Research on the Differential Protection of the SFC Output Transformer for Pumped Storage Hydro Unit

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Abstract. Pumped storage power stations play an great role in promoting new energy consumption, ensuring the safety of power grid, building clean, low-carbon, safe and efficient energy system, and has a broad development prospect. SFC is the most important start-up mode of pumped storage unit, and the output transformer is an important equipment of SFC system, which needs to be equipped with reliable and fast differential protection to ensure its safe and reliable operation. The current frequency varies from 0 to 50Hz during SFC start-up, so the conventional transformer differential protection can not adapt. In this paper, the output transformer differential protection technology is studied according to the electrical characteristics and short circuit fault characteristics of SFC start-up process, the high precision frequency algorithm and the RMS integration algorithm with compensation are proposed to realize the precise measurement of frequency and amplitude, and the ultra-low frequency CT saturation identification technology is proposed to realize the whole process protection of the output transformer from start-up to grid-connection.

1. Introduction
For the purpose of realizing the “peak carbon dioxide emissions and carbon neutrality”, and achieving the clean and low-carbon transformation of energy and green economic development, we need to strive to develop the clean energy and constantly improve our consumption ability of new energy. The pumped storage power station, as a kind of flexible power source, plays a big role in facilitating the new energy consumption, ensuring the power grid safety and building the clean, low-carbon, safe and efficient energy system, and is an important part of the electric power system based on new energy with a broad development prospect.

Pumped storage power station unit is subject to coaxial electromotor start, coaxial water turbine start, asynchronous start, back-to-back start and frequency converter start. When being operated under electromotor pumping condition, the pumped storage hydro unit cannot be started by water turbine under generator operation condition. At present, large-scale pumped storage hydro units are mainly started in the form of static frequency converter (SFC) start, with back-to-back start under backup application. Characterized by continuously variable transmission, smooth start and promptly response, SFC start could rapidly and steadily drag the unit from static state to a synchronous speed, by virtue of the operating principle of converting the power-frequency AC to variable-frequency AC of which power increases gradually with thyristor frequency converter, outputting to the motor stator winding and generating the rotating magnetic field of stator further advanced than the rotor field, thus
accelerating rotor to a synchronous speed through the interaction between stator field and rotor field \[2\].

At present, the domestic static frequency converter equipment have been successfully developed and applied in Jiangsu Shahe, Anhui Xiangshuijian, Shandong Tai’an and other pumped storage power stations. SFC start system consists of the input transformer, controller, network bridge, machine bridge, smoothing reactor and output transformer. Basically identical to the structure of common transformer, the output transformer, as an important equipment of static frequency converter system, would affect normal operation of the pumped storage power station in case of any equipment damage due to a fault, so that the output transformer must be configured with reliable and rapid differential protection. Foreign SFC system output transformers are usually configured with conventional differential protection and non-electricity protection, but on either side of the output transformer, there is the variable-frequency current ranging from 0 to 50Hz, which is of high harmonic content. Moreover, for the conventional differential protection, 50Hz fixed-frequency algorithm is adopted, which is of low protection sensitivity and cannot adapt to SFC starting condition; One differential protection of domestic SFC system output transformer has proposed to apply the start-up and shut-down protection algorithm independent of frequency (zero-crossing-point integral algorithm or current peak discrimination method) in the generator protection, achieved accurate current measurement during SFC start, and used the variable-slope ratio braking characteristic, so as to prevent external-fault differential protection from malfunction \[2\][3]. During the process of SFC start, the harmonic wave takes a high proportion, and the current might decline and cross zero upon forced phase change at the stage of low-frequency start, severely affecting the frequency and the accuracy of algorithm calculating current amplitude based on zero crossing point; At the point of SFC low-frequency start (0~5Hz), current transformers at both sides of the output transformer might suffer from low-frequency saturation, causing differential protection malfunction \[4\][5][6]. Therefore, at the stage of SFC low-speed start, normally, the start with bypass knife switch is normally used, such that during the stage of start at low speed, the output transformer would be isolated through bypass knife switch to lead the device to the auxiliary node of bypass knife switch, and the differential protection would be blocked when the bypass switch is off \[7\][8]. However, the bypass knife switch is operated frequently, so it is easy to break down, while the start-up might fail if the auxiliary node of position is abnormal.

