

Research on Neutral Point Grounding Technology for Marine High Voltage Power System

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Abstract—The type of neutral point grounding is a key technology and hot point for marine high voltage power system. In order to study the special type of neutral point grounding for marine high voltage power systems, the feature of various types of neutral point grounding for general marine power systems was discussed. A mathematical model of single phase grounding current for any different neutral point grounding method was developed by using Kirchhoff's Laws. A general formula of single phase grounding current for any different neutral point grounding method was deduced, and then a formula of single phase grounding current for marine high voltage power system was deduced, too. The selection and calculation basis for designing high resistor was given. The reason why high resistance grounding should be adopted for marine high voltage power system was summarized, and thus a sound theory and practice basis is provided for further research on marine high voltage power systems.

Keywords- *Ship; Marine Power System; Neutral Point; High Resistance Grounding; High Voltage*

I. INTRODUCTION

With the continuous improvement of ship on large-size and automation level, the capacity of the marine power system is increasing sharply, so the traditional marine low voltage power system has been unable to satisfy the requirements of marine high power system. It is necessary to select marine high voltage power system for marine high power system, such as large passenger liner, oil tanker, electric propulsion ship, some special working ship and so on[1].

The voltage level of marine high voltage power system is limited between 1KV and 15KV, according to the Rules for Classification of Sea-going Steel Ships (2012). There is a big difference between marine low voltage power system and high voltage power system on safety protection devices, the type of neutral point grounding, transformer,

distribution methods, the structure and processing ways of cable socket. There is different structure of function in all panel of high voltage switchboard, such as isolated switch room, cable room, low voltage chamber, and so on. The operation requirements of interlocking protection are known as the "five-prevention measures" inside the panel. In order to prevent internal fault, high-voltage generator is equipped with longitudinal differential protection and the excitation device of high-voltage generator has the performance of de-excitation which can demagnetize generator after circuit breaker tripping. In particular, marine high voltage power system which always adopts neutral point grounding system is essentially different from low voltage power system which employs generally neutral point insulation system. The type of grounding method of neutral point is the key technology to be solved in the marine high voltage power system. From the view of domestic and foreign application, marine high voltage power system commonly adopts high resistance grounding method at the moment[2-3].

II. NEUTRAL POINT OPERATION MODE OF THE POWER SYSTEM

Neutral point operation mode of the power system is what grounding method neutral point of power or transformer adopts. [4-5]

A. The type of neutral point operation mode

Neutral point operation can be commonly classified as the following types:

a) *Neutral point un-earth*: Namely isolated neutral point;

b) *Neutral point directly earth*: Neutral point is connected to grounding device directly.

c) *Neutral point earth with Petersen-coil*: Neutral point is connected to grounding device by means of reactor (Petersen-coil).

d) *Neutral point earth with resistance*: Neutral point is connected to grounding device by resistance..

B. The analysis of neutral point grounding way

Neutral point grounding way of power system is a comprehensive technical problem, so the following factors must be considered: the security, continuity and reliability of power system; the coordination between over-voltage protection and insulation technology; the constituent of rely protection and the method of circuit breaker tripping; the construction of electric distribution network and circuit; the personal and equipment safety, and so on.

1) *Neutral point un-earth way*

Neutral point un-earth way is safe and reliable, because it is insulated from the earth, and don't affect the symmetry of voltage among the three phases when earth fault occurs in power system, and what's more, it can continue to run with single-phase earth fault for 2 hours, so the continuity of power supply is good. Single-phase grounding current is determined by grounding capacitance current in the neutral point un-earth power system. Earth fault current is very small, and transient fault always can be automatically eliminated, because single-phase earth capacity of power transmission line is relatively small. Due to small earth current, the interference to communication circuit is also small. The disadvantage of neutral point un-earth way is that the other two phase voltage may rise to $\sqrt{3}$ times, when one phase is grounded, which makes the point where insulation is weak breakdown, and causes the two phase grounding short circuit.

The single-phase grounding capacitive current is very big in general in the high voltage and long-distance transmission lines, and the capacitive current leads voltage by 90°. The voltage on the point of fault reaches its peak when the capacitive current on the point of fault passes zero and blows out arc. If the capacitive current is too large and the air is ionized seriously, it will break down the point of failure again, and the reigniting is difficult to avoid sometimes. The reigniting and extinguishing of arc easily, so-called intermittent arc occurs on the point of grounding, which can cause high-frequency oscillation, form the intermittent arc over-voltage, may break down the insulation of equipment, and cause a short circuit fault. In order to avoid intermittent arc, the grounding current of 3~10KV power grid is less than 30A, and the grounding current of more than 35KV power grid is not more than 10A. Therefore, the neutral point un-earth mode is not suitable for the high voltage and long-distance transmission lines.

Neutral point un-earth way is generally adopted for traditional marine low voltage power system.

2) *Neutral point directly earth way*

The advantage of neutral point directly earth way is that the other two phase voltage don't rise, and there is no over-voltage caused by intermittent arc, when one phase grounds, so the insulation level of whole power system can be reduced, which is important to reduce the cost of ultra-high voltage grid above 110kV. Therefore, the power grid more than 110kV widely adopts neutral point directly earth. Besides, short circuit current is so high that protection relay operates quickly and accurately, and the reliability of protection is improved. However, the large capacity switch

and equipment needs to be chosen because of big short circuit current, which can cause some deficiencies, such as unstable system and strong interference with communication line.

3) *Neutral point earth with Petersen-coil way*

The inductive current of reactor compensates the capacitive current of power grid in the way of neutral point earth with Petersen-coil, which can reduce the grounding current. If the inductive current is equal to the capacitive current, namely full compensation, it is very advantageous to extinguish grounding arc. However, full compensation is impossible because of the line resistance, the grounding resistance, the leaking resistance, the active power loss of Petersen-coil and transformer, etc, which generate a little residual current on the point of fault. If the three phase distributed capacitors between ground isn't symmetrical during normal operation, or one phase is open circuited, the Petersen-coil and the distributed capacitors are likely to resonate serially, which may cause the dangerous high potential on the neutral point of the power system. Therefore, Petersen-coil is generally used for over-compensation operation, in other words, the inductor current is greater than capacitive current, which also is a disadvantage of the neutral point earth with Petersen-coil. In addition, the system is more complex, and the investment in equipment is larger.

4) *Neutral point earth with high resistance way* [6-7]

The most outstanding characteristic of Neutral point earth with high resistance is that the power system can continue to run with fault for 2 hours, and also can trip quickly or periodically by choosing.

To limit the transient over-voltage caused by arc grounding fault, the design of earth with high resistance should the principle that the grounding resistance isn't more than total distributed capacitive reactance of each phase.

The purpose of earth with resistance is injecting resistance current in the power system, which can make the fault current have the nature of resistor-condenser, reduce the phase angle difference between fault current and voltage, and reduce the reigniting rate of grounