Research and Verification of Setting Value Coordination Method Considering the Responding Deviation of under Excitation Limit and Loss of Excitation Protection for Generator

Quan HONG¹, Li LI¹, Haifeng LIU¹, Wenqi MAO², Wenjun LU³

¹ State Grid Hunan Electric Power Co. Ltd. Power Research Institute, Changsha 410007, Hunan Province, China;
² State Grid Hunan Electric Power Co. Ltd., Changsha 410004, Hunan Province, China;
³ School of electrical and information engineering, Hunan University, Changsha 410082, China)
Email: 78851329@qq.com

Abstract: The general principle of the matching between the under excitation limit and the loss of excitation protection has been extensively described, which mostly concentrated on the theory and method of converting them to the same power plane or impedance plane for verifying, but there is little literature of considering the influence of the action characteristics of the field device to the matching results for the setting value. In theory, the influence of parameter variation to the matching result is analyzed in detail. This paper proposed the matching testify principle based on the application operation deviation and expounds the adjustment method of setting value mismatch, which provides an effective guidance principle for power plants with verification and cooperation of under excitation limit and loss of excitation protection.

1. Introduction
Excitation system grid-related and related protection parameter coordination is an important content of grid-source coordination. At present, there are many papers on the cooperation of the excitation system parameters and related protection, which are mainly concentrated on cooperation between under excitation limit and loss of excitation protection [1]-[5]. The general principle of the matching of under excitation limit and loss of excitation protection has been extensively discussed, mostly concentrated in the principles and methods of transfer the loss of excitation protection and under excitation limit parameter to the same impedance plane or a power plane for checking. However, there is no in-depth analysis of the influence of protection and limit parameter variation to the coordination relationship. There is no research on how to choose the coordination difference between under excitation limit and loss of excitation protection and no verification method for whether the match relationship is reasonable is given. In particular, there is a lack of consideration of the influence of the actual device action error on the setting value matching result. This paper theoretically analyzes the influence of various parameter changes on the loss of excitation protection and the under excitation limit, and proposes to use the measured limit curve of the generator as the setting and coordination basis, and proposed the matching and check principle of under excitation limit and the loss of excitation protection based on the device operation error. And the method of setting value adjustment when the value is mismatched is discussed, which provides...
effective guiding principles for current power plants to carry out the calibration and setting of under excitation limit and loss of excitation protection.

2. The cooperation of under excitation limit and loss of excitation protection.

2.1. The cooperation principle

According to relevant regulations and standards, the operation relationship between the loss of excitation protection of the generator and the under excitation limit should be that the under excitation limit works precedes to the loss of excitation protection operation. Under excitation limit setting in excitation system mainly based on the static stability, as well as the stator end heat, plant power voltage constraints. The under excitation limit is generally calculated on the P-Q plane. The main consideration of generator loss excitation protection is the damage of the generator after the loss of excitation [6], [7]. For example: the stator end heating, voltage collapse, rotor overheating, unit vibration, stator winding overheating [8]. The setting parameter of the loss of excitation protection is calculated on the R-X impedance plane. Therefore, the basic theory of the Under excitation limit and the loss of excitation protection is a little bit different, which makes the research point focusing on the method of transformation of coordinates. The loss of excitation protection impedance circle is transformed into the P-Q plane through the coordinate transformation, and its cooperation with the static stability circle is shown in Figure 1.

![Figure 1 Matching of under excitation limit and loss of excitation protection](image)

In the R-X plane, the under excitation limit circle contains a static stability circle for loss of excitation, and the static stability circle for loss of excitation contains an asynchronous impedance circle. The matching relationship to the P-Q plane is shown in Figure 1(B). The under excitation limit precedes the loss of excitation protection. Studies have shown that as long as the under excitation limit can be matched with the static stability of the loss of excitation protection, it can certainly cooperate with the asynchronous impedance circle protection of the loss of excitation protection [2]. The salient pole static stability circle and the hidden pole static stability circle characteristics are very different and will be discussed in another article. Therefore, in this paper, we only study the relationship between the loss of excitation protection and the under excitation limit in the use of the static stable circle as the criterion for the non-salient pole generator.