In conclusion, analysis must be made to the electrical and fault characteristics of current at the machine bridge side during SFC start, and research must be performed to eliminate the influence of pseudo zero crossing point, with application of frequency algorithm and effective value integral algorithm improving accuracy in case of severe waveform distortion and high harmonic content, so as to achieve the accurate measurement of wide frequency range, high harmonic content current frequency and amplitude during the process of SFC start. Study is made to the ultra-low frequency CT saturation identification technology in the course of SFC start to realize the whole-course protection when SFC is started without bypass knife switch, and ensure that any fault of output transformer could be eliminated reliably and rapidly during SFC start-up, so as to guarantee the safe and reliable operation of SFC system.

2. Analysis on electrical characteristic during SFC start-up

Static frequency converter start-up system consists of the incoming circuit breaker, input transformer, controller, network bridge (rectifier), machine bridge (inverter), smoothing reactor, bypass knife switch, isolating switch and output transformer (as shown on Fig.1). When, in the absence of output transformer, an isolation transformer is used as the input transformer in Fig.1, such mode of connection is called as high-high type; When a step-down transformer is used as the input transformer, and a step-up transformer is used as the output transformer, such mode of connection is called as high-low-high type; Combined with change in number of pulse waves and voltage characteristic, common topological structures of the major loop are high-low-high 6-6 pulse wave type, high-low-high 12-6 pulse wave type, high-low-high 12-12 pulse wave type and high-high 6-6 pulse wave type \[2\][11].
Figure 1. Typical Configuration of SFC System.

Major functions of SFC controller include the frequency converter power control, protection monitoring, motor rotor position detection, and rotating speed control of unit, etc. For the input and output transformers, their functions mainly are to realize the isolation of the power grid with SFC and SFC with pumped storage hydro unit, reduce the withstanding voltage of power bridge, and restrict the short-circuit current. The smoothing reactor is mainly to restrain DC ripple and restrict the DC climbing speed in case of any fault. Network bridge converts the power frequency AC rectification to DC with high-power thyristor, and machine bridge reversely changes DC to AC at variable frequency [2].

There mainly are two kinds of start-up for SFC, and currently, the start with bypass output transformer at the stage of low-frequency start-up is more used, that is: at low frequency (below 5Hz), with bypass output transformer, SFC machine bridge directly drags the unit to start up, and when the frequency is over 5Hz, SFC machine bridge drags the unit through output transformer to continue starting up until completion of grid connection. Starting mode without bypass knife switch (namely, the output transformer is input throughout the course of start-up, and SFC machine bridge drags the unit from static state to grid connection through output transformer) has advantages of simple operation and high start-up success rate and has already been used in Shandong Tai’an Pumped Storage Power Station.

SFC system of pumped storage hydro unit is applied at rising frequency and rising voltage with constant frequency-voltage ratio (Fig.2). During the overall process of start-up, the ratio of voltage to frequency at high voltage side of the output transformer is basically invariant, while the motor stator current is also fundamentally remained unchanged at rated current. The start-up is basically categorized into 5 stages as follows: detect the initial position of unit rotor; initially trigger the machine bridge and network bridge valve bank to drive the unit rotor to rotate; at the low-frequency rotate speed stage of the unit, control the machine bridge valve bank through forced phased change to achieve frequency raising and speed raising of unit rotor; Upon high frequency of the unit (>5 Hz), control the machine bridge valve bank by natural phase change to increase the speed of unit rotor to the set rotate speed; when the unit frequency is greater than the set frequency of grid connection, input into the grid connection at the corresponding period, and SFC system quits. As per the operation requirement, the pumped storage unit should be started for dozens of times every day, generally no more than 5min per start-up [1].

Figure 2. Motor voltage and current characteristics of SFC constant voltage-frequency ratio startup mode.
Throughout SFC start-up, the frequency of current on either side of the output transformer changes from 0~50Hz, with abundant harmonic wave. At the initial phase of unit start-up, when the rotate speed is relatively low (0~5Hz), there is relatively small voltage at AC side of the machine bridge, and for the thyristor, natural phase change cannot be made, so that the forced phase change is required; When rotate speed of the unit is relatively high (more than 10% of rated rotate speed), there are relatively high motor back-emf and machine bridge AC voltage, so the thyristor could reach natural phase change by virtue of motor back-emf. Besides, when turning off the thyristor through forced phase change of thyristor, the current at AC side of the machine bridge might decline and cross zero (Fig.3), and when turning off the thyristor with natural phase change at relatively high rotate speed (>5 Hz), the current at machine bridge side may also fluctuate and drop below zero. On account of a relatively long time, about 30s, at the low-frequency (0~5Hz) start-up stage, the current transformer at both sides of the output transformer are very easy to be saturated (Fig.4), causing differential protection malfunction of the output transformer.

