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A New Protection Strategy Based on Negative Sequence Current Coordinated Control on the Generator Extremity

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ABSTRACT When the single-phase reclosing of the high-voltage circuit, there will be tremendous negative sequence current generation. The connection of inverter-type new energy sources may increase the negative sequence current of the power system. The risks will be greatly increased if a large negative sequence current invades the generator, and it will cause the general stator damaged and offline. Based on the chain STATCOM compensation, a new strategy of negative sequence current coordinated control protection on the generator extremity is put forward. This strategy can predict the operation time of inverse time negative sequence current protection by monitoring the negative sequence current on the generator extremity. Once it is determined that the negative sequence current has an effect on the power system, according to the relationship between the STATCOM capacity and the magnitude of negative sequence current, two schemes of full compensation and incomplete compensation are proposed. The negative sequence current output by STATCOM suppresses the magnitude of the negative sequence current invading the generator. It eliminates or prolongs the operation time of the negative sequence current protection and gets more time for power system security and stability control. Finally, the simulation results verify the correctness and feasibility of the proposed strategy.

INDEX TERMS New energy, negative sequence current, inverse time, STATCOM.

I. INTRODUCTION

The development of society has brought about an increase of the electricity demand. Traditional electric power development concept can hardly meet the quality demand of the electric energy. The research and development of new energy is a general trend. New energy has the advantages of higher cleanliness and larger reserves than traditional energy, and the modern power network systems become diverse and complex because of its widespread application. It has also brought serious imbalances to the system [1]–[3]. Negative sequence current will be generated when the system is unbalanced. It will cause local burns in some parts of the generator stator and even more serious accidents. The renewable power integration may increase the negative sequence current of the system. It will result in operation of the negative sequence protection and the group will be switched off, which will significantly impact the safety and stable operation of power system [4]–[6].

New energy sources connected to the power grid can be divided into two types: asynchronous power sources and inverter power sources. For asynchronous power sources, such as double-fed wind generator, negative sequence current will be injected into the power grid during operation. For inverter power sources, only positive sequence current is generated when the grid fails, and no negative sequence or zero sequence current is generated. Virtual synchronous generator control is widely used in wind power and photovoltaic inverters, but it may help increase the system's large negative sequence current when the grid voltage is unbalanced.

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New energy integration will change the operation mode of the power system. In order to make that the operation time of all protection levels can still be matched automatically under the circumstance when the operation mode of power grid changes greatly, the generator is equipped with inverse time overcurrent protection. But it is not yet mature, and its setting coordination is very complicated. Many experts and scholars are conducting the deeper research on it. Reference [7] proposed an inverse time protection strategy when the distributed inverter power is connected, which based on the electrical characteristics of the voltage drop during a fault. However, the traditional inverse time limit is mostly based on the lower voltage level, but it doesn't consider the heat dissipation of the generator rotor. Reference [8] proposed to use the natural distribution of the grid voltage under faults, and the inverse time characteristic curves are modified by constructing the voltage correction factor and the voltage gradient index.

In addition, many experts and scholars focus on the compensation methods to suppress negative sequence current under the inverse time operation current. Reference [9] proposed to reduce the negative sequence current by increasing the negative sequence impedance; Reference [10] proposed a method of current tracking control which based on coordinate transformation, but it was limited to compensating for three phase balanced loads; Reference [11] proposed a two-layer control strategy which included reactive power compensation, negative sequence compensation and capacitor voltage equalization, but it was too complicated. And there was no quantitative analysis of negative sequence current; Reference [12] proposed a control method with a loop current suppression controller based on carrier phase-shifting. However, the control strategy of the inner loop direct current control and the outer loop power control are added. The in-phase current control and voltage balance control are also added to it. But the process is more complicated. These results can well decrease the negative sequence current, but they don't combine the characteristics of the negative sequence current with the coordination of the negative sequence current protection.

This article analyzes the impact on the increase of negative sequence current. It accurately predicts the operation time of the protection device according to the change of the negative sequence current and proposes a current control strategy to compensate the negative sequence on the generator extremity. Finally, extensive simulations using the PSCAD/EMTDC software are performed to evaluate the performance of the proposed strategy.

II. ANALYSIS OF NEGATIVE SEQUENCE CURRENT WITH NEW ENERGY INTEGRATION

Negative sequence current will be generated when the power system is unbalanced. The main reasons for the imbalance include the imbalance of the power supply voltage of the generator, the asymmetry of internal parameters or the occurrence of asymmetric short-circuit faults and the non-full-phase operation of the power system [13], [14]. When a fault occurs in the power system, the negative sequence current generated by the fault flows from the fault point to the entire system, most of which flows to the power supply via the fault line. The negative sequence current of the fault line is much larger than that of the non-fault line, and its direction is consistent with the voltage of the fault phase. This is opposite to the negative sequence current flowing to the system [15].

Many hazards will be brought with the occurrence of negative sequence current. Due to the existence of a large negative sequence current, the capacity utilization efficiency of electrical equipment, the maximum rotating torque and maximum load capacity of equipment such as motors are reduced. Moreover, the equipment body is vibrated, the electrical equipment is heated and its useful life is reduced [16]–[18].