2.2. Analysis of influence of parameters on coordination

2.2.1 Influence of the loss of excitation protection parameters on coordination relationship

The loss of excitation protection is set in the R-X impedance plane, and the under excitation limit is set in the P-Q plane. Therefore, in order to study the cooperation relationship between the two function, these two must be reduced to a same plane, and the loss of excitation protection action equation is:

$$R^2 + (X - X_0)^2 < R_0^2$$  \hspace{1cm} (1)
The loss of excitation protection action equation is a circle whose center point coordinates are \((0, X_0)\) and radius is \(R_0\). The action equation after converting it to the P-Q plane is:

\[
P^2 + \left(Q - \frac{X_j U_g^2}{X_0^2} \right)^2 > \left(\frac{R_d U_g^2}{R_0^2 - X_0^2} \right)^2
\]

Where \(U_g\) is the actual voltage of the generator stator. The under excitation limit criterion for the static stability circle equation is:

\[
P^2 + (Q - \frac{U_g^2}{2}(\frac{1}{X_s} - \frac{1}{X_d}))^2 > \left(\frac{U_g^2}{2}(\frac{1}{X_j} + \frac{1}{X_d})\right)^2
\]

Where \(X_s\) is the contact resistance of the generator to the system and \(X_d\) is the synchronous reactance of the turbine generator.

The setting parameters for the static stability criteria of the loss of excitation protection are generally the upper boundary impedance \(X_c\) and the lower boundary impedance \(X_b\). Its relationship with the impedance circle is as follows:

\[
X_0 = -\frac{X_b - X_c}{2}
\]

\[
R_0 = \frac{X_c + X_b}{2}
\]

From the above formula, it can be seen that the main parameters affecting the loss of excitation protection action are the upper boundary impedance \(X_c\) and the lower boundary impedance \(X_b\) and the generator terminal voltage \(U_g\). Therefore, it is important to study how the changes of the three parameters of the loss of excitation protection affect its cooperation with the under excitation limit curve.

When the generator is in leading phase operation, its curve in the P-Q plane is in the fourth quadrant. From the formula (2), it can be seen that the allowable leading power factor depth is determined by the radius size and the center of the circle.

Substitute (4), (5) into (2) to get the center coordinates and radius:

Center ordinate:

\[
\frac{1 - \frac{X_c}{X_b} U_g^2}{2X_c} \text{ or } \frac{X_c - 1}{2X_b} U_g^2
\]

Radius:

\[
\frac{1 + \frac{X_c}{X_b} U_g^2}{2X_c} \text{ or } \frac{X_c + 1}{2X_b} U_g^2
\]

When \(P=0\), the maximum allowable leading power factor depth is:

\[
Q = \frac{R_d U_g^2}{R_0^2 - X_0^2} - \frac{X_j U_g^2}{X_0^2 - R_0^2} = -\frac{U_g^2}{R_0 - X_0}
\]

Substitute (4) and (5) into and simplify to:

\[
Q = -\frac{U_g^2}{X_b}
\]

Keep \(X_c, U_g\) unchanged, \(X_b\) increases. From equation (6), it can be seen that the ordinate of the center of the circle increases. From equation (7) it can be seen that the radius decreases. The loss of excitation protection allows the leading power factor depth to become smaller, and it appears in the P-Q plane that the fourth quadrant circle translates in the positive direction of the Q axis. On the contrary, \(X_b\) decreases, and the loss of excitation protection allows the leading power factor depth to
become larger. In the P-Q plane, the circle of the fourth quadrant moves in the negative direction of the Q axis.