Figure 3. Current characteristics of Forced communication.

Figure 4. Current characteristics of Ultra-low frequency CT saturation.
3. Analysis on short circuit fault of output transformer during SFC start-up

During SFC start-up, SFC controller may turn off the thyristor and trigger pulse (about 3ms) immediately after detecting a fault, if any, at the start-up circuit, so that provision of short-circuit current by SFC machine bridge may not be considered when analyzing the short circuit fault of output transformer, and the short-circuit currents are all supplied by the unit.

Take one pumped storage power station unit and SFC primary equipment parameters as the example for short-circuit fault analysis. Given that the unit’s apparent power is 278MVA, rated voltage is 15.75kV, rated frequency is 50Hz, rated rotate speed is 300r/min, and subtransient reactance per-unit value is 0.22 (saturation value); The apparent capacity of output transformer is 15.96MVA, the rated voltage at high voltage of the output transformer is 15.75kV and the rated voltage at low voltage side is 5kV, Dyn11 (delta connection at unit side) wiring mode, and the short-circuit impedance per-unit value is 12%.

Based on the unit capacity of 278MVA, the subtransient reactance per-unit value of unit $X''_d$ is 0.22, so the short-circuit impedance per-unit value of the output transformer $X''_T$, is calculated as follows:

$$X''_T = 0.12 \times \frac{278}{15.96} = 2.09$$  \hspace{1cm} (1)

Rated current at high voltage side of the output transformer based on the unit capacity is:

$$I_e = \frac{S}{\sqrt{3}X''_d} = \frac{278000}{\sqrt{3} \times 15.75} = 10190.69$$  \hspace{1cm} (2)

During start-up of SFC system, the voltage-frequency ratio remained constant, that is, $\frac{\nu_{change}}{\nu_{change}} = k$.

During start-up of SFC system, three-phase short-circuit fault current at low voltage side of the output transformer is:

$$I_d = \frac{I_e}{X''_T + X''_d} \times \frac{\nu_{change}}{\nu_{change}} = 4411 \times k$$  \hspace{1cm} (3)

$$I_d = \frac{I_e}{X''_T + X''_d} \times \frac{\nu_{change}}{\nu_{change}} = 46321 \times k$$  \hspace{1cm} (4)
Figure 7. Three-phase short circuit Three-phase short circuit equivalent circuit of output transformer HV side.

Figure 8. Current characteristics of output transformer HV side Three-phase short circuit.

SFC controls the strategic start-up with constant voltage-frequency ratio, and during the low-frequency start-up, even though the voltage at unit side is relatively low, the probability of fault are the same at fault current and under rated voltage, greatly endangering the output transformer, so that any fault found during start-up of SFC must be eliminated reliably and rapidly to guarantee the equipment safety.

4. Research on differential protection of output transformer

Output transformer, as an important equipment of SFC system, requires configuring the differential protection as the main protection in case of any transformer winding fault. Upon normal operation or external fault of transformer, the phasor sum of current on either side is 0, and upon internal fault of transformer, the phasor sum of current on either side is equal to short-circuit current at the fault point. In this context, the differential protection covers the parts of current transformers at each side, consisting differential protection, including the transformer body and lead.

Differential protection of the output transformer is based on the current phase at delta side to perform phase shift for the current at star side. The phasor difference between currents at both sides is applied as the restraint current to improve the protection sensitivity upon internal fault of the output transformer. Differential protection difference current and restraint current are respectively calculated as follows:

\[
\begin{align*}
I_d &= |I_1 + I_2| \\
I_{res} &= \frac{1}{2} \times |I_1 - I_2|
\end{align*}
\]

Where: \(I_1\) and \(I_2\) respectively are the currents at both sides of output transformer after phase shift.

Upon start-up of SFC system, the currents at both sides of output transformer are subject to severe distortion, frequency change between 0~50Hz and high harmonic content, so the variable-frequency protection must adapt to the dynamic frequency change, current waveform declination, ultra-low
frequency CT saturation and other problems occurred during SFC start-up, without malfunction and failure to operate.

4.1. High-performance digital low-pass filter adaptive frequency switching

During start-up of SFC system, currents at both sides of the output transformer contain a great number of higher harmonics, so at the stage of forced commutation, the current may decline and cross zero, and at the stage of natural commutation, it may also fluctuate and decline and cross zero for multiple times. Such “pseudo zero crossing point” of the current waveform would affect the accuracy of frequency measurement algorithm and effective value integral algorithm based on current zero crossing point. Cut-off frequency of the ultra-low frequency digital low-pass filter is designed at 20Hz, and cut-off frequency of the low-frequency digital low-pass filter is designed at 100Hz, with amplitude-frequency characteristic as shown on Fig.9 and Fig.10. Ultra-low frequency and low-frequency low-pass filters are subject to adaptive frequency switching, with their frequency after start-up lower than that of the ultra-low frequency digital low-pass filter used at 5Hz stage, and frequency greater than that of low-frequency digital low-pass filter used at 5Hz stage. From Fig.11 and Fig.12, it can be seen that the “pseudo zero crossing points” in the current waveform are efficiently eliminated, and the higher harmonics are well suppressed at the same time, so as to create conditions for realizing the accurate measurement of frequency and effective value measurement of current.

Figure 9. Amplitude-frequency characteristics of ultra-low frequency digital low-pass filters.

Figure 10. Amplitude-frequency characteristics of low frequency digital low-pass filters.
4.2. High precision frequency algorithm

During SFC start-up, especially at the ultra-low frequency stage, the current waveform distorts severely and is likely to decline and cross zero, and the current contains a great number of harmonic component, severely affect the frequency measurement accuracy, which is greatly improved for the current waveform after treatment by high-performance digital low-pass filter. This provides conditions for the zero-crossing-point frequency measurement algorithm. Zero-crossing-point time interval of two sampling values from negative to positive is calculated, which is the current period $T$. As the sampling values are not likely to just cross zero, the accurate time of zero crossing point of the sampling values is calculated with Lagrangian’s 3-point interpolation algorithm, greatly improving the accuracy of frequency measurement during the start-up, especially in the natural commutation stage.
Figure 13. Schematic diagram of high precision zero-crossing frequency measurement algorithm. 3-point Lagrangian’s interpolation formula is:

\[ y = y_0 \frac{(x-x_3)(x-x_2)}{(x_0-x_3)(x_0-x_2)} + y_1 \frac{(x-x_0)(x-x_2)}{(x_1-x_0)(x_1-x_2)} + y_2 \frac{(x-x_0)(x-x_1)}{(x_2-x_0)(x_2-x_1)} \]  \hspace{1cm} (6)

Assign the sampling interval as \( T_0 \), and the 1st zero-crossing-point compensation time of the current sampling value from negative to positive as \( T_{c1} \). According to the above formula, \( x - x_3 = T_{c1}, x - x_0 = T_{c1} - T_s, x - x_2 = T_s + T_{c1} \), sampling value upon zero crossing \( y=0 \), so it is available as follows:

\[ (y_0 - 2y_1 + y_2)T_{c1}^2 - (y_2 - y_0)T_sT_{c1} + 2y_1T_s^2 = 0 \]  \hspace{1cm} (7)

Solve the equation, and \( T_{c1} \) can be obtained. In a similar way, the 2nd zero-crossing-point compensation time of the current sampling value from negative to positive \( T_{c2} \) can be obtained through calculation, so the electrical cycle of current is \( T = T_{c2} - T_{c1} + T_{c2} \), and the current frequency is \( f = \frac{1}{T} \).

4.3. RMS integration algorithm with compensation

For the effective value integral algorithm, in case of frequency change, non-integer-period sampling is inevitable as the different interval sampling is used for the protective devices [12]. If the integral window length cannot be adjusted at real time as per the frequency change, the calculation accuracy would be affected. On the basis of achieving accurate measurement of current frequency, dynamic adjustment is made to the data window length of effective value integral algorithm, the integer-period compensation time \( \Delta t \) is calculated, and non-integer-period sampling point is compensated, which can greatly improve the current measurement accuracy.

Figure 14. Schematic diagram of high precision effective value integral algorithm.
N sampling points within the integration period \( T \) respectively are \( x(0), x(1), \ldots, x(N - 1) \), and the calculation method of discretized effective value integral algorithm with compensation is:

\[
I = \sqrt{\frac{1}{(N-1)T_0 + \Delta t} \sum_{i=0}^{N-2} x^2(i) + x^2(N - 1)\Delta t}
\] (8)

Where: sampling interval is \( T_0 \); data window length is \( N \); \( \Delta t \) is compensation time; \( I \) refers to effective value of current.

