

The voltage control for self-excited induction generator based on STATCOM

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Abstract: The small independent induction generator can build up voltage under its remanent magnetizing and excitation capacitance, but it is prone to voltage sag and harmonic increment when running with load. Therefore, the controller for constant voltage is designed based on the natural coordinate system to adjust the static synchronous compensator (STATCOM), which provides two-way dynamic reactive power compensation for power generation system to achieve voltage stability and harmonic suppression. The control strategy is verified on Matlab/Simulink, and the results show that the STATCOM under the controller can effectively improve the load capacity and reliability of asynchronous generator.

1. Introduction

In recent years, the rapid development of wind power has enabled the steady stream of wind energy to become the standard electricity for home use. Especially equipped with advanced chargers, inverters, wind power has gradually become a technology-based power generation systems. Wind turbines are generally composed of wind wheel, generators (including devices), regulators (rear wings) and energy storage devices. The generator generally adopt asynchronous generator.

Asynchronous generators are generally used in wind power generation system due to the advantages of simple structure, high reliability, free from the use of places, no voltage regulator device and so on. However, the asynchronous generator can operate independently by means of capacitor excitation, the voltage regulation and load carrying capacity is still very weak. When the generator reaches the critical load, it can trigger voltage collapse. In addition, the load asymmetry will cause the stator produce larger harmonic current, resulting in the generator is burned or rotor vibration problems. Therefore, it is very necessary to stabilize the voltage and harmonic suppression.

There are three kinds of control methods of self-excited asynchronous generator to maintain voltage stability ^[1-3]: Thyristor switching capacitor (TSC) method, electronic load controller method and STATCOM reactive power compensation method. Each of the three ways has its own advantages and disadvantages: (1) Switching capacitor banks are easy to operate; besides, the matching capacitance calculation method is simple to understand. But it is difficult to realize continuous regulation, and once the load increases, the number of capacitors also increases, as well as the cost. (2) The electronic load controller has the advantages of energy saving, small size and high efficiency. It has been well applied in the fields of power supply, communication, automobile, storage battery and the like, and also can realize the stable control of the power supply parameters. The disadvantage is that the excess energy generated in the working process, which is consumed as heat energy, resulting in a waste of energy. (3) STATCOM reactive power compensation method is to control the power



semiconductor switch on and off to achieve real-time dynamic compensation. With fast response, strong anti-interference, this method is the most commonly used and effective method, but the higher cost and the controller performance requirements are quite strict.

In this paper, aiming at the problems of poor load capacity of small independent induction generator after building up voltage, the STATCOM compensation device is proposed to control the voltage. The controller designed in natural coordinate system is used to drive the STATCOM to control the power generation system. Moreover, harmonic injection is used to regulate STATCOM generate equal large reverse compensation current to counteract high order harmonics to improve generator voltage and stator current waveform, so as to improve power quality.

2. Composition of self-excited induction generator system

The overall structure of small independent power generation system [4], as shown in Figure 1, can be divided into three major parts: motive power and generator, the workload and STATCOM compensation device. Without load energy consumption, the prime mover drives the self-excitation asynchronous generator. The generator produces voltage under its own residual magnetization and excitation capacitor. The connection mode of the generator is a star connection, in which the neutral point is earth free. And the transformer connected to the generator and the loads. The neutral point of the loads is connected to the neutral point of the transformer and then grounded. Loads, transformer and STATCOM are connected in parallel at the point of common coupling, that STATCOM can change the power of two-way flow in order to achieve terminal voltage stability by controlling the switch on and off.