Keep $X_b, U_s$ unchanged, $X_c$ increases. From equation (6), it can be seen that the ordinate of the center of the circle decreases. From equation (7) it can be seen that the radius decreases. From equation (9), it can be seen that the maximum allowable reactive power at $P=0$ remains unchanged, but because of the radius decreasing, the loss of excitation protection allows the leading power factor depth smaller when $P>0$. In the P-Q plane, the circular arc rotates in the positive direction of the Q axis, except for the position of the intersection of the fourth quadrant and the ordinate. In contrast, $X_c$ decreases, the maximum allowable leading power factor depth at $P=0$ remains unchanged, and increase when $P>0$. In summary, as the $X_b$ increases, $X_c$ decreases, the allowable leading power factor depth decreases, As the $X_b$ decreases, $X_c$ increases, the allowable reactive power increases. In addition, as can be seen from equations (6) and (7), The actual voltage of the generator $U_s$ affects the actual allowance of leading power factor depth.

2.2.2 The influence of under excitation limit parameters on the coordination relationship.

At present, the principle of under excitation limit is to connect the multi-point allowable leading power factor depth coordinates $(P, Q)$ into a poly-line. Below the poly-line is the action area. Considering the influence of the actual voltage $U_s$, the coordinate value are multiplied by coefficients $(U_s / U_n)^2$ for correction. The influence of $U_s$ to the under excitation limit action is exactly the same as the effect to the loss of excitation protection. Therefore, the effect of $U_s$ on cooperation setting can be neglected. The under excitation limit setting value is determined by the $(P, Q)$ coordinate value. Increasing the Q value allows the leading power factor depth to increase, but it is easier to mismatch with the loss of excitation protection. Decreasing the Q value allows leading power factor depth to be reduced, which is easier to match with the loss of excitation protection.

2.2.3 The influence of the phase-in test curve of generator on the coordination relationship.

Both of the under excitation limit and the loss of excitation protection use the generator static stability circle as the boundary for action. However, the generator is restrained by factors such as the heating of the stator terminal and the factory electrical voltage. The actual allowance of leading power factor depth is less than the amount by the static stability circle. Different generator parameters and operating environments may not be the same, and it is difficult to describe the allowable leading power factor depth range of the generator with several simple system parameters. Stator end heating, factory electrical voltage and other conditions may be more restrictive than the static stability criterion of the generator. It is generally inconvenient to express the amount of leading power factor depth of the actual generator determined by the three constraints expressed above in an exact mathematic model, which is not necessary in engineering as well. In practical applications, the under excitation limit curve is generally formulated according to the leading power factor test. In the actual measurement process, several conditions such as static stability, stator heating, and factory power voltage have been comprehensively considered. Therefore, it is recommended that taking the allowable leading power factor depth limit curve measured by the generator as an important reference for the under excitation limit and the loss of excitation protection. In principle, the under excitation limit works precede to the generator limit curve action, the generator limit curve works precede to the loss of excitation protection action, and the loss of excitation protection works precede to the standard static stability circle. The ideal matching relationship between the four groups of curves in the P-Q plane is shown in Figure 2.
1. under excitation limit curve
2. Generator limit curve
3. loss of excitation protection operation curve
4. Generator standard static stability circle

**Figure 2** Ideal matching relation of curves

### 2.3 the principle of the matching and checking of the under excitation limit and the loss of excitation protection in consideration of the device action error

There is no regulation or standard to quantify the matching differential levels of the under excitation limit and the loss of excitation protection, which only qualitatively stipulates that the under excitation limit works precede to the loss of excitation protection action. The under excitation limit must meet the three constraints of the excitation system at first, followed by the cooperation with the loss of excitation protection. How to ensure adequate safety margin and maximize the depth of the generator's leading power capability is worth of studying. The maximum allowable protection operating value error is ± 5% according to the relay protection regulations and ± 0.2% of the excitation systems according to national standards. The error of excitation limiter can be ignored during calibration. Considering various errors in a comprehensive manner, it is feasible to set the differential level of each curve as 5%. With reference to the matching relationship shown in Figure 2, the under excitation limit action value is 5% less than the measured value of the generator leading power factor depth curve, and the loss of excitation protection action value is 5% greater than the limit curve action value. The loss of excitation protection operation value is 5% less than the standard static circle operation value.

The generator terminal voltage $U_g$ affects the leading power factor depth, but the influence of this parameter is already included in the under excitation limit action curve and the loss of excitation protection action equation, and its effect on the two curve operation ranges is the same, so $U_g$ does not affect the coordination relationship between the under excitation limit and the loss of excitation protection. But when $U_g$ decreases, the under excitation limit and the loss of excitation protection allowable generator leading power factor depth becomes smaller, and the under excitation limit more easily matches the leading power factor ability curve, but the loss of excitation protection may be mismatched. Considering that the actual voltage of the generator during the leading power factor test is generally lower than the rated voltage, it should be checked whether the loss of excitation protection and the limit curve are mismatched under the condition of decreasing $U_g$.

The standard static stability circle of the generator is determined by $X_s$ and $X_d$. When $X_s$ becomes larger, the standard static stability circle allowable leading power factor depth becomes smaller, and it is easily mismatched with the loss of excitation protection. Therefore, whether the loss of excitation protection and the standard static stability circle is mismatched should be checked in the minimum operating mode of the system.

### 2.4 Parameter adjustment method in case of mismatch

In total, when the generator is in leading power factor operation, the correct matching relationship must be ensured between the excitation system's under excitation limit curve, the loss of excitation protection operation curve, the generator leading power factor depth limit curve, and the standard static stability circle. The generator leading power factor depth curve is determined by the leading...
power factor test. The standard static circle is determined by the system parameters. There is no parameter adjustment problem for the two curves. Generator under excitation limit is a polyline forming action area composed of multi point (P, -Q) coordinates. Adjusting the coordinate value can modify the action range of the curve. The leading power factor depth of the loss of excitation protection is mainly determined by the upper boundary impedance $X_c$ and the lower boundary resistance $X_b$. When $X_b$ becomes larger or $X_c$ becomes smaller, the leading power factor depth becomes smaller, and when $X_c$ becomes smaller or $X_b$ becomes larger, the leading power factor depth becomes greater.

If the under excitation limit and the loss of excitation protection or leading power factor depth curve gets unmatched, the following method can be used to adjust the parameters:

The first step is to adjust the parameters of the under excitation limit (P, -Q) coordinate values so that the under excitation limit curve matches the leading power factor depth limit curve and meet the 5% differential. Considering the maximum +5% error in the loss of excitation protection and the decrease in $U_b$ at the same time, the allowed leading power factor depth reduced. If the loss of excitation protection works precedes to the leading power factor depth limit curve, it is recommend to decrease $X_b$ or increase $X_c$ setting value and keep a 5% difference from the limit curve.

The second step: considering the maximum -5% error in the loss of excitation protection. At the same time, the system is in the minimum operating mode, which makes the leading power factor depth to be larger, and the action curve may be unmatched with the standard static stability circle. At this time, $X_c$ can be increased or $X_b$ can be decreased to reduce the leading power factor depth determined by the loss of excitation protection. After adjusting $X_b$ and $X_c$, it is necessary to check whether the matching meets the 5% differential requirement, between the loss of excitation protection and the leading power factor depth ability curve, if it does not meet the requirements, it needs to further adjust $X_b$, until it meets the requirements.

By adjusting the above parameters, the correct matching relationship can be guaranteed among the four, under excitation limit, generator leading power factor depth ability curve, loss of excitation protection curve and the standard static stability circle.