As shown in Fig 1, where $\dot{U}_{s1}, \dot{U}_{s2}$ are the generator voltage. The Output DC power of new energy is converted to AC power through a grid-connected inverter and then the grid connected is realized. Due to new energy integration, the traditional power supply network is made into a multi-source network. At the same time, it has caused serious three-phase imbalance problems in the power system. When a large amount of new energy is connected to the power system, the imbalance is exacerbated, and the negative sequence current is boosted [19]. The connection of new energy can be regarded as a short-term failure. Because the duration of the failure is short, it is assumed that the input power during the failure remains unchanged. The inverter is controlled on the condition that the output power of the new energy is kept constant. Since the current is mainly studied in the event of a fault, new energy can be equivalent to a controlled current source model [20].

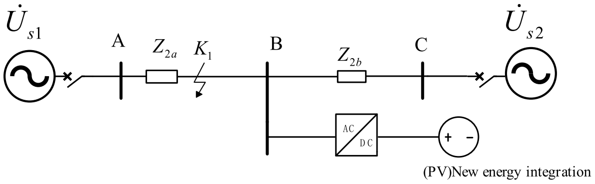

FIGURE 1. New energy integration.

When a single-phase short circuit fault occurs at K_1, the equivalent diagram of negative sequence network is shown in Fig 2. After a fault occurs in the power grid, new energy is considered as a dynamic current source. The generated positive and negative sequence components of the short circuit current are injected into the network.

The total negative sequence current is composed of the negative sequence on the generator extremity and generated inside the generator. The formula is as follows:

$$\dot{I}_2 = \dot{I}_{2g} + \dot{I}_{2f} \tag{1}$$

where $\dot{I}_{2g}$ is total negative sequence current on the generator extremity; $\dot{I}_{2f}$ is the negative sequence current caused by a short circuit fault between the stator windings. When an asymmetric fault occurs on the external circuit of the generator, it can be considered that $\dot{I}_{2f} = 0$.

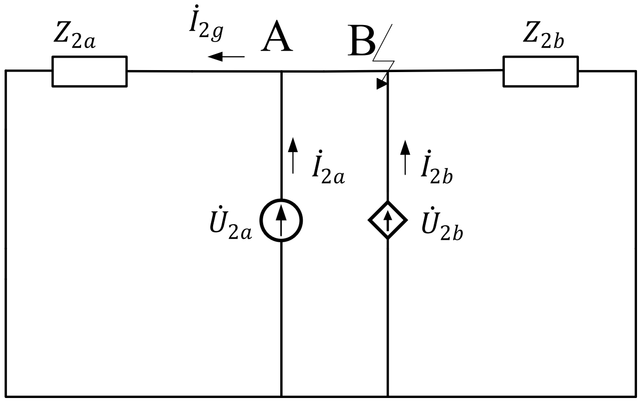

FIGURE 2. **Equivalent graph of negative sequence network.**

In Fig 2, $\dot{U}_{2a}$ is the negative sequence source generated by fault point K_1; $\dot{I}_{2a}$ is the negative sequence current generated by $\dot{U}_{2a}$; $\dot{U}_{2\mathrm{b}}$ is the negative sequence current generated by new energy; $\dot{I}_{2b}$ is the negative sequence current generated by $\dot{U}_{2\mathrm{b}}$, and it flows to the generator extremity $\dot{U}_S$. Z_{2a} and Z_{2b} are the equivalent negative sequence impedance of the original system and new energy; $\dot{I}_{2g}$ is the negative sequence current on the generator extremity, which can be regarded as the superposition of the negative sequence components $\dot{I}_{2a}$ and $\dot{I}_{2b}$. That is $\dot{I}_{2g} = \dot{I}_{2\mathrm{a}} + \dot{I}_{2\mathrm{b}}$. At this time, the negative sequence current which originally flows through the generator extremity is increased with the new energy integration, and the new energy plays a role in boosting.

III. INVERSE TIME LIMIT NEGATIVE SEQUENCE CURRENT PROTECTION AND TIME PREDICTION

In order to prevent the rotor from being damaged by negative sequence current, generators are often equipped with reverse time negative sequence overcurrent protection. The operation time of the reverse time limit varies with the current, and the coordination relationship between the upper and lower stages has the natural adaptability, which can meet the requirements of speedy and selectivity at the same time.

The generator's ability to withstand negative sequence current must match the curve of inverse time operation characteristic. The curve of operation characteristic is above the curve of negative sequence current allowable. To prevent the rotor surface from overheating, inverse time limit negative sequence overcurrent protection that matches the generator characteristics should be installed. Thus, it can prevents the generator from being switched off before the dangerous state is reached.

