn by the load is rich in harmonics. Under this circumstance both control schemes seems to work in similar nature and respective Harmonic distortions are shown. Simulation is extended to un-balanced sinusoidal conditions with same SAPF. It is observed that rather than *p-q* method, i_d- i_q performance is quite good.

FFT spectrum gives about 12.45% in id-iq method and 26.10% in p-q for unbalanced non sinusoidal voltage condition. The THD of i_d-i_q is 3.15% whereas p-q method is 3.78%, so the performance of i_d-i_q method is superior compared to p-q method under balanced condition.

4.1 Id-Iq Method

4.1.1 Source Current without Filter

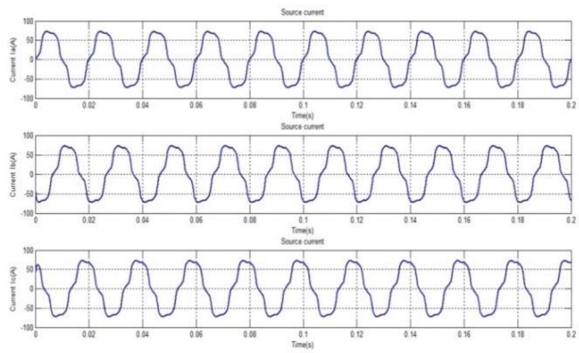

Figure 4.Source current without filter

4.1.2 Source Voltage without Filter

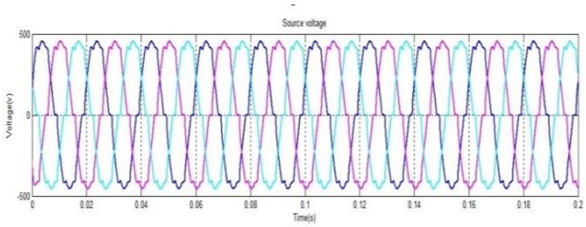

Figure 5.Source voltages without filter

4.1.3 THD Value without Filter

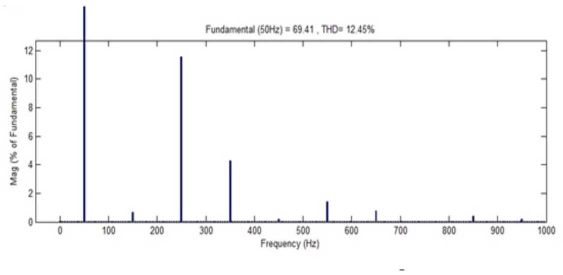

Figure 6.THD value without filter

4.1.4 Source Current with Filter

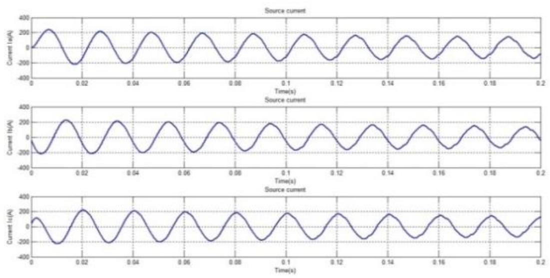

Figure 7.Source current with filter

4.1.5 Source Voltage with Filter

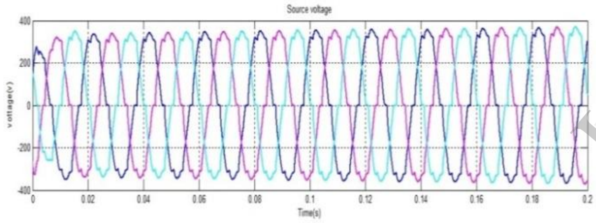

Figure 8.Source voltages with filter

4.1.6 Capacitor Voltage

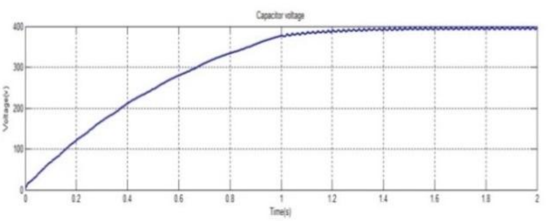

Figure 9.Capacitor voltage

4.1.7 THD Value with Filter

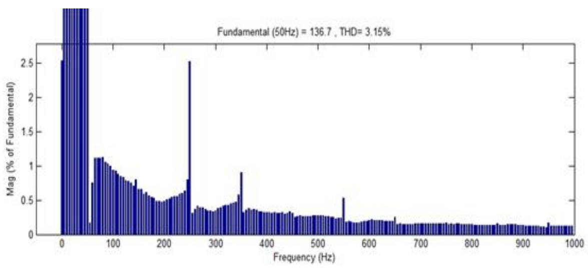

Figure 10.THD value with filter

4.2 P-Q Method

4.2.1 Source Current without Filter