3. **Coordination examples**

The parameters of a 300MW unit in a power plant are as follows: $S_b=353$MVA, $P_b=300$MW, $U_N=20$KV, $X_d=204.7\%$, $X_d^*=0.2957$, $X_c^*=0.2063$(the system minimum operation mode), $n_{a}=15000/3$, $n_{f}=20/0.1$, the action field of the loss of excitation protection uses the static stability circle criterion, Setting value: upper boundary resistance $X_c=8.55\Omega$. Lower boundary impedance $X_b=85.49\Omega$, (General setting $X_c=X_s$, $X_b=X_d+0.5X_d^*$. Because $X_c$, $X_b$ generally use the nominal value, in the calculation process, $X_s$ and $X_c$ must be first converted to a nominal value. After getting the $X_c$, $X_b$ nominal values, convert $X_c$, and $X_b$ into standard values.)

The under excitation limit curve coordinates are:

{0, -105}, {70, -95}, {140, -70}, {210, -50}, {300,0},

Generator leading power factor ability curve coordinates are:

{0, -130}, {80, -120}, {160, -110}, {200, -100}, {300, -60}

The calculation process is as follow:

Both $X_c^*$ and $X_b^*$ use the generator's rated voltage and apparent power as benchmarks, and their standard values do not need to be converted. Loss of excitation protection impedance needs to be converted. Each impedance calculation formula is as follow:

$$Z_b^* = \frac{U_N^2}{S_b}, \quad X_c^* = \frac{X_c n_{TV}}{Z_b^* n_{TV}},$$
The impedance plane is converted to the P-Q plane center coordinates
\[
\{0, \frac{X_0^*U_g^{*2}}{X_0^{*2} - R_0^{*2}} \},
\]
Radius is:
\[
\frac{R_0^*U_g^{*2}}{R_0^{*2} - X_0^{*2}}^0.
\]

The calculation results are shown in Figure 3–Figure 6.
As shown in Figure 3 that regardless of the operating error of the protection device, when system \( X_s \) operates in the minimum operating mode, generator \( U_s \) maintains the rated voltage, the curves maintain the correct matching relationship.
As shown in Figure 4, considering the protection parameter a +5% error, and \( U_s \) maintains the rated voltage, the loss of excitation protection curve is almost unmatched with the generator leading power factor ability curve.
As shown in Figure 5, when the other parameters remain unchanged and \( U_s \) decreases to 19KV, the loss of excitation protection curve actions precedes to the generator leading power factor ability curve, which is unmatched with the generator ability. Therefore, the verification should be performed when \( U_s \) is lower than the rated voltage. At this time, the setting impedance value of the loss of excitation protection setting should be reduced.
From the data of Figure 6, it can be seen that considering the -5% error of protection parameters, the radius of the impedance circle is smaller, the radius of the action circle in the P-Q plane becomes larger, the allowable leading power factor depth gets larger, and it is easier to match with the under excitation limit curve. Comparing with the data of Figure 3, the loss of excitation protection curve will be easier to get unmatched with the generator leading power factor ability curve at this time. Therefore, it is necessary to consider whether the protection curve is matched with the standard static stability circle when there is a negative error for the protection.

**Figure 3** protection without deviation(\( X_c=8.55, X_b=85.49, U_g=20KV \))

**Figure 4** protection of +5% deviation(\( X_c=8.98, X_b=89.76, U_g=20KV \))
4. Conclusion
This paper theoretically analyzes the influence of various parameter changes on the loss of excitation protection and the under excitation limit, and proposes to use the measured limit curve of the generator as the setting and coordination basis, and proposed the matching and check principle of under excitation limit and the loss of excitation protection based on the device operation error. The method of adjusting parameter when mismatching occurs is discussed .With a calculation of an engineering example, the influence of various parameter changes on the matching relationship is verified, and the effectiveness of the adjustment method is verified. The combination of the under excitation limit and the setting value of the loss of excitation protection and the checking method proposed in this paper provide a effective guiding principle for the current power plants to check and adjust the setting value of the under excitation limit and the loss of excitation protection. But the equations of salient pole synchronous generator for transformation of coordinate is much more complex and needs for further discussion.

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Acknowledgments
This work was supported by Science & Technology Project of State Grid Electric Power Corporation in China (Project name: Research on Synchronous condenser and HVDC converter station reactive power compensation device coordinate control strategy ).