Impact analysis of tap switch out of step for converter transformer

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Abstract. AC transformer load regulation is mainly used to adjust the load side voltage level, improve the quality of power supply, the voltage range is relatively narrow. In DC system, converter transformer is the core equipment of AC and DC power converter and inverter. converter transformer tap adjustment can maintain the normal operation of the converter in small angle range control, the absorption of reactive power, economic operation, valve less stress, valve damping circuit loss, AC / DC harmonic component is also smaller. In this way, the tap switch action is more frequent, and a large range of the tap switch adjustment is required. Converter transformer with a more load voltage regulation switch, the voltage regulation range of the switch is generally 20~30%, the adjustment of each file is 1%~2%. Recently it is often found that the tap switch of Converter Transformers is out of step in Converter station. In this paper, it is analyzed in detail the impact of tap switch out of step for differential protection, overexcitation protection and zero sequence overcurrent protection. Analysis results show that: the tap switch out of step has no effect on the differential protection and the overexcitation protection including the tap switch. But the tap switch out of step has effect on zero sequence overcurrent protection of out of step star-angle converter transformer. The zero sequence overcurrent protection will trip when the tap switch out of step is greater than 3 for out of step star-angle converter transformer.

1 Introduction
Converter transformer is one of the most important equipment in HVDC transmission project. The converter transformer is the core equipment of converter and inverter interface in AC / DC transmission system [1-2], and it provide a phase difference of 30 degrees of commutation voltage for converter valve. The converter transformer group is usually connected in parallel by a star-angle converter transformer and a star-star converter transformer [3-4]. There are many stages of load tap switch for converter transformer. The use of voltage tap switch not only can make the DC transmission system often run in the near optimal state, but also can put converter trigger angle into the appropriate range for the operational safety and economy. The tap switch voltage range is generally 20~30%, the regulation of each gear is 1%~2%, in order to achieve the joint control of tap changer and converter bridge, also in order to adjust no obvious regulation dead zone and avoid frequent reciprocating action. Transformer tap switch three-phase should be in the same position. In converter station, a star-angle converter transformer and a star-star converter transformer must put parallel operation.so the tap switch is in the same position for six phase. if the tap switch of one phase is not consistent, it is called transformer tap switch out of step. Literature [5-8] analyzed in detail the main of converter station’s step switch event, but it doesn’t involve protection. Literature [9-15] mainly describes the present situation of the protection, and literature [16] has analyzed the trip event of zero sequence overcurrent protection due to the tap switch out of step of star-angle converter transformer.
when the converter transformer is no-load switching. According to the recent frequent event of the tap switch out of step in the converter station, it is necessary to analyse converter transformer differential protection, over excitation protection and zero sequence overcurrent protection when the tap switch is out of step in the converter station.

At present, the converter transformer tap switch has been set up step function against loss. There are mainly two kinds of realization principle.

Principle one: When the tap switch is adjusted, gear time relay control circuit, time relay of the tap switch control loop acts, time relay of the tap switch will return when the tap switch adjustment is completed. If there is out of step, the time relay will be acting, delay 14.5s tripping control circuit power switch, lock the tap switch, in order to ensure that a gear up / down command regulation caused by the tap switch action does not exceed 3.

Principle two: in the tap switch regulation process, check the corresponding circuit contactor is closed or open. if the adjustment process is not in place due to circuit component failure or stall regulation, the contactor abnormal state will jump control circuit power switch and lock the tap switch, so the tap switch will not be adjusted continuously greater than 1.

2 Converter transformer protection principle
The converter unit of high voltage and extra high voltage DC transmission system usually adopts twelve pulse forms. The Converter transformer adopts Parallel connection form of a star-angle converter transformer and a star-star converter transformer, and it provides a phase difference of 30 degrees of commutation voltage for converter valve. A HVDC project dc field main connection schematic diagram is shown in figure 1.