The relationship between conductor temperature and time is

$$\theta = \theta_N(1 - e^{-\frac{t}{\tau}}) + \theta_0 e^{-\frac{t}{\tau}} \tag{2}$$

where θ_N is the temperature when the conductor is stable at the rated current; θ_0 is the temperature of the conductor when $t = 0$, and it is the initial stable temperature of the conductor; When the conductor heats up, the temperature increases exponentially and eventually reaches a stable value. As shown in Fig 3. Where, $\theta_{\max}$ is the maximum allowable temperature of the conductor.

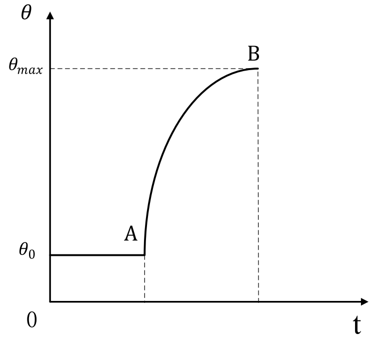

FIGURE 3. **The temperature of the conductor varies with time.**

Assume generator is adiabatic, which means the generator will not emit heat to the external medium when it accumulates heat. When the temperature of conductor exceeds its allowed maximum temperature, the protection devices start to operate. The operation time of protection is [22]

$$t = \frac{mc(\theta_{\max} - \theta_N)}{I_{2N}^2 R(I_{2*}^2 - 1)} \tag{3}$$

Among them, $I_{2*} = I_2 / I_N$ is the standard value of negative sequence current; I_N is the rated current of the generator; m is the mass of the conductor; c is the specific heat capacity of the conductor.

$$A = \frac{mc(\theta_{\max} - \theta_N)}{I_{2N}^2 R} \tag{4}$$

In the formula, A is a constant related to the generator type and cooling method. The operation time of the protection device is

$$t = \frac{A}{I_{2*}^2 - 1} \tag{5}$$

From equation (4), it can be known that when the generator is accumulating heat, both of θ_N and A decreases, and the time of protection operation t decreases accordingly. This can more truly reflect the process of heat accumulation. The inverse time limit negative sequence overcurrent protection operation characteristic curve of generator includes the upper time limit part, the inverse time limit part and the lower time limit part. Where formula (5) is the part of inverse time.

The connection of electric locomotive or distributed photovoltaic power (PV) will cause changes in the power system. When the thermal stability is balanced, the heat generated by the rated negative sequence current in the conductor is exactly balanced with the heat emitted from surface of the conductor to surrounding medium. The temperature of conductor does not change at this time.

$$I_{2N}^2 R dt = \alpha S \theta_N dt \tag{6}$$

where α is the coefficient of heat effect; S is the surface area of the conductor.

If the system is disturbed and the negative sequence current continues to increase in the rated operating state, all the heat generated in excess of the rated current will be applied to the conductor, which will increase the temperature of conductor. Then

$$I_2^2 R dt = mcd\theta + \alpha S \theta_N dt = mcd\theta + I_{2N}^2 R dt \tag{7}$$

When $t = 0, \theta = \theta_N$. When it overloads, the relationship between conductor temperature as well as negative sequence current and time [22].

$$\theta = \frac{I_{2N}^2 R}{mc} t(I_{2*}^2 - 1) + \theta_N \tag{8}$$

Assume that the negative sequence current on the generator extremity is I_{21*}, the operation time of protection device is t_{21}; If the stable control time is required to be Δt, the duration of allowable negative sequence current should be $t_2 = t_1 + \Delta t$. From Equation (8), when the protection device operates within the limit time, the temperature of conductor reaches at:

$$\theta_2 = \frac{I_{2N}^2 R}{mc} \Delta t(I_{21*}^2 - 1) + \theta_N \tag{9}$$

Substitute into formula (4)

$$A_2 = \frac{mc(\theta_{\max} - \theta_2)}{I_{2N}^2 R} \tag{10}$$

From equations (5), (9) and (10), after compensation the negative sequence current should be

$$I_{22*} = \sqrt{\frac{A - \Delta t(I_{21*}^2 - 1)}{t_1 + \Delta t} + 1} \tag{11}$$

IV. CONTROL STRATEGY OF NEGATIVE SEQUENCE CURRENT AND OPERATION TIME ANALYSIS

Aiming at the problem that new energy integration could increase negative sequence current, it is necessary to compensate the negative sequence current on the generator extremity to protect the generator from being damaged by it [20]. According to the relationship between the allowable value of negative sequence current and the current duration of the generator, the negative sequence current should be compensated below the curve of negative sequence current allowed by the generator. The power electronic device such as STATCOM, has provided a reliable guarantee for reactive power and compensation of negative sequence current. Chained STATCOM has become a research hotspot due to its advantages such as high modularity, easy level expansion, and ideal output characteristics [21]. When only the fundamental component is considered, voltage source type STATCOM can be equivalent to an AC voltage source whose amplitude and phase are controllable at the same frequency as the system voltage.

Generally, we assume:

1) The capacity of power system is infinite, and the system voltage is completely symmetrical and constant.

2) There are only fundamental wave components in the system. DC and harmonic components are not considered.

3) In the steady state, the loss of each part of STATCOM is constant.

The diagram of negative sequence compensation on the generator extremity is shown in Fig 4. The generator is on the left side of the line and a complete power network system is on the right side. A compensation device of negative sequence current is built on the generator end and connected to the power system through a breaker. The chain STATCOM is used to compensate the negative sequence on the generator extremity and complete the coordinated control of the negative sequence current. In order to ensure the stability of the DC side voltage, the zero sequence current (intra-angle circulation) is injected to realize the power balance between phases, and the principle of susceptance balance is used to control the circulation. The circulating current does not affect the output current of the device, but it does affect the power flow between the three phases. PWM was used to control the on-off of the chain STATCOM to obtain the required current for compensation.

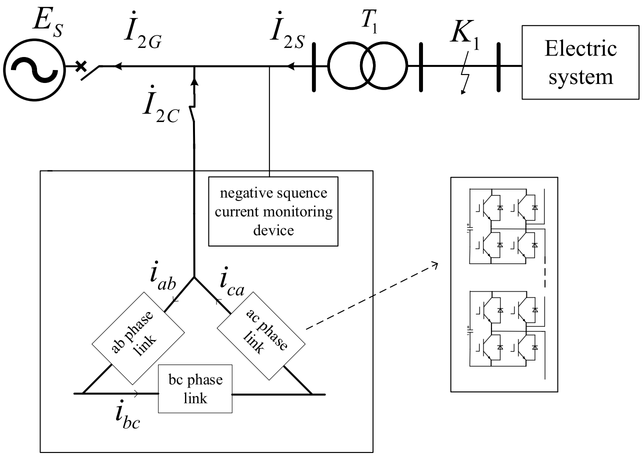

FIGURE 4. Negative sequence current compensation of the power system.

A negative sequence current monitoring device was installed at the compensation device STATCOM to monitor the magnitude of the negative sequence current on the line side. When the line-side negative sequence current is greater than the starting current of the compensation device, adaptive compensation is started. The startup criteria of the device is

$$\left|\dot{I}_{2S}\right| > \left|\dot{I}_{2sta}\right| \tag{12}$$

Starting time of the device is

$$t_{2set} = t_{2sta} - t_{op} - t_{mar} \tag{13}$$

Among them, I_{2sta} is the starting current of the device; I_{2sta} is the protection operation time when the negative sequence current on the inverse time curve is I_{2sta}; t_{op} is the reoperation time when the device starts; t_{mar} is the reserved time to prevent the negative sequence current from increasing too much. In this way, not only can the compensation device be wasted due to too small negative sequence compensation, but

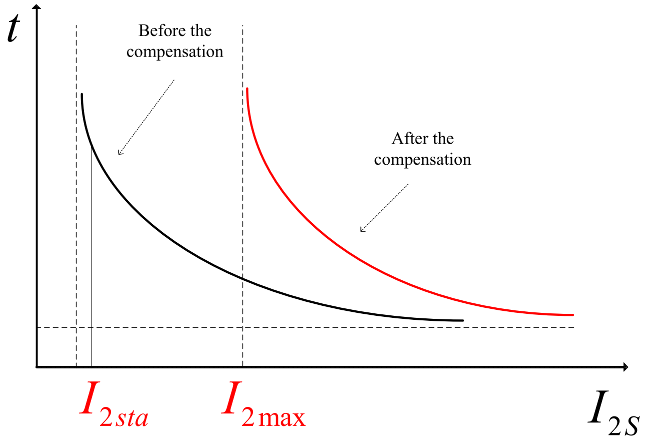

FIGURE 5. **Negative sequence inverse time limit operation curve of the generator without compensation.**

also the protection device can be prevented from being turned off due to excessive negative sequence current.

Considering the capacity of the compensation device, assume that the maximum negative sequence current from the compensation device STATCOM is $I_{2\max}$. When $I_{2\max} \geq I_{2S}$, it means that the capacity of the compensation device STATCOM is large enough, and the negative sequence current issued by the compensation device can completely compensate the original negative sequence current on the line side. At this time, the negative sequence current on the generator extremity is zero, that is, $I_{2G} = 0$; When $I_{2\max} < I_{2S}$, the capacity of the device is not enough to fully compensate the negative sequence current on the line-side. At this time, the negative sequence current on the generator extremity has not been completely absorbed, but it is maintained within the range that the generator can bear. That is $0 < I_{2G} < I_{2\max}$. The relationship between the protection device operation time without compensation and the amounts of negative sequence current at the generator terminal is shown in Fig 5.

A. CURRENT DETECTION AND EXTRACTION OF THE REFERENCE CURRENT

The method of current detection is improved from the instantaneous reactive power theory, and it mainly through the network voltage to construct the corresponding transformation matrix. So that the current component in the grid can be directly detected.