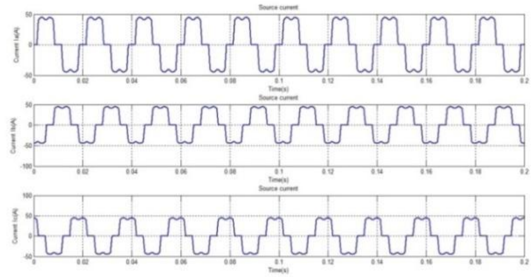

Figure 11.Input source current without filter

4.2.2 THD Value without Filter

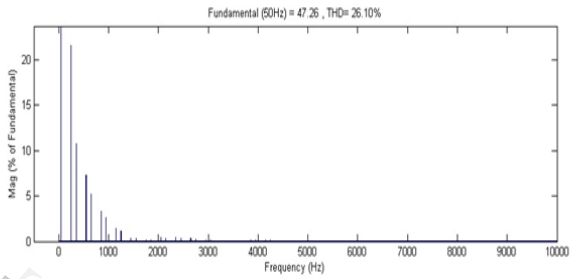

Figure 12.THD value without filter

4.2.3 Source Current with Filter

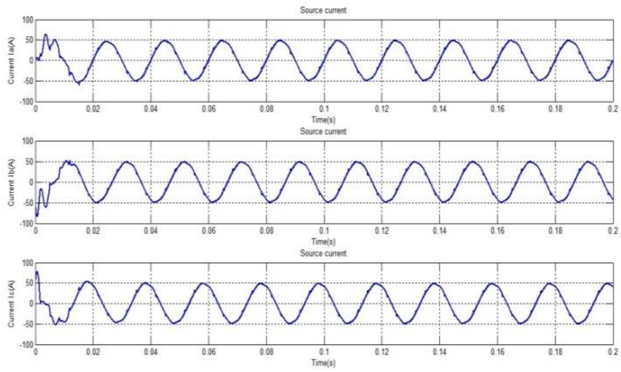

Figure 13.Input sources current with filter

4.2.4 Source Voltage, Filter Current and Capacitor Voltage

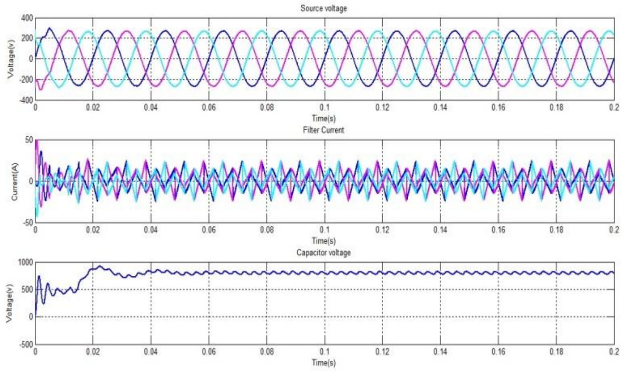

Figure 14.Input voltage, filter current and capacitor voltage

4.2.5 THD Value with Filter

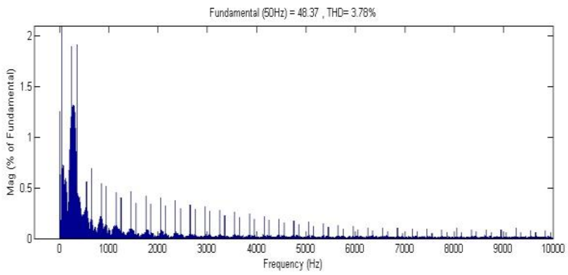

Figure 15.THD value with filter

5. Conclusion

In this paper an Active filter based on the instantaneous active and reactive current component I_d-I_q method is studied. Current harmonics consist of positive and negative sequence including the fundamental current of negative sequence can be compensated. Therefore, it acts as a harmonic and unbalance current compensator. The active filter compensation currents are generated by a three-leg VSI with hysteresis current control. In I_d-I_q method angle θ can be directly calculated from the main voltages and thus enables the method to be frequency independent. Thus large numbers of synchronization problems with un-balanced voltages can be avoided. The I_d-I_q control method which is studied in this project allows the operation of the AF in variable frequency conditions without adjustment.

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