![Fig.1 A HVDC project dc field main connection schematic diagram](image)

In converter transformer protection device, the protection associated with the tap switch has differential protection, over excitation protection, zero sequence overcurrent protection, and protection configuration, as shown in figure 2.

![Fig.2 Converter transformer protection configuration diagram](image)
2.1 The principle of differential protection
The tap of the converter transformer is more than the conventional transformer. When the tap was adjusted in some operation state, if the starting element is too sensitive, the device is easy to start by error in normal operation state. Therefore, the criterion of the starting element of the differential protection is:

\[ I_{op} > 0.18 I_c \]  

Among \( I_{op} \) as action current, \( I_c \) as rated current.

The differential protection is mainly used to reflect the inter phase short circuit fault, the single phase to ground fault and the inter turn short circuit fault. Action current and brake current is:

\[ I_{op} = \left| \hat{i}_1 + \hat{i}_2 \right| \]  
\[ I_{res} = \left| \frac{\hat{i}_1 - \hat{i}_2}{2} \right| \]

\( \hat{i}_1, \hat{i}_2 \) individually as the two side current of the network side and the valve side current transformer, \( I_{res} \) as brake current.

When the differential current is more than 0.5 times of brake current, the differential protection will trip.

2.2 The principle of over excitation protection
Over excitation protection is mainly used to reflect high magnetic flux density of converter transformer caused by lower frequency and (or) overvoltage. Over excitation degree can mainly use over excitation of multiple \( n \) to measure.

\[ n = \frac{B}{B_n} = \frac{U}{f} \frac{U_n}{f_n} = \frac{U}{f} \frac{U_n}{f_n} \]  

Among \( U, f \) individually as system voltage and system frequency.

Among \( U_n, f_n \) individually as the reference voltage and reference frequency, generally replaced rated voltage and rated frequency.

If we increase the converter transformer tap switches signal in overexcitation protection, then overexcitation protection with tap switch changes, can realize the adaptive regulation of reference voltage. The reference voltage \( U_n \) is calculated as follows:

\[ U_n = U_{set} * \left[ 1 + (A-C) \right] \]

Among \( U_{set} \) as the reference voltage setting value, A as the tap output, B is the change of the tap, and C is the voltage value of the shift.

2.3 The principle of zero sequence overcurrent protection
Zero sequence overcurrent protection is mainly used as backup protection for grounding fault of transformer neutral grounding operation. Zero sequence overcurrent protection fixed transformer current transformer neutral point special zero sequence TA current. Its action current:

\[ 3I_0 > I_{0,op} \]

Among \( I_{0,op} \) as he zero flow current setting value.

In order to avoid the influence of the inrush current of the converter transformer on the zero sequence overcurrent protection, the device is equipped with two harmonic locking measures.

3 The influence on transformer protection due to the tap switch out of step
The converter switch equipment is provided with a step function against loss, making the step tap maximum of not more than three. In discussing the impact of the tap switch out of step on converter transformer protection, it is necessary to consider the commutation failure of the tap changer. In this paper, the commutation failure of the tap changer is analyzed in three cases:
(1) out of step 1
(2) out of step 3
(3) out of step maximum gear
To step -6 ~ +18, the step variation is 1.25% as an example. The maximum loss of converter transformer is 18 stalls. The number of out of step steps is relative to the reference 0.

3.1 The influence on differential protection due to the tap switch out of step
Normally, the differential current is zero, as shown in equation (7).

\[ I_{\text{op}} = |K_h \dot{I}_h + K_i \dot{I}_i| = |\dot{I}_h + K_i \dot{I}_i| = 0 \] (7)

Among \( I_h \) as net side current, \( I_i \) as valve side current, \( K_h \) as net side balance coefficient.

\( K_h = 1, \ K_i \) as valve side balance coefficient.

Normally, the differential current balance, as shown in equation (7). When the tap switch is out of step, the differential current is no longer balanced, as shown in equation (8).

\[ I'_{\text{op}} = |\dot{I}_h + K_i \dot{I}_i| = \left| \frac{1.25\% \times k}{(1 \pm 1.25\% \times k)} \right| \dot{I}_h \] (8)

It can be seen from the formula (8) that the differential unbalance current is related to the regulating tap switch and the load current. The higher the regulating gear is, the greater the differential unbalance current is. The larger the load current is, the larger the differential unbalance current is.