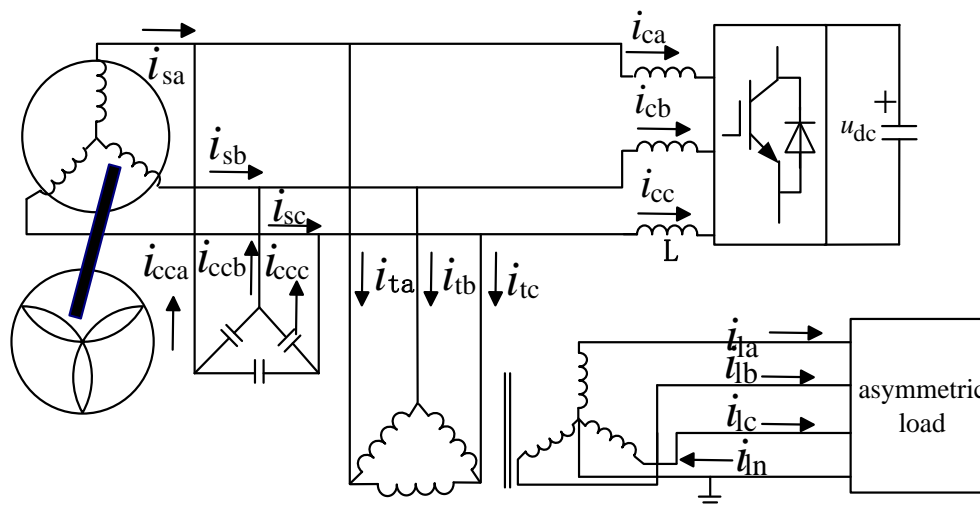


Figure1. The overall structure of small independent power generation system

3. The mathematical model of STATCOM

In order to improve the load capacity of the generator and stabilize the terminal voltage, the diode-clamped three-level STATCOM voltage source is designed for reactive power compensation [5] in this paper. STATCOM is a switch control current device, consisting of 6 IGBT fully controlled high speed power electronic devices. DC side parallel with a large capacitor can ensure voltage variation gently when charge and discharge or switch direction change. At the three-phase bridge side, the filter reactor and induction generator are in series to reduce current fluctuations when the device switch-change or charge and discharge. The circuit structure of STATCOM shown in figure (3).

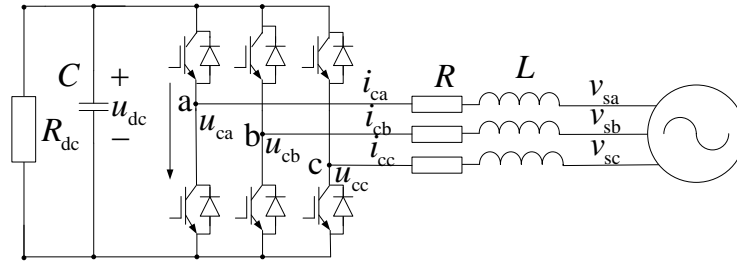


Figure 2. The circuit of STATCOM

According to the circuit structure of figure (2), the dynamic equation of STATCOM in three-phase stationary coordinate system can be obtained by Kirchhoff's law.

$$\begin{cases} L \frac{di_{ca}}{dt} = v_{sa} - Ri_{ca} - u_{ca} \\ L \frac{di_{cb}}{dt} = v_{sb} - Ri_{cb} - u_{cb} \\ L \frac{di_{cc}}{dt} = v_{sc} - Ri_{cc} - u_{cc} \\ C \frac{du_{dc}}{dt} = i_{dc} - \frac{u_{dc}}{R_{dc}} \end{cases} \quad (1)$$

Where L , R , C_{dc} , R_{dc} are respectively for the filter reactor inductance, resistance, DC side capacitance and resistance.

4. Design of STATCOM controller

The asynchronous generator relies on excitation capacitor^[5] and STATCOM to maintain the balance of reactive power. Excitation capacitor can not only issue capacitive current for generator to establish voltage, but also absorb excess reactive current for reverse charging. In addition, STATCOM can control bidirectional flow of reactive power by adjusting the amplitude or phase of the AC output voltage. The abc natural coordinate system is used to convert the three-phase transient signal to the pq coordinate system to achieve active and reactive decoupling. The instantaneous reactive power can be adjusted by controlling i_d and i_q to stabilize the terminal voltage. The control strategy diagram is shown in figure 3.

