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Voltage Control of Rectification-type Three-Phase Squirrel-Cage Induction Motor

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Abstract. The VSCF squirrel-cage generation system mostly adopt full power double pulse width AC/DC/AC modulation. In order to reduce the capacity of the rectifier, a rectification system and its voltage control strategy is proposed. The rectifier and capacitor in parallel with the generator are used to compensate the excitation current and to adjust the generator voltage. Uncontrolled rectifier bridge and inverter are connected to the generator to supply electricity for the AC loads. The selection of build-up voltage capacitor is analyzed and system voltage control method is simulated and experimented. The rectification voltage can be kept basically a constant when the rotor speed and load change in a certain range. The rectifier compensating current is small which proves that the system structure is feasible and control method is effective.

Keywords: squirrel-cage asynchronous generator; converter; voltage control.

1. Introduction

Recent years, wind power has been highly valued by countries all over the world. The squirrel cage asynchronous generator has the advantages of simple structure, low price, convenient maintenance and large range of speed[1], which is very suitable for the development and application of wind power generation. But the traditional squirrel cage asynchronous generator has the disadvantages of unstable voltage and frequency and poor adjustment ability. Therefore, it is necessary to use a power electronic converter to control an asynchronous generator to build a high-performance wind power generation. The squirrel cage asynchronous motor VSCF currently adopts double pulse width modulation rectification inverter structure. The active power in this structure needs to be transmitted through a PWM rectifier which can be considered as a rectifying asynchronous generator system and the power of the rectifier is equivalent to that of the generator and the capacity is large. Another structure is used in these articles[4-5]. The converter is connected in parallel with the motor through a reactor (such a converter is called a compensator) to regulate the reactive power required for the excitation of the motor. The active power transfers to the load directly. Since the compensator only provides reactive power, its capacity is smaller than that of the rectifier with dual PWM, but the compensator also needs to provide reactive power to the load and since the load is directly connected to the motor output, it is difficult to ensure the power frequency a constant value.

In order to get the VSCF power generation and at the same time to reduce the capacity of the compensator, this paper proposes a topology structure and a voltage control method of the rectified asynchronous motor system and proves its effectiveness through simulation and experiment.



2. System Structure

The system structure is shown in Fig.1. It consists of a squirrel cage asynchronous motor, a compensator, capacitors used for voltage forming, a rectifier bridge and an inverter. The compensator and the capacitors provide reactive power to the generator. The active power of the motor transfers to the load through the uncontrolled rectifier bridge and the inverter by AC-DC-AC conversion.

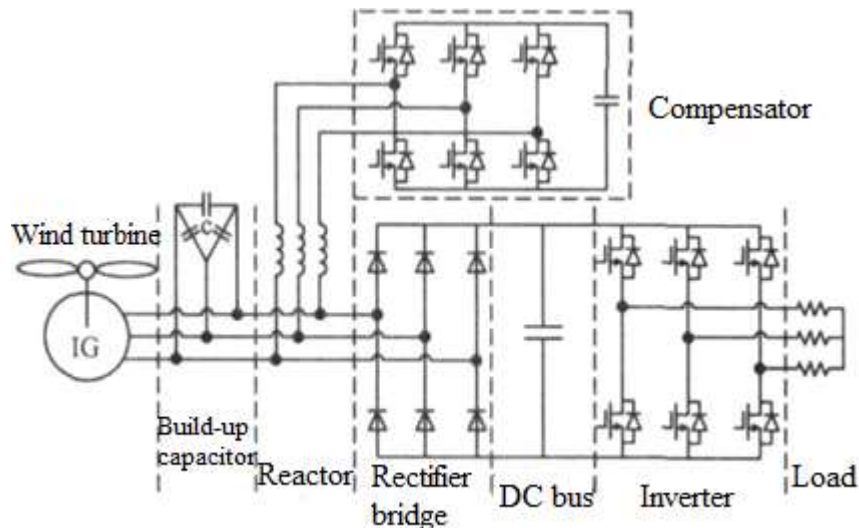


Fig.1 System topology diagram

The capacitors are used for establishing voltage of self-excited induction generator because the voltage established by the remanent magnetism is usually low. Experiments show that the voltage established by the remanent magnetism is basically consumed by the circuit and anode voltage drop through the compensator. Without external power, it is difficult for the generator to establish the voltage only by the compensator.

