Adjustment of Active and Reactive Power of Synchronous Generator in Grid-connected Operation

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Abstract. The regulation of active power and reactive power of generators in grid-connected operation has always been an important research issue of power plants and power grids for efficient use of energy and stable operation of motors. In daily life, residential electricity consumption is always changing, more at night and less during the day; more in summer and winter, less in spring and autumn, so in order to make rational use of resources and improve the economy, real-time monitoring and regulation of active power are needed. And most of the loads connected to the grid are inductance loads, so a power system should load a lot of reactive power besides active power. According to statistics, the reactive power required by an asynchronous motor in a power system accounts for 70% of the total reactive power supplied by the power grid, 20% of transformers and 10% of other equipment. The reactive power supplied by the power grid is shared by all generators, which will bring about the problem of how much each generator should bear and how to regulate the reactive power of generators. In this paper, the regulation methods of active and reactive power, the regulation range, the power angle characteristics and the electromagnetic relationship of active and reactive power are analyzed in detail.

Key words: power angle; excitation current; active regulation; reactive power regulation; static stability.

1. Introduction
This paper discusses how to adjust the active and reactive power after the generator is connected in parallel, mainly for the infinite power grid. This limits the adjustment to only one generator considered, and since \( U = \text{constant} \), \( f = \text{constant} \), the object being adjusted can only be by adjusting the prime mover valve and by changing the field current. The internal process is analyzed by vector diagram or power angle characteristics during adjustment. Adjusting the active power must change the input power of the prime mover to change the output power of the generator according to the characteristic of the power angle. If only the generator excitation current is changed, only the reactive power of the generator can be adjusted. When overexcited, the inductive reactive power is emitted, and the armature reaction is demagnetization; when the excitation is weak, the generator emits capacitive reactive power, and the armature reaction may increase. Magnetic may also demagnetize. A normal excitation generator only outputs active power with a power factor of 1.
2. Synchronous generator reactive power regulation and its operation analysis

The premise of analysis is that the hidden pole motor is taken as an example. The saturation effect and the armature resistance are neglected. When the grid is regarded as an infinite grid, there is $U=constant$ value and the frequency $f=normal$ value.

2.1. Output from no Load to Stable Active Power

When the generator does not output active power, the power input by the prime mover just compensates for various losses, and does not output electromagnetic loss (ignoring the copper loss of the stator), so the power angle $\delta=0^\circ$, the electromagnetic power $P_M=0$, as shown in Figure 1. At this time, although the field electromotive force $E_0$>the grid voltage $U$ can be present and there is a current output, it is a reactive current. When the prime mover input power $P_1$ is increased, the input torque $T_1$ is increased, and $T_1>T_0$ ($T_0$ is the no-load torque). At this time, the residual torque ($T_1-T_0$) acts on the motor shaft, so that the rotor Acceleration, the rotor main magnetic field ($B_0$) and the straight-axis d-axis lead the stator equivalent synthetic magnetic field ($B_\mu$). Since the magnetic field is limited by the grid frequency, the rotational speed is still synchronous, and the corresponding electromotive phase

The quantity $\dot{E}_0$ leads the generator terminal voltage phasor $\dot{U}$ a phase angle, so $\delta>0^\circ$, $P_M>0$, the generator outputs the active current to the outside, and the electromagnetic torque $T_M$ corresponding to the electromagnetic torque $P_M$ appears at the same time. When $\delta$ is increased such that the corresponding electromagnetic torque is exactly equal to the residual torque ($T_1-T_0$), the rotor returns to the synchronous speed, and the generator operates stably at the $\delta$ angle, as shown in Figure 1(B) and (C). At this time, the generator output active power is

$$P_2 \approx P_M = \frac{mUE_0}{X_s} \sin \delta$$  \hspace{1cm} (1)

If it is a salient-pole synchronous generator, its power angle characteristic is

$$P_2 \approx P_M = \frac{mUE_0}{X_s} \sin \delta + m \frac{U^2}{2} \left( \frac{1}{X_q} - \frac{1}{X_d} \right) \sin 2\delta$$  \hspace{1cm} (2)

It can also be seen that the Angle of power Angle is the Angle between the axis of the rotor magnetic pole and the axis of the air gap magnetic pole in space and the Angle between the excitation electromotive force $E_0$ and the voltage $U$ in time.
Figure 1. In parallel with an infinite power grid, the synchronous generator produces active power from no load to stable output.

2.2. Active power regulation in static and stable operation of synchronous generator

Stability in synchronous generator output active power, the excitation current $I_f$ unchanged, adjust the active power, namely, adjust the power output of the prime mover changes the size of the valve or gate, power Angle is about to change, because the $\vec{E}_o$ track is a circular arc, $\vec{U}$ is changeless, therefore $j\vec{I}X_s$ trajectory is a circular arc, then $\vec{I}$ trajectory is a circular arc, the corresponding emf vector diagram for non-salient pole generator (for example) as shown in Figure 2. Current I Tim track can be controlled by

$$\dot{E}_o = \dot{U} + j\dot{I}X_s$$ (3)

$$\dot{I} = \frac{\dot{E}_o - \dot{U}}{jX_s} = j\frac{\dot{U}}{X_s} - j\frac{\dot{E}_o}{X_s}$$ (4)