According to the instantaneous reactive power [23]

$$\begin{cases} p = UI\cos\varphi = u_\alpha i_\alpha + u_\beta i_\beta \\ q = UI\sin\varphi = u_\alpha i_\alpha + u_\beta i_\beta \end{cases} \tag{14}$$

$$\begin{cases} i_p = I\cos\varphi \\ i_q = I\sin\varphi \end{cases} \tag{15}$$

$$\text{Suppose,} \quad \begin{cases} u_a = E\sin\omega t \\ u_b = E\sin(\omega t - 120^\circ) \\ u_c = E\sin\omega t(\omega t + 120^\circ) \end{cases} \tag{16}$$

Perform Clark transformation on equation (16)

$$\begin{aligned} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} &= \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} E\sin\omega t \\ E\sin(\omega t - 120^\circ) \\ E\sin\omega t(\omega t + 120^\circ) \end{bmatrix} \\ &= U \begin{bmatrix} \sin\omega t \\ -\cos\omega t \end{bmatrix} \end{aligned} \tag{17}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{18}$$

The expression for active and reactive components of the current can be obtained from equations (14-18)

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = \begin{bmatrix} \sin\omega t & -\cos\omega t \\ -\cos\omega t & -\sin\omega t \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{19}$$

The negative sequence current of the generator extremity is detected, and the phase current of STATCOM reference is

$$\begin{cases} i_a^* = I_{pm}sin(\omega t + \theta_a) \\ \qquad +I_{nm}sin(\omega t + \theta_a + \theta_n) \\ i_b^* = I_{pm}sin(\omega t + \theta_a - {}^{2\pi}/_{3}) \\ \qquad +I_{nm}sin(\omega t + \theta_a + \theta_n + {}^{2\pi}/_{3}) \\ i_c^* = I_{pm}sin(\omega t + \theta_a + {}^{2\pi}/_{3}) \\ \qquad +I_{nm}sin(\omega t + \theta_a + \theta_n - {}^{2\pi}/_{3}) \end{cases} \tag{20}$$

Equation (20) is the output current expression of I_{2C}. Among them, I_{pm} and I_{nm} are the peak values of the positive sequence currents and the negative sequence currents; θ_n is the angle that the negative sequence current leads a phase of grid voltage. For the fundamental component, the current of each phase and the grid voltage must be orthogonal to ensure that the DC side voltage of the chain link is constant.

The line current reference of the STATCOM is

$$\begin{cases} i_{ab}^* = I_{pm}sin(\omega t + \theta_a \pm {}^{\pi}/_{2}) \\ + \qquad I_{nm}sin(\omega t + \theta_a + \theta_n) \\ i_{bc}^* = I_{pm}sin(\omega t + \theta_a \pm {}^{\pi}/_{2} - {}^{2\pi}/_{3}) \\ \qquad +I_{nm}sin(\omega t + \theta_a + \theta_n + {}^{2\pi}/_{3}) \\ i_{ca}^* = I_{pm}sin(\omega t + \theta_a \pm {}^{\pi}/_{2} + {}^{2\pi}/_{3}) \\ \qquad +I_{nm}sin(\omega t + \theta_a + \theta_n - {}^{2\pi}/_{3}) \end{cases} \tag{21}$$

B. CONTROL STRATEGY OF STATCOM AND OPERATION TIME OF PROTECTION

STATCOM is suitable for compensating negative sequence current due to its advantages of small output harmonic and fast response. STATCOM adopts a double closed-loop control strategy, in which the current inner loop adopts direct current control. It can realize decoupling control of active and reactive components and realize real-time compensation of reactive power. The voltage outer loop realizes the balanced control of the overall voltage, so that the overall average voltage of the DC side capacitor follows a given value and provides a reference for the active component of the current inner loop.

STATCOM can change the angle of voltage and current to achieve the active power interaction with the power grid, which maintains the balance of DC-side capacitor voltage through the active power interaction. Reference [23] studies the operation of STATCOM under unbalanced grid voltage and proposes a new dual-loop control scheme to maintain the stability of DC voltage. According to the reference signal, the compensation current generated from compensation circuit flows into the power grid. At this time, the energy exchange occurs between the DC side and AC side of STATCOM to adjust the DC side voltage to a given value. Based on this, The control of STATCOM in this paper adopts the control of three phase PWM converter combined with the current inner loop and the voltage outer loop to realize the fast and stable output of cascaded H-bridge STATCOM [24]. The strategy is the voltage and current double closed-loop controlling method in the dq coordinate system, and it has an excellent dynamic performance and a high accuracy. While achieving accurate separation of sequence components, it can also achieve precise phase-locking of asymmetric grid voltage. The basic control idea is to make the current in dq coordinate system kept constant after it through the application of three phase locked loop. The zero-steady-state error control of the given and feedback are realized through PI control, which is used to control the output voltage and current of the PWM converter.

The STATCOM control module is shown in Fig. 6. Among them, U_{dc} is the DC bus voltage; U_{dref} is the reference value of instruction voltage. i_{sq} is reactive component on the generator extremity. I_{sqref} is its reference value and set it to 0.

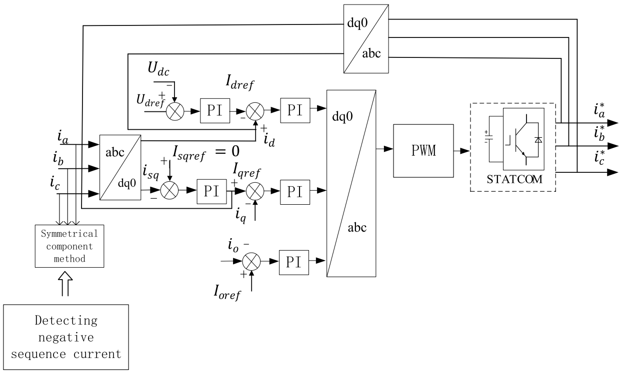

FIGURE 6. STATCOM control module.

First, the three phase currents i_a, i_b, and i_c are decoupled into a current active component i_d and a current reactive component i_{sq} after the synchronous rotating coordinate transformation. Then the active current reference I_{dref} is obtained by the voltage outer loop control and the reactive current reference I_{qref} is calculated by the method of reference current detection. In the dq rotating coordinate system, the PI controller is used to track the given active, reactive reference currents and zero sequence current from the symmetric component method on the machine extremity directly, and dq0-abc inverse transformation is used to obtain the modulated wave. Finally, the inverter switching signal is obtained from the PWM link and a line current reference is output from the STATCOM device. The current sent from the chain STATCOM compensation device is combined with the active and reactive current components of three phase current decoupling to form a negative feedback, and it is used as the input of the control signal to compensate negative sequence current.

This module integrates negative sequence current detection, voltage balance control and negative sequence current compensation. By monitoring the magnitude of the negative sequence current on the machine side in real time, it is determined that the capacity of the negative sequence current needs to be compensated, and the corresponding control strategy is implemented for STATCOM. The STATCOM control flow chart is shown in Fig 7.

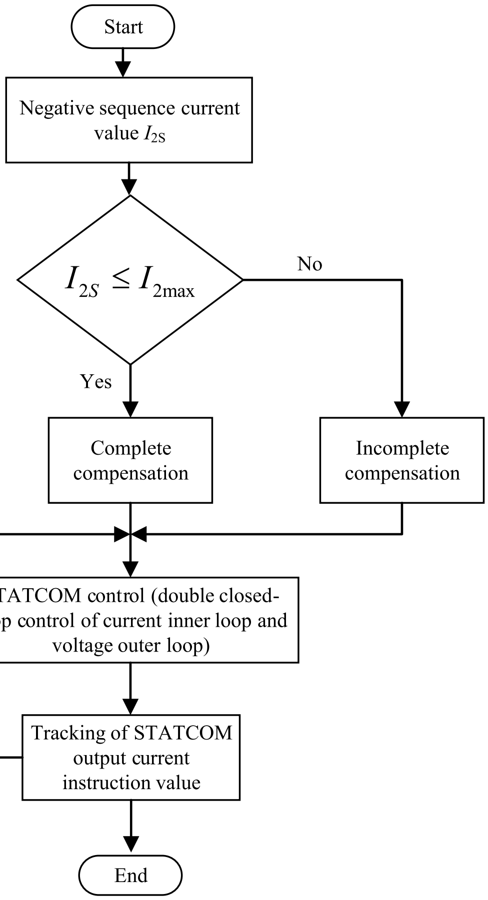

FIGURE 7. STATCOM control flow chart.

When a line fault occurs, the negative sequence current of the system increases. If the allowable time of long-term negative sequence current is required to be controlled below a certain value and the protection operation time is t_x, the maximum value of the allowable negative sequence current is obtained from equation (3)

$$I_{2x} = \sqrt{\frac{mc(\theta - \theta_N)}{I_{2N}^2 R t_x} + 1(t_x \neq 0)} \tag{22}$$

The temperature of the rotor conductor does not drop sharply, and there is a heat dissipation process. If the negative sequence current decreases to I_{2y} after the compensation. According to equation (4), $A_{yact} = mc(\theta_{\max} - \theta_x)/I_{2x}^2 R$, but the predicted value $A_{ypre} = mc(\theta_{\max} - \theta_y)/I_{2y}^2 R$. A_{yact} is larger than A_{ypre}.The generator allows the negative sequence current I_{2y} to exist longer than the predicted value actually, which leaves a certain margin. So it meet the needs.

According to equations (2) and (3), the actual protection operation time should be

$$t_y = \frac{mc[\theta_{\max} - \theta_N(1 - e^{-\frac{t}{\tau}}) - \theta_0 e^{-\frac{t}{\tau}}]}{I_{2N}^2 R(I_{2y*}^2 - 1)} \tag{23}$$

V. SIMULATION ANALYSIS

In this paper, the simulation is performed on the PSCAD. The simulation model of negative sequence compensation is set up according to Fig. 5, which is to verify the effect of the above control strategy on the negative sequence current. Among them, the level of the system voltage is 220kV and the frequency is 50Hz; the number of H-bridge submodules per phase is 3, and the inductance of the bridge arm reactor is 3.8mH. Set the phase A earth fault at t = 1s, and the fault duration is 0.33s.