After the self-excited induction generator establishes a certain voltage through the capacitors, the compensator will start to work together with the capacitor, providing the reactive current required for excitation and controlling the voltage of the generator. So that the output voltage of the rectifier bridge (the DC bus voltage of the inverter) u_L remains a constant value. Since the compensator only needs to provide a part of the reactive power required by the generator and doesn't need to provide reactive power to the load, its capacity can be greatly reduced compared to the rectifier and compensator in the documents cited above.

Once the DC voltage u_L remains constant, we can get the AC voltage we need through the inverter according to the given frequency f^* and voltage u^* . So that the independent control of active and reactive power is realized and the control algorithm of the system is simplified. It can be seen that the critical problem of the system control is the voltage control of the generator. The principles and strategies are mainly introduced in the following part.

3. Voltage control principle and method

3.1. Build-up capacitor selection

According to the equivalent circuit of the traditional squirrel cage asynchronous motor, we can calculate the capacitance required to maintain a certain voltage at different speeds and different loads. In this system, build-up capacitors are mainly used for self-excited induction generator voltage establishing. Although they also provide the reactive current required for excitation of the generator together with the

compensator, they aren't used for adjusting the voltage of the generator. So, the capacitance of the capacitor doesn't need to change once it is determined.

It can be seen that the capacitance value not only affects the initial build-up voltage level but also affects the capacity of the compensator and is related to the motor speed when the compensator is required to be put into the system. These effects should be taken into consideration when choosing the capacitance value. The minimum required capacitance should meet the requirements for self-excited build-up at a certain motor speed. The article[6] shows that the motor speed and capacitance must be greater than their critical value and the generator can establish the ideal voltage only when the motor speed (capacitance) is for sure, the capacitance (speed) must be greater than a certain value. According to the motor no-load characteristic, the slope of the motor linear working area is k , and the minimum build-up motor speed is n_{min} . The minimum excitation required capacitance value C should satisfies the following condition:

$$C \geq \frac{30}{\pi p k n_{min}} \quad (1)$$

where p is the number of pole-pairs.

3.2. Voltage Control Principle

Ignoring the stator resistance and the stator and rotor leakage reactance, the generator voltage and flux linkage equation can be simplified to following forms in the dq rotating coordinate system.

$$\begin{cases} u_{sd} = -k j_{mq} \\ u_{sq} = k j_{md} \\ 0 = R_r i_{rd} - j_{mq} (k - k_r) \\ 0 = R_r i_{rq} + j_{md} (k - k_r) \\ j_{md} = f(i_{sd}, i_{rd}) \\ j_{mq} = f(i_{sq}, i_{rq}) \end{cases} \quad (2)$$

In the formulas, u is the voltage, i is the current, j is the flux linkage; the subscripts s and r represent the stator and the rotor respectively; m represents air gap value, d and q represent the d and q axis components respectively; $f(i_{sd}, i_{rd})$ and $f(i_{sq}, i_{rq})$ are the d and q axis air gap flux linkage functions, k is the synchronous frequency of the induction motor and k_r is rotor frequency.

According to article[5], in order to analyze the instantaneous active and reactive power of the motor conveniently, the stator voltage vector is directed to q axis in dq rotating coordinate system. So

$u_{sd} = \sqrt{2/3(u_{sa}^2 + u_{sb}^2 + u_{sc}^2)}$ and $u_{sq} = 0$. From the formula (2) and the derivation of the article[5], formulae (3) are proposed as follows.

$$\begin{cases} u_{sd} = R_r i_{sd} - k_r j_{mq} \\ j_{mq} = f(i_{sq}) \\ k = k_r - R_r i_{sd} / j_{mq} \end{cases} \quad (3)$$

Suppose the compensator current is i_i , its d-axis component i_{id} is used to balance the compensator loss and maintain the compensator DC side voltage u_c a constant which can be ignored in steady state. The q-axis component i_{iq} is used to regulate the generator voltage u_{sd} . Since the rectifier bridge mainly transmits the active power, the calculation of the fundamental component of the input current in steady state can be equivalent to the resistance R_L .

$$i_{sd} = -\frac{u_{sd}}{R_L} - i_{id} \approx -\frac{u_{sd}}{R_L} \quad (4)$$

Substituting it into equation (3) and get equation (5) as follows.

$$u_{sd} = -\frac{k_r R_L}{R_L + R_r} f(i_{sq}) \quad (5)$$

The generator reactive current i_{sq} includes the reactive current i_{cq} provided by the build-up capacitors and i_{iq} provided by the compensator.

$$i_{sq} = -i_{cq} - i_{iq} = -k C u_{sd} - i_{iq} \quad (6)$$

It can be seen from equations (5) and (6) that when the load or speed change, the u_{sd} can be adjusted by adjusting i_{iq} and further to adjust the DC bus voltage u_L . As for the compensator DC side voltage u_c , if the compensator DC side capacitor is C_i and the voltage on the AC side is u_i , ignoring line loss, there is

$$C_i \frac{du_c}{dt} = \frac{3}{2u_c} (i_{iq} u_{iq} + i_{id} u_{id}) = \frac{3}{2u_c} i_{id} u_{id} \quad (7)$$

Therefore, u_c can be adjusted by adjusting the active component (i_{id}) of the component current.