4.4. Ultra-low frequency CT saturation identification criterion

Through the equivalent circuit of current transformer, CT secondary circuit voltage equation can be obtained:

\[
u = R i + L \frac{di}{dt}
\] (9)

From the integrals of above formula, the iron-core flux linkage of current transformer can be obtained:

\[
\psi = \psi(0) + R \int_0^t i(t) \, dt + L[i(t) - i(0)]
\] (10)

Where: \( u \) is CT secondary voltage drop; \( i \) is CT secondary current; \( L \) is CT secondary circuit reactance; \( R \) is CT secondary circuit resistance; \( \psi \) is CT winding iron-core flux linkage.

When SFC is started without bypass knife switch, 0~5Hz low-frequency start-up requires a long time, and the ultra-low frequency current acts on CT secondary circuit resistance component for such a long time, so the flux linkage is accumulated gradually, which would cause current transformer saturation at both sides of the output transformer, and lead to differential protection malfunction, thus affecting the start-up success rate.

During SFC start-up, when CT is transmitted correctly, for secondary current of current transformer at both sides of output transformer, its self-produced zero-sequence current is 0; and when CT is saturated, the self-produced zero-sequence current is not equal to 0, and the amplitude of saturated phase current decreases. At low voltage side of the output transformer, the wires are under start connection, with neutral point grounded via high resistance, and at the high voltage side, there is the delta connection, so there is no zero-sequence current component at both sides upon fault while the zero-sequence current and difference current occur synchronously upon CT saturation. Therefore, the ultra-low frequency CT saturation identification criterion could be established on the basis of above characteristics, and if it is distinguished as CT saturation, the action threshold of variable-frequency differential protection should be adjusted dynamically, so as to ensure no differential protection malfunction upon ultra-low frequency CT saturation.

![Figure 15. Criterion of ultra-low frequency CT saturation.](image_url)

5. Conclusion

This paper studies the differential protection technology of output transformer, and the high-performance digital low-pass filter with adaptive frequency switching is designed, eliminating the pseudo zero crossing points affecting the frequency and amplitude accuracy. In addition, the high-accuracy frequency algorithm and the RMS integration algorithm with compensation are used to realize the accurate measurement of frequency and amplitude. Furthermore, the initiative ultra-low frequency CT saturation identification criterion can adapt to SFC start-up without bypass knife switch, achieving whole process protection of pumped storage hydro unit from start-up to grid connection. The protective device of output transformer, developed on the research content in this paper, has been applied and performed well.
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References
[1] Petersson T. (1972) Starting of large synchronous motor using static frequency converter[J]. IEEE Trans on PAS, 91(1): 172-179.
[2] Jun Chen, Yuhong Chang. (2019) The technologies of pumped storage hydro unit and auxiliary equipment. Relay protection[M], China Electric Power Press.
[3] Jun Chen, Hongjian Si, Rongbin Zhou, et al. (2013) Key technologies of SFC system protection for pumped storage hydro unit. Electric Power Automation Equipment, 33(8): 167-171.
[4] Jun Zhou. (2004) Variable-frequency starting of SFC in pumped storage power plant[J]. Electric Power Automation Equipment, 24(11): 99-101.
[5] Baojun Ge, Yuling Li, Bo Li. (2002) Study of starting process of pumped storage machines by static frequency converter[J]. Electric Machines and Control, 6(3): 200-203.
[6] Zheng Zhao. (2010) Static frequency converter for pumped storage station[J]. Water Power, 36(1): 66-69.
[7] Dongqi Huang, Xuebiao Shan, Jiaxi He, et al. (2020) Start-up control strategy of static frequency converter in stages[J]. Power Engineering Technology, 39(6): 184-190.
[8] Xueqin Hu. (2007) Summary and probe of static frequency converter of pumped storage power station[J]. Water Power, 3(5): 51-54.
[9] Hua Shan, Yufei Peng, Gang Xu. (2017) Application and parameter optimization of SFC in pumped storage power plant[J]. Power Engineering Technology, 36(1): 109-112.
[10] Hongtao Yang. (2004) Analysis of static frequency converter system in Tiantang pumped storage power plant[J]. Hydropower Automation and Dam Monitoring, 28(4): 25-28.
[11] Zhijian Li, Chonghao Wu, Luofei Wan, et al. (2020) Analysis of start-up process and implementation of start-up protection of a large synchronous condenser, 48(20): 148-154.
[12] Huihui Yang, Huanian Zhang, Tongzhong Fang, et al. (2013) Analysis of effective value integral on frequency offset[J]. Journal of Electric Power, 28(2): 119-121.