Taking a generator set as an example, some parameters are shown in Table 1.

TABLE 1. Main parameters of generator.

Generator parameter	Values
Rated capacity S_N/MVA	12
Rated voltage U_N/kV	35
Rated current I_N/kA	0.3
Power factor	0.8

According to the manufacturer, the data of negative sequence current capability for the generator has been provided and calculated, as shown in Table 2.

TABLE 2. Data of unit's negative sequence capability.

（ I_2/I_N ）/p.u.	T/s	t/s
1.21	6.91	6.14
1.12	8.19	7.17
0.94	11.61	10.18
0.82	15.34	13.38
0.70	20.98	18.37
0.64	25.36	21.97
0.58	31.07	26.75
0.52	42.58	33.28
0.46	58.46	42.53
0.41	73.58	53.54
0.32	117.64	87.89
0.28	154.26	114.8
0.25	203.42	144

Among them, T is the time when the generator bears the maximum current; t is the operation time of the protection device. A is taken as 9s, and the data of Table 1 are plotted to obtain the relationship between the maximum negative sequence bearing time of the generator, the operation time of the protection device and the amounts of negative sequence current at the generator extremity, as shown in Fig 8. It can be seen that the operation time of the protection device is greatly extended when the negative sequence current decreases. The curve of the protection operation characteristic is always below the curve of the generator overload capacity, which makes it possible to make the best use of the unit 's ability to withstand negative sequence current, and it can also ensure the safety of unit to the fullest extent.

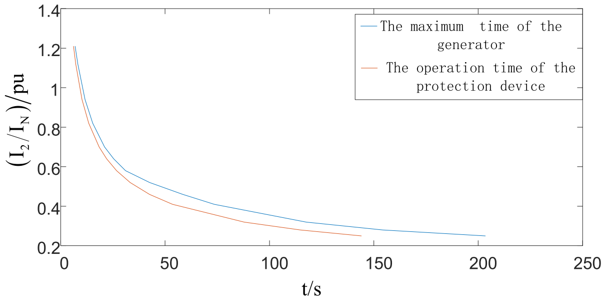

FIGURE 8. Negative sequence current on the generator extremity and operation time.

When different loads are connected to phase A, the current contains negative sequence components. The system is in an unbalanced operating state. When the monitoring device of negative sequence current detects I_{2S}> 0.15kA, the circuit breaker is closed immediately and the compensation device STATCOM starts, that is I_{2sta} = 0.15kA. Record the magnitude of the negative sequence current at the generator terminal when it is at different loads, and measure it without compensation. Calculate the compensation value and operation time of the protection devices without compensation, as shown in Table 3.

Table 3 Negative sequence current compensation and operation time of the protection devices without compensation.

The operation time of the protection device without compensation is shown in Fig 9.

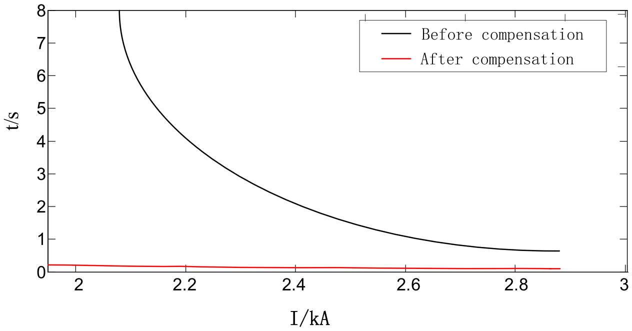

FIGURE 9. Operation time of the device without compensation.

TABLE 3. Negative sequence current and operation time without the compensation.

Negative sequence before compensation I_{2S} /kA	Negative sequence after compensation I_{2G} /kA	Compensation value ΔI /kA	Operation time before compensation t_L /s	Operation time after compensation t_G /s
0.15	0.011	0.139	36	6574.1
0.29	0.014	0.276	9.77	4074.2
0.46	0.018	0.442	3.84	2500
0.70	0.021	0.679	1.66	1836.7
0.98	0.024	0.956	0.84	1406.2
1.27	0.028	1.242	0.50	1040.6
1.58	0.031	1.549	0.32	848.3
1.7	0.034	1.666	0.28	704.8
1.82	0.1	1.72	0.24	82.64
1.95	0.23	1.72	0.213	15.3
2.14	0.42	1.72	0.177	4.59
2.39	0.67	1.72	0.142	1.80
2.56	0.84	1.72	0.124	1.148
2.69	0.97	1.72	0.112	0.863
2.82	1.1	1.72	0.102	0.669
3.01	1.29	1.72	0.089	0.487
3.13	1.414	1.72	0.083	0.405

It is known from the table that the capacity of the compensation device STATCOM to compensate negative sequence current is $I_{2\max} = 1.72$ kA. When $I_{2S} < 1.72$kA, it is basically zero after compensation, so it can be regarded as complete compensation. When $I_{2S} > 1.72$kA, it is incomplete compensation. After the compensation, the negative sequence current on the generator extremity is greatly reduced, and the operation time of the protection device is greatly extended.