3.3. Voltage control strategy

The voltage control strategy is based on synchronous rotating coordinate transformation and uses double closed loop control as shown in Fig 2. The outer control is the voltage loop. After the build-up capacitor current i_{cq} is subtracted from the difference between the DC voltage reference value u_L^* and the feedback voltage value u_L which is regulated by the PI regulator, the reactive component of compensating current i_{iq} is obtained. The active component specified value of compensating current i_{id} is regulated through the difference between the compensator DC side voltage specified value u_c^* and feedback voltage value u_c by PI regulator. The inner loop is current loop which controls the compensator current so as to regulate the u_L and u_c .

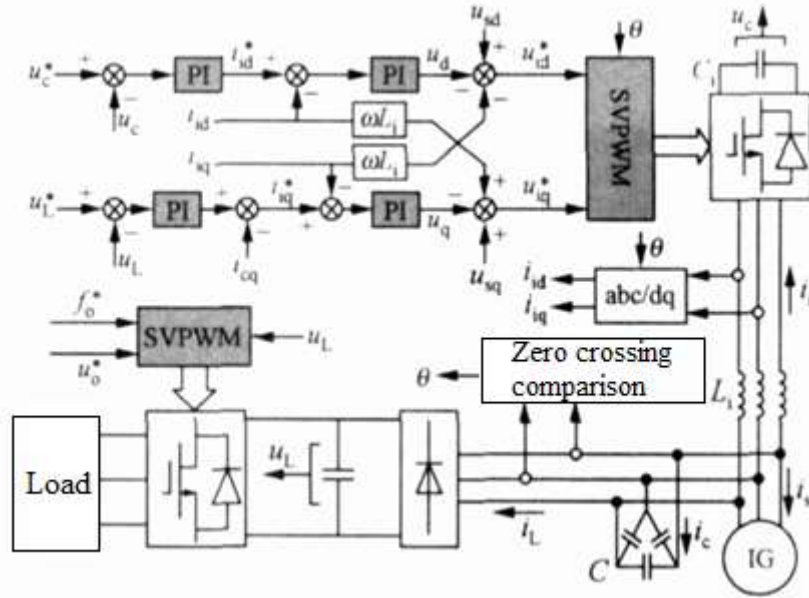


Fig.2 system control block diagram

The stability of the DC bus voltage u_L is obtained by adjusting the compensator current. So, the inner loop determines the quality of the voltage control. The compensator can be regarded as a PWM rectifier. In the dq rotating coordinate system, the equation is as follows.

$$\begin{cases} L_i \frac{di_{id}}{dt} - kL_i i_{iq} + R_i i_{id} = u_{sd} - u_{id} \\ L_i \frac{di_{iq}}{dt} + kL_i i_{id} + R_i i_{iq} = 0 - u_{iq} \end{cases} \quad (8)$$

It can be seen that i_{id} and i_{iq} can be controlled by adjusting u_{id} and u_{iq} . But i_{id} and i_{iq} are coupled. To eliminate it, a feed forward decoupling method is employed. If the new controlled variable is defined as follows.

$$\begin{cases} u_d = u_{sd} - u_{id} + kL_i i_{iq} \\ u_q = 0 - u_{iq} - kL_i i_{id} \end{cases} \quad (9)$$

For the controlled variable u_d and u_q , i_{id} and i_{iq} are decoupled and i_i can be well controlled by adjusting u_d and u_q . If the reference values of u_d and u_q are obtained by the error of i_{id} and i_{iq} through PI regulator, as shown in Fig.2, then the given values of the final controlled variables u_{id} and u_{iq} are shown as follows.

$$\begin{cases} u_{id}^* = u_{sd} + kL_i i_{iq} - \left(K_{pd} + \frac{K_{id}}{s}\right)(i_{id}^* - i_{id}) \\ u_{iq}^* = -kL_i i_{id} - \left(K_{pq} + \frac{K_{iq}}{s}\right)(i_{iq}^* - i_{iq}) \end{cases} \quad (10)$$

K_p and K_i are the proportion and integral coefficient respectively.

As shown in Figure 2, adopting space vector pulse width modulation (SVPWM) to control the compensator can increase the DC side voltage efficiency of the compensator and is easily applied by Digital Signal Processing (DSP).

4. Simulation Results

In the Matlab/Simulink environment, a system control model is established based on Fig.1 and Fig.2. The DC bus voltage control and reactive current compensation are simulated when the load and generator speed change. The generator per-unit value is: $R1=0.0457$, $Xm=1.59$, $R2=0.0416$, $X1=X2=0.0567$. Phase voltage base value and phase current base value are the amplitude of the rated phase voltage and phase current of the generator respectively.

Simulation experiment 1: The change of DC bus voltage u_L when the compensator is not working. The results are shown in Fig.3(a) (per-unit value, rated value is 1, the same as follows), the operating conditions are: 0-5s, speed $n=1$; 1.2s input 50% load; 2.5s input 50% load; cut off load at 4s; 5-6.8s load is maintained at 50%; speed n rise to 1.1 at 5s; 6.8s speed n drops to 0.85.

Simulation experiment 2: The change of voltage u_L and compensation current when the compensator is working. As shown in Fig.3(b). The experiment condition is the same as experiment 1 and the compensator start to work at 1s.

It can be seen from Fig.3 that u_L has large fluctuations with load or speed change when uncompensated. When the compensator is running, u_L can be stabilized at the rated value and after the compensator DC side voltage is steady, the compensation current active component i_{id} is nearly zero. The reactive component of the compensation current is less than 0.4 from no load to full load and speed changes $\pm 10\%$ as shown in Fig.3(c).

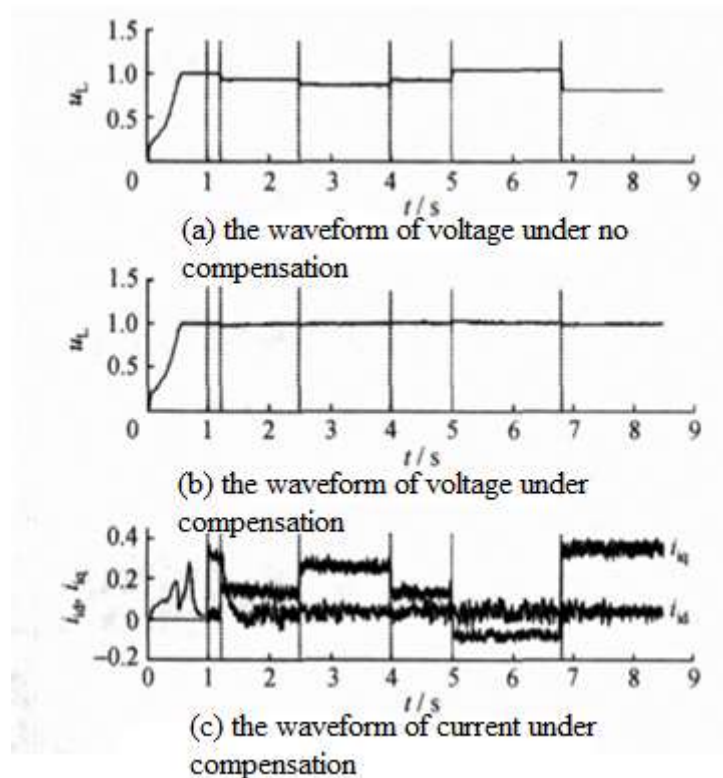


Fig.3 Waveform of voltage u_L and current i_{id} and i_{iq}

5. Summary

This paper presents a topology and voltage control method for a rectified squirrel-cage asynchronous system. The power electronic converter(compensator) connected in parallel with the generator is used to adjust the reactive power required for the excitation of the generator. The active power is supplied to the load through the AC/DC/AC conversion by the rectifier bridge and the inverter thus the VSCF

generation system is achieved. As a result of the appropriate built-in capacitors are used in the system, so there is no need for external power to establish voltage. The capacitor also supplies the excitation current to the generator without providing reactive power to the AC load.

Simulation and experiment results show that the generator voltage can be kept a constant under the condition of changes in load and speed. The current of the compensator is not large which achieves the purpose of reducing the converter capacity and proves the proposed topology and voltage control method effectiveness. The system doesn't require a position/speed sensor and only requires 2 voltage and current sensors which makes the control system simple and reliable.

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