If the tap switch is out of step, it is equivalent that the unbalanced differential current of the three-phase is not the same for the differential protection, but the calculation method is the same as the method for calculating unbalanced differential current caused by regulating tap. For the way of raising tap and voltage and for the way of rising tap and reducing voltage, the corresponding differential current is shown in table 1.

| Table 1 | Simulation result statistics of no-load closing switch with the tap switch out of step |
|---------|-----------------------------------------------|
|         | differential current of raising tap and voltage | differential current of rising tap and reducing voltage |
|         | \( (A) \) | \( (A) \) |
| 1       | \( 0.0127I_h \) | \( 0.0123I_h \) |
| 3       | \( 0.0390I_h \) | \( 0.0361I_h \) |
| 18      | \( 0.2903I_h \) | \( 0.1836I_h \) |

The regulation mode of rising tap and increasing voltage, refers to the increase in the tap, the network side winding input less. The regulation mode of rising tap and reducing voltage, refers to the increase in the tap, the network side winding input more.

Table 1 shows that the tap switch out of step is less than 3, the differential protection will not start and trip. the tap switch out of step is maximum, the differential protection will start, but will not trip.

3.2 The influence on over excitation protection due to the tap switch out of step
Adaptive adjustment of reference line voltage is based on converter transformer taps adjustment, and change \( U_n \) in real time change in formula(4). The overexcitation curve correspondingly change when \( U_n \) change, in order to better response overexcitation tolerance.

The magnetic multiple considering the tap variation is:

\[ n = \frac{B'}{B_n} = \frac{U_i}{U_n (1 \pm 1.25\% \times k)} / \frac{f'}{f_n} \] (9)
From (9) knowable, the excessive magnetic multiple will change with the change of the tap. For the way of raising tap and voltage and for the way of rising tap and reducing voltage, the corresponding excess magnetic multiples are shown in table 2.

| Out of step tap | Excessive magnetic multiple of raising tap and voltage | Excessive magnetic multiple of rising tap and reducing voltage |
|-----------------|------------------------------------------------------|---------------------------------------------------------------|
| 1               | 1.013N                                               | 0.988N                                                        |
| 3               | 1.039N                                               | 0.964N                                                        |
| 18              | 1.290N                                               | 0.816N                                                        |

As can be seen from table 2: the tap switch out of stap has no effect on over excitation protection.

3.3 The influence on zero sequence overcurrent protection due to the tap switch out of step

3.3.1 Zero sequence impedance circuit of converter transformer. The equivalent circuit diagram of the zero sequence circuit and the zero sequence reactance of a star-angle converter transformer and a star-star converter transformer are shown in Figure 3 and Figure 4 respectively.[14]:

![Figure 3](image3.png)

**Fig.3** Zero sequence equivalent circuit of star-angle Converter transformer

According to the equivalent circuit, the zero sequence reactance of a star-angle converter transformer:

\[ X_{T0} = X_f + \frac{X_m X_m}{X_m + X_m} \]  \hspace{1cm} (10)

![Figure 4](image4.png)

**Fig.4** Zero sequence equivalent circuit of star-star Converter transformer

According to the equivalent circuit, the zero sequence reactance of a star-star converter transformer:

\[ X_{T0} = X_f + X_m \]  \hspace{1cm} (11)

In the above two formulas, \( X_f \), \( X_m \) and \( X_m \) as represent the leakage reactance of the primary side of the converter transformer, the leakage reactance and the reactance of the two side. In the DC transmission system, the star-angle converter transformer and star-star converter transformer are composed of 3 single-phase transformers. The zero sequence magnetic flux can take the iron core as the loop. The excitation reactance is much larger than the leakage reactance due to the large magnetic conductivity.