4.1. Design of voltage control ring

In the voltage control ring of figure 3, the peak value of the three-phase voltage is compared with the reference value^[6-7]. The resulting deviation is passed through the PI regulator and the output value is used as the q-axis current command, namely reactive component i_q . The peak voltage u_t calculated by the formula (2).

$$u_t = \left\{ \left(\frac{2}{3} \right) (v_{sa}^2 + v_{sb}^2 + v_{sc}^2) \right\}^{1/2} \quad (2)$$

$$u_{err(n)} = U_{ref} - u_{t(n)} \quad (3)$$

Where v_{sa} , v_{sb} , and v_{sc} are the three-phase voltage, and U_{ref} , $u_{err(n)}$, $u_{t(n)}$ are respectively on behalf of a constant reference voltage, the voltage error, the instantaneous peak voltage in the n th instant.

$$i_{q(n)} = i_{q(n-1)} + K_{qp} \{ u_{err(n)} - u_{err(n-1)} \} + K_{qi} u_{err(n)} \quad (4)$$

Where $i_{q(n)}$ and $i_{q(n-1)}$ denote the reactive components of the reference current in n th and $(n-1)$ th instant. While K_{qp} and K_{qi} are the proportional and integral coefficients of the PI controller. And $u_{err(n-1)}$ is the voltage error value in $(n-1)$ th instant.

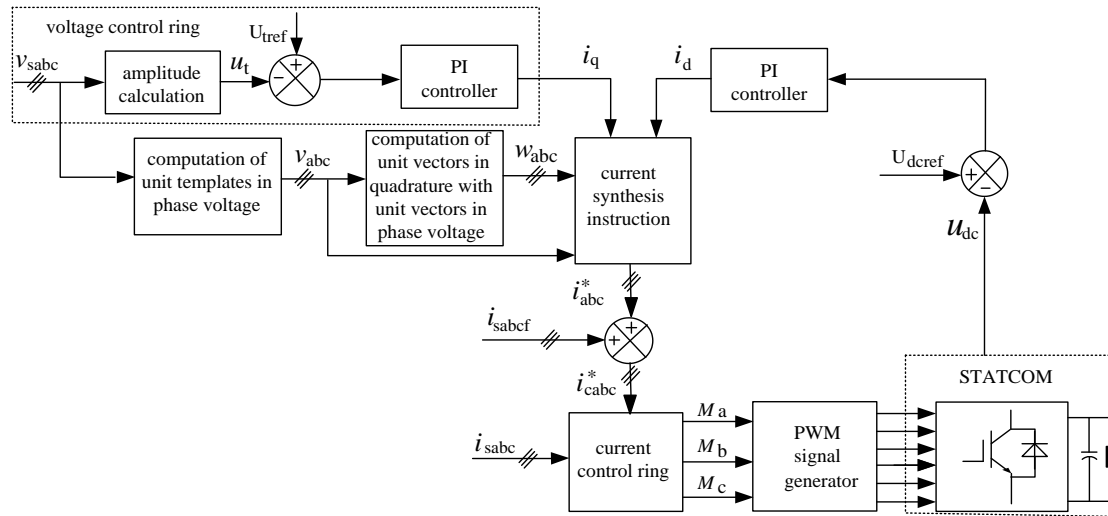


Figure 3. Voltage control diagram

The unit vector of voltage in phase with v_{sa}, v_{sb} and v_{sc} can be expressed as (v_a, v_b, v_c) ,

$$v_a = \frac{v_{sa}}{u_t}, v_b = \frac{v_{sb}}{u_t}, v_c = \frac{v_{sc}}{u_t} \quad (5)$$

The unit vectors in quadrature with unit vectors in phase voltage (v_a, v_b, v_c) is (w_a, w_b, w_c)

$$\begin{aligned} w_a &= -v_b / \sqrt{3} + v_c / \sqrt{3} \\ w_b &= \sqrt{3}v_a / 2 + (v_b - v_c) / 2\sqrt{3} \\ w_c &= -\sqrt{3}v_a / 2 + (v_b - v_c) / 2\sqrt{3} \end{aligned} \quad (6)$$

Then, three-phase reactive current component can be obtained.

$$i_{qa} = i_q w_a, i_{qb} = i_q w_b, i_{qc} = i_q w_c \quad (7)$$

The orthogonal component of the reference current is derived as follows: the DC reference voltage is compared with the instantaneous voltage of the STATCOM DC side. The voltage error is input to the PI regulator and the output value is used as the d-axis current command i_d .

$$u_{dcerr(n)} = U_{dcref} - u_{dc(n)} \quad (8)$$

Where $u_{dcerr(n)}$ and $u_{dc(n)}$ are the DC voltage error and the instantaneous value of the DC side voltage in the nth instant, and U_{tref} is the constant reference DC voltage.

$$i_{d(n)} = i_{d(n-1)} + K_{dp} \{u_{dcerr(n)} - u_{dcerr(n-1)}\} + K_{di} u_{dcerr(n)} \quad (9)$$

Where $i_{q(n)}$ and $i_{q(n-1)}$ are the active current components of the reference current in the nth and (n-1)th instant, and K_{dp} and K_{di} are the proportional and integral coefficients of the PI controller. The $u_{err(n-1)}$ is the voltage deviation value at the (n-1) time.

Then, three-phase active current components can be expressed as:

$$i_{da} = i_d v_a, i_{db} = i_d v_b, i_{dc} = i_d v_c \quad (10)$$

The vector sum of active and reactive components is used as the three-phase reference current control ring.

$$i_a^* = i_{qa} + i_{da}, i_b^* = i_{qb} + i_{db}, i_c^* = i_{qc} + i_{dc} \quad (11)$$

In the current ring, compare dq axis current command and feedback current to obtain the voltage control signal. The PWM modulation technology is used to obtain six PWM pulse signals to control the STATCOM on and off in order to regulate the reactive current and maintain the voltage stability. This control strategy can better solve the problem of voltage drop.

5. The extract of the stator harmonic

A large number of harmonic currents will produce when the power generation system run with unbalance loads, which endangers the generator. Therefore it is need to suppress the harmonic of the stator current. The harmonics are extracted and then injected into the reference current of to generate equal large reverse compensation current, which can offset the harmonic content of the stator current.

The i_p - i_q method^[8] based on instantaneous reactive power theory can accurately detect and track harmonic current. The realization of this theory is that the stationary coordinate system abc is transformed into a two-phase vertical coordinate system $\alpha\beta$ to realize Clarke transformation, and then the two-phase orthogonal coordinate system $\alpha\beta$ is transformed into a two-phase synchronous rotating coordinate system dq to realize Park transformation. It means that the stator three-phase current i_{sa} , i_{sb} and i_{sc} are transformed into i_α and i_β by Clarke transformation, and transformed into i_p and i_q by Park transformation, and then filtered by the low-pass filter to obtain the fundamental current i_{af} and i_{bf} . The above results inverse transformation can derive the three-phase fundamental current, and then subtract the three-phase fundamental current from the three-phase instantaneous current to obtain the harmonic current. The process is shown in figure 4 below.

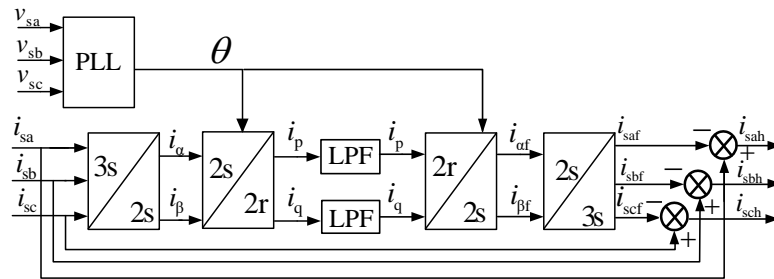


Figure 4. The harmonic detection of stator current

The coordinate transformation matrix is:

$$C_{abc-dq} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin \theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \end{bmatrix} \quad (12)$$

The stator harmonic currents i_{saf} , i_{sbf} and i_{scf} , obtained after transformation are added with the three-phase reference current of formula (11), and the sum of both is used as the reference current of the current inner loop. All is for the sake of the harmonic injecting into the three-phase reference current so that the inverter produces a large reverse compensation current to restrain the stator harmonic current generator.

$$\begin{cases} i_{ca}^* = i_{saf} + i_a^* \\ i_{cb}^* = i_{sbf} + i_b^* \\ i_{cc}^* = i_{scf} + i_c^* \end{cases} \quad (13)$$

6. Another section of your paper Simulation analysis

The voltage control simulation of asynchronous generator is carried out by MATLAB/Simulink. First of all, a fixed speed is given to drive the generator running, the generator parameters shown in table 1.

Table 1. The parameters of generator

parameter	value	parameter	value
rate capacity	2.2kw	polar numbers	2
rate voltage	380V	stator resistance	3.383 Ω
rate current	5A	rotor resistance	2.973 Ω
rate speed	1430r/min	stator inductor	0.008 H
winding connection	Y	rotor inductor	0.008 H
method			
DC voltage	550V	excitation capacitance	60 μF

filter inductor

1.2mH

IGBT capacity

300V,1200A

6.1. The simulation of generator disconnect with STATCOM

Without STATCOM device running, the generator build up voltage with no load, and the terminal voltage peak value is about 311V. In the first second, three-phase symmetrical load 50Ω , 0.0025H is suddenly put into system, the simulation results shown in Fig. 4

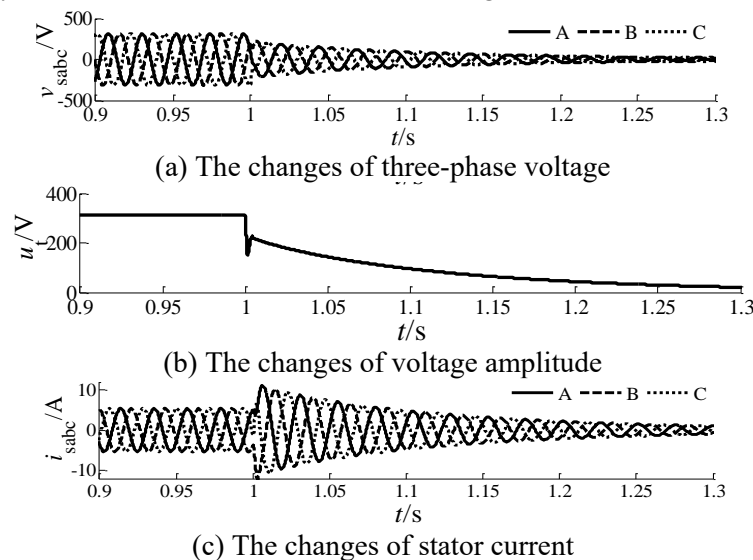
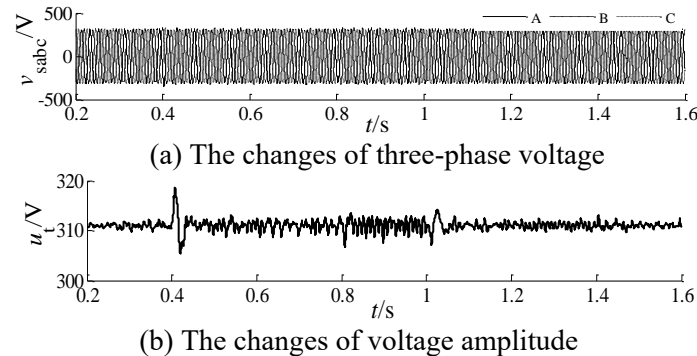


Figure 5. System dynamic response under three-phase symmetric loads without STATCOM

As can be seen from Figures 5(a), 5(b), and 5(c), the three-phase voltage rapidly drops from 311V to about 0V within 0.4s, and the stator has a starting current peak about 5A. After the load is applied, the stator current increases immediately and then gradually reduces to zero because the generator is difficult to support the system operation. According to the national electricity standard low voltage distribution network (220V / 380V) voltage drop does not allow more than 5%, indicating that the asynchronous power generation system has poor load capacity.

6.2. The simulation of generator connect with STATCOM

In order to stabilize the terminal voltage of asynchronous generator, the STATCOM compensation device is put into system. Simulation process is as follows: adding A, B and C three-phase asymmetric loads at 0.4 s, removing C phase 20Ω , 0.002H , 0.001F resistance load at 0.8 s; closing B phase 50Ω , 0.001H inductive load at 1.0 s; disconnecting A phase 20Ω resistance load at 1.4 s. The simulation results show in Figure 6.



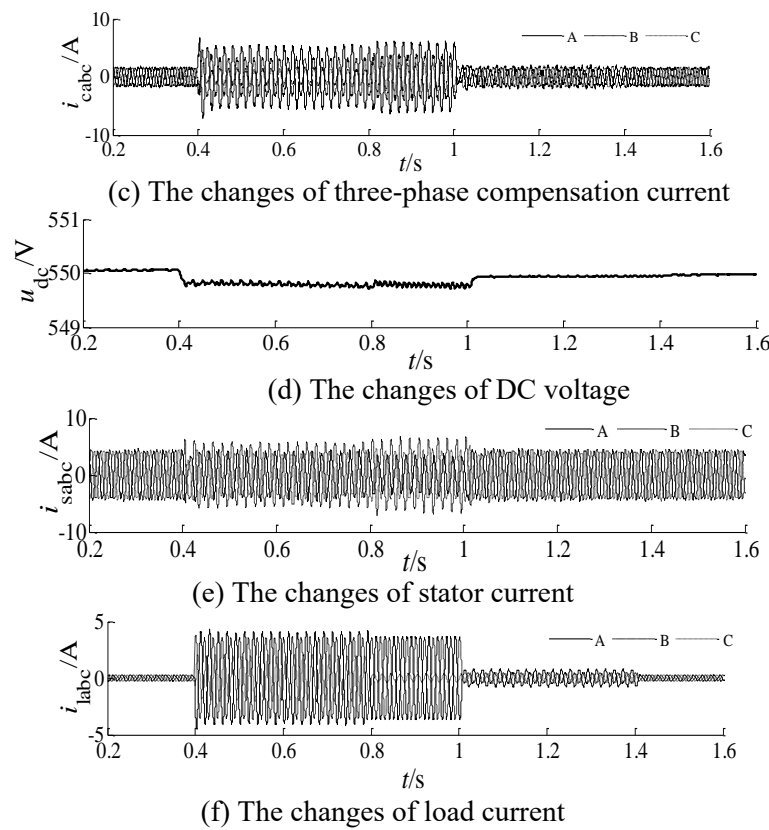


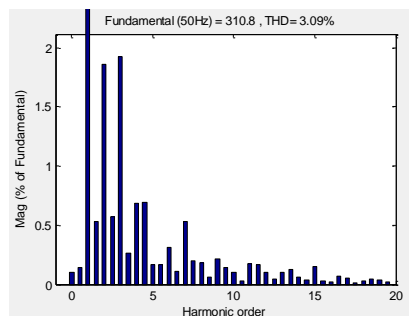
Figure 6. System dynamic response under three-phase asymmetric loads