Find out. It can be seen from the figure that as the active power changes, the $\delta$ angle changes, and then the $\phi$ angle changes, $I\cos\phi$ changes, and $I\sin\phi$ also changes, that is, the magnitude of reactive power changes, and the nature also May change. Specifically, when the active power increases and the excitation current does not change, and the active power $P = mU\cos\phi$ increases, $I\cos\phi$ increases. Then $P_m = \frac{mUE_0}{X_s}\sin\delta$ increases, then $\sin\delta$ increases, that is, $\delta$ increases, and $Q = \frac{mUE_0}{X_s}\cos\delta - m\frac{U^2}{X_s}$ is decreasing, armature current $I$ is increasing, and the power factor angle $\phi$ is decreasing. Therefore, the power angle $\delta$ actually reflects the angle of the stator synthetic magnetic field torsion, and the larger the electromagnetic power $P_m$ and the electromagnetic torque $T_m$ are. The reason for the formation of $\delta$ is that there is a cross-armature armature reaction current $I_q$ (the component of the armature current $\vec{I}$ in the $\dot{E}_0$ direction), so the cross-armature armature reaction magnetomotive force generates electromagnetic torque and performs electromechanical energy conversion. Necessary conditions.

However, the input power from the prime mover cannot be increased without limitation to increase the electromagnetic power of the generator. For a hidden pole generator, when the power angle $\delta$ reaches 90°, the electromagnetic power will reach the maximum value $P_{M_{\text{max}}}$. If the input power from the prime
mover is increased, a new balance cannot be established, and the motor speed will continuously rise and lose the step and static stability.

\[ U \]
\[ E \]
\[ U \]
\[ E \]
\[ I \]
\[ \phi \]
\[ x \]
\[ B' \]
\[ \delta \]

**Figure 2.** The synchronous generator keeps the excitation current \( i_f \) constant to adjust the active power of the generator

3. **Reactive power regulation and operation analysis of synchronous generator**

The study of reactive power regulation of a generator can also be considered that the power grid capacity is large enough, that is, the power grid voltage will not change and the frequency will not change. If the generator is connected in parallel to the grid under the above ideal conditions.

3.1. **Analysis of No-load Excitation Current Regulation**

When the armature current is zero when the no-load switch is closed, as shown in Figure 3 (a), the excitation current is normal excitation when the no-load switch is closed, and the generator will not generate active power or reactive power. If the prime mover output remains unchanged, if the excitation current is increased, it will be in an overexcited state, and the generator will send out backward reactive current to generate demagnetizing armature reaction, as shown in Figure 3 (b). If the excitation current starts to decrease from the normal excitation, it will be in the underexcited state, and the generator will send out the leading reactive current to generate the magnetized armature reaction, as shown in Figure 3 (c).

**Figure 3.** Phase vector diagram of adjusting excitation current under no-load condition
3.2. Reactive Power Regulation under Active Load

When the generator is loaded with active load and the output active power remains unchanged, the relationship between the generator armature current and excitation current can also be analyzed by electromotive force phasor diagram. Considering that the voltage is constant and the resistance is ignored, there is

\[ P_M = \frac{mU E_0}{x_s} \sin \delta = \text{constant}, \quad \text{That is } E_0 \sin \delta = \text{constant} \quad (5) \]

\[ P_2 = mUI \cos \varphi = \text{constant}, \quad \text{That is } I \cos \varphi = \text{constant} \quad (6) \]

Because \( P_M = P_2 \) at this time

\[ \frac{E_0}{x_s} \sin \delta = I \cos \varphi \quad (7) \]

When the excitation current is adjusted to change \( E_0 \), the generator stator current and power factor also change accordingly. From Figure 3, the vector diagram of visible active current \( I \cos \varphi = \) constant, the stator current \( \hat{I} \) phasor at the end of the trajectory is a horizontal line \( \overrightarrow{AB} \), perpendicular to the voltage vector \( \hat{U} \) from type (5) the \( E_0 \sin \varphi \) delta = constant, the phasor \( E_0 \) change at the end of the track is a and voltage phasor \( \hat{U} \) parallel straight line \( \overrightarrow{CD} \).

According to the above conditions, there are four typical vector diagrams in Figure 4. The first case, the stator current minimum \( I_1 \), \( \cos \varphi = 1 \), for the normal excitation when the load, active power generator only, without reactive power output. In the second case, the excitation current is increased on the basis of normal excitation. At this time, \( E_{02} > E_{01} \) is in the over-excited state. The stator current \( I_2 \) is behind the terminal voltage. In the third case, the excitation current is reduced on the basis of normal excitation. At this time, \( E_{03} < E_{01} \) is in the under-excited state, and the stator current \( I_3 \) leads the terminal voltage \( \hat{U} \). In addition to the active power to the grid, the motor also sends the grid advanced capacitive reactive power, which means that the generator absorbs inductive reactive power from the grid. In the fourth case, it is in the third case to further reduce the excitation current, the electromotive force \( E_0 \) is more decreased, the power Angle and the leading power factor Angle \( \varphi \) will continue to increase to make the stator current value is larger. However, this change is limited. When the no-load emf reaches \( E_{04} \), the generator has reached the limit state of stable operation due to the limit of power Angle of delta <90°. Further reduction of excitation current will not be able to operate stably, and will also lose static stability.
Figure 4. Vector diagram of adjusting excitation current when $U$ = constant and $P_2$ = constant

4. Conclusion
The regulation of active power will affect the change of reactive power. When the active power of the generator is increased, the decrease of reactive power will be caused by the constant excitation current and grid voltage. When adjusting the excitation current to change the reactive power, although the value of the active power of the motor is not affected, and the armature current decreases first and then increases, if the excitation current is set too low, the motor may lose stability and be forced to stop running.

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