In order to compensate the negative sequence current on the generator extremity, the compensation device starts quickly and calculates the required compensation current. The compensation current responds at about 1.01s, and the corresponding value reference of load current is tracked. The comparison of the negative sequence current without compensation is shown in Fig 10.

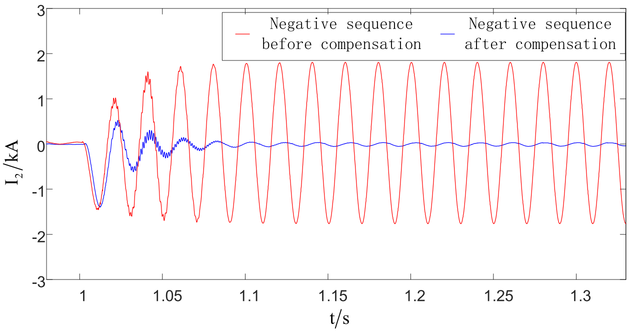

FIGURE 10. Negative sequence current on the generator extremity with complete compensation.

It is known from Fig. 10 that the compensation is fully compensated. It is about 1.8kA when the negative sequence current is stable before the compensation. After the compensation, the negative sequence current oscillates and decays. After 0.03s, the negative sequence current decays to 0.5kA. After 0.1s, the negative sequence current component is basically 0.

The condition of incomplete compensation is shown in Fig 11. It is about 2.42kA when the negative sequence current is stable before the compensation. After the compensation, the amounts of the negative sequence current is stable at about 1.7kA. It can be seen that the compensation value is about 1.72kA.

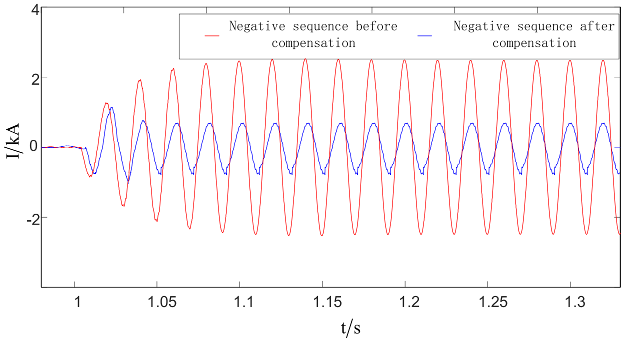

FIGURE 11. Comparison of negative sequence on the generator extremity with incomplete compensation.

In view of inverse time current protection, the negative sequence current compensated can be stabilized below the maximum allowable value of the generator's, which can effectively ensure that the relay protection device does not malfunction.

The STATCOM compensation device sends positive, negative and zero sequence current as shown in Fig 12. As it can be seen from the Fig 12, the compensation device does not generate zero sequence current, and the positive sequence current issued is almost zero. Therefore, the compensation device STATCOM in this article can be regarded as a pure negative sequence source, which only compensates the negative sequence current on the machine side. It has little effect on the positive sequence and zero sequence of both the line side and generator side. Comparing the sequence currents on the line side and on the generator side without compensation, we can find that the positive and zero sequence current on

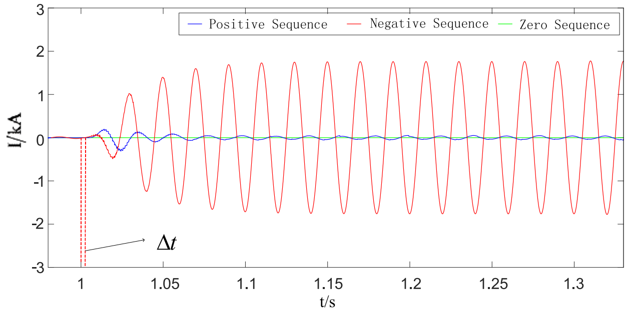

FIGURE 12. Positive, negative and zero sequence current provided by STATCOM.

the generator side are basically unchanged compared to the line side, except that the negative sequence current on the machine side is significantly reduced. After the compensation, the symmetry of the three-phase current is significantly increased, which meets the requirements of power system balance.

VI. CONCLUSION

This article analyzes the change of negative sequence current when new energy is connected to the power system. It accurately derives the limit operation time of the protection device, and finally a simulation model is established to compensate the negative sequence current on the generator extremity. Summarized as follows:

(1) Considering the thermal accumulation effect of the generator stator, the relationship between the magnitude of the negative sequence current and the protective device operation time is derived. The detailed parameters of the inverse time negative sequence current have been given, which solves the problem of inaccuracy in calculating the operation time of inverse time negative sequence overcurrent protection in existing literature.

(2) The proposed negative sequence current control protection strategy on the generator extremity proves the effectiveness for the compensation of negative sequence current. According to the capacity of the negative sequence current compensation device, it discusses two cases: complete compensation and incomplete compensation. It ensures that the relay protection device is reliable and does not malfunction, so that the generator is protected from negative sequence currents.

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