1. Zero sequence reactance of the star-angle converter transformer:

\[ X_{T0} = X_f + \frac{X_m X_m}{X_m + X_m} \approx X_f + X_m \]  \hspace{1cm} (12)

2. Zero sequence reactance of the star-star converter transformer:

\[ X_{T0} = X_f + X_m \approx \infty \]  \hspace{1cm} (13)
3.3.2 Zero sequence impedance loop of the star-angle converter transformer when tap switch is out of step. Zero sequence network of the star-angle converter transformer when tap switch is out of step as shown in figure 5.

![Fig.5 zero sequence network of the tap switch out of step for the star-angle Converter transformer](image)

Among $X_{70}$ as zero sequence reactance of the star-angle Converter transformer in the state of tap switch out of step, $X_0$ as equivalent power zero sequence reactance, $X_{70}'$ as the zero sequence reactance of the other three star-angle converter transformers in the state of tap switch in step.

Because the zero sequence current of the valve is only in the ring, the size of the zero sequence current is independent of the operating mode of the DC system.

Zero sequence current of the star-angle converter transformer when tap switch is out of step:

$$3I_0 = \frac{U(1 \pm 1.25\% \cdot K)}{X_{70} / / X_{0} / / X_{70}'} \cdot \frac{X_0 / / X_{70}'}{X_{70} + X_0 / / X_{70}}$$  \hspace{1cm} (14)

From (9) knowable: The zero sequence current is gradually increased with the increase of tap switch is out of step. It should be analyzed in detail with the specific system that sequence overcurrent protection act or not.

4 Simulation analysis of tap switch is out of step

The author regard a 800KV UHVDC transmission project shown in Figure 1 as the RTDS test model. The tap control is modified from the original unified control to the split phase control for adopting Parallel connection form of a star-angle converter transformer and a star-star converter transformer. In this paper, we mainly do the transformer transformer tap switch out of step test in Transformer no-load closing and bipolar operation mode.

4.1 Test parameters

Test parameters are shown in table 3.

| Test parameters name | rated parameter |
|----------------------|-----------------|
| capacity             | 3×404MVA        |
| network side rated voltage | 530kV           |
| star angle valve side rated voltage | 171.4kV       |
| star star valve side rated voltage | 171.4kV       |
| short circuit impedance Uk% | 0.195          |
| the network side TA ratio | 2000/1          |
| zero sequence TA ratio | 2000/1          |
| adjusting range of tap | -5/+23          |
| adjusting step of tap | 1.25%            |
| time constant        | 1.85s           |
| AC system impedance  | 4.8\Omega       |

Zero sequence overcurrent protection setting value as shown in table 4.
Table 4 Setting value of zero-sequence over-current protection

| Setting name                                      | Value (primary value) |
|--------------------------------------------------|-----------------------|
| zero sequence overcurrent setting                | 200A                  |
| zero sequence overcurrent delay                  | 5s                    |
| Zero sequence overcurrent harmonics              | 0.15                  |
| Zero sequence two harmonic control               | 1                     |

4.2 Tap switch out of step test in Transformer no-load closing

In order to better distinguish the converter transformer tap switch out of step with the mutual influence of no-load, we choose that the converter transformer close 10B1.C switch shown in figure 1. in Voltage zero crossing. The specific test is shown in figure 6.

![Figure 6](image)

Fig.6 Zero sequence current of no-load closing switch with the tap switch out of step

As can be seen from Figure 6, in the no-load closing moment, amplitude of inrush current is the maximum, and amplitude of inrush current decays with time. but amplitude of inrush current due to tap switch out of step does not decay with time.