From figure 6(a) and 6(b), it can see that the three-phase terminal voltage and its peak have a slight fluctuation about 5V after the input and the cut-off load, but it can resume the stability within three cycles and keep at about 311V. As shown in figure 6(c), when the three-phase asymmetric load is applied at 0.4s, the peak value of compensation current from STATCOM increases to about 5V. Since the reactive power consumed by the inductance in phases B and C is much more, the compensation current amplitude is the largest, and the phase A is pure resistance the compensation current amplitude is relatively small. Therefore, the peak value of the compensation current also change at different switching time. As shown in figure 6(d), the voltage amplitude of the DC side decreases and rises as the load is switched on and off at different times, and the original value is recovered after the three phases are disconnected. Using the STATCOM inverter function to provide compensation for the system, make it remained stable. Figure 6(e) and 6(f) show the stator current and load current also change with loads.

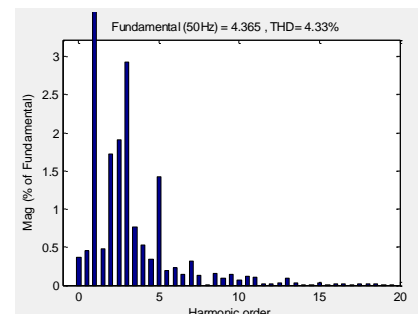
It can be seen from Fig. 6(a) ~ 6(f), the voltage of the generator system can be restored to its original state in three cycles. The STATCOM device can control the power supply stable, indicating that the control strategy achieves the expected goal in application.

To analyze the effect of post-compensation regulation, FFT analysis was performed on the terminal voltage and stator current. Figure 7(a) and 7(b) show that the system non-adopted harmonic suppression, while figure 8 (a) and 8(b) show that the system adopted harmonic suppression.

From figure 7 and figure 8, it can be seen that the total harmonic distortion (THD) of voltage and stator current is less than 5%, which meet the relevant requirements of GB/T14549-1993, "Power Quality Utility Harmonic". At the same time, The THDu of generator terminal voltage was reduced from 3.09% to 1.66%, while the stator current THDi was reduced from 4.33% to 1.62%, indicating the effectiveness of the harmonic suppression control after adding harmonic suppression control.

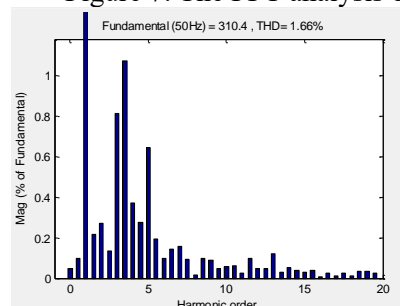


(a) The FFT analysis of voltage

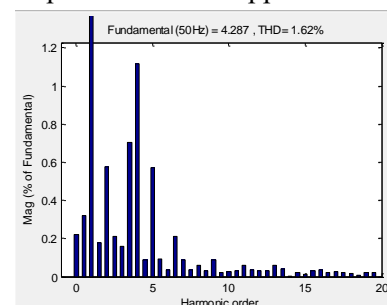


(b) The FFT analysis stator current

Figure 7. The FFT analysis of the system non-adopted harmonic suppression



(a) The FFT analysis of voltage



(b) The FFT analysis stator current

Figure 8. The FFT analysis of the system adopted harmonic suppression

7. Conclusion

In this paper, the above control scheme, only mention the external voltage characteristics of asynchronous motor without the need for in-depth analysis of the motor. Aiming at the problem of small independent self-excitation asynchronous generator with poor load capacity after voltage has been build-up. The STATCOM devise is proposed to compensate the reactive power of the generator. Moreover, the method of harmonic is injected into the reference current to reduce harmonic to improve stator current wave, which ensures the safe and stable operation of the generator. Through the analysis of the simulation results, the effectiveness and stability of the control method and compensation device for voltage regulation and harmonic suppression are demonstrated.

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