Table 5 Simulation result statistics of no-load closing switch with the tap switch out of step

| Out of step tap | Fundamental current at 0s moment | Two harmonic current at 0s moment | Fundamental current at 5s moment | Two harmonic current at 5s moment |
|-----------------|---------------------------------|----------------------------------|---------------------------------|----------------------------------|
| 0               | 2022A                           | 1469A                            | 12A                             | 18A                              |
| 1               | 2152A                           | 1504A                            | 88A                             | 18A                              |
| 3               | 2209A                           | 1477A                            | 237A                            | 18A                              |
| 18              | 2317A                           | 1606A                            | 1450A                           | 16A                              |

From table 5 we can see:

(1) In the no-load closing moment for converter transformer of the valve 1 high-end, amplitude of inrush current is the maximum, and the two harmonic content exceeds 15%, adopting zero sequence overcurrent protection with two harmonic block criterion is effective.

(2) Amplitude of inrush current decays with time. when the time reaches 5s, tap switch out of step of star-angle converter transformer is more than 3 steps, zero sequence current action value reached 200A, and the two harmonic blocking criterion of zero sequence overcurrent protection is not satisfied, so zero sequence overcurrent protection of star-angle converter transformer will trip.

4.3 Tap switch out of step analysis in power transfer process

In this paper, the variation of zero sequence current caused by the difference of the step switch out of step for star-angle converter transformer, in full power bipolar operation mode, full power unipolar operation mode and low power bipolar operation mode.
4.3.1 Under the same transmission power, the simulation of the difference of the step switch out of step. In the case of full power monopole operation, the zero sequence current due to the difference of the step switch out of step is shown in figure 7.

As can be seen from Figure 7: under the same operating mode of the DC system, the zero sequence current of the transformer is gradually increased with the increase of the step switch out of step; Specific values are shown in table 6.

| Out of step tap | Zero sequence fundamental current in 4000MW operation mode |
|-----------------|----------------------------------------------------------|
| 1               | 78A                                                      |
| 2               | 156A                                                     |
| 3               | 222A                                                     |
| 8               | 651A                                                     |
| 18              | 2256A                                                    |

4.3.2 The simulation of the tap switch in the same step out of step and under different transmission power. When the star angle transformer tap switch out of step is 3 steps, in the case of different power levels, the zero sequence current is shown in figure 8.

As can be seen from figure 8, the zero sequence current generated by a transformer with a tap changer is independent of the operating mode of the DC system. Specific values are shown in table 7.

| Out of step tap | Zero sequence fundamental current in 800MW operation mode | Zero sequence fundamental current in 4000MW operation mode | Zero sequence fundamental current in 8000MW operation mode |
|-----------------|----------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| 1               | 81A                                                      | 78A                                                      | 72A                                                      |
| 3               | 218A                                                     | 222A                                                     | 219A                                                     |
| 18              | 2304A                                                    | 2256A                                                    | 2280A                                                    |

According to the experiment, we can draw the following conclusions:
(1) the zero sequence current generated by the tap switch out of step is a steady state current, and the amplitude of the current does not change with time.

(2) under the same operating mode of the DC system, the zero sequence current of the transformer is gradually increased with the increase of the star angle transformer tap switch out of step.

(3) the zero sequence current generated by a transformer with a tap changer is independent of the operating mode of the DC system.

(4) the tap switch out of step of star-angle converter transformer is more than 3 steps, zero sequence current act because of action value reaching 200A.

(5) there is no zero sequence current in the other star angle transformers that does not happen the tap switch out of step.

5 Conclusion
In view of the recent frequent tap switch out of step in converter station, this paper analyzes the effect of converter transformer differential protection, over excitation protection and zero sequence overcurrent protection generated by the tap switch out of step. The conclusions are as follows:

(1) Influence of differential protection and the tap over excitation protection generated by tap switch out of step is not enough to cause the protective action, it can not take measures. The tap switch out of step will cause the zero sequence overcurrent protection of the tap switch out of step of star-angle converter transformer tripping.

(2) the zero sequence current generated by a transformer with a tap changer is independent of the operating mode of the DC system. under the same operating mode of the DC system, the zero sequence current of the transformer is gradually increased with the increase of the star angle transformer tap switch out of step. the tap switch out of step of star-angle converter transformer is more than 3 steps, zero sequence current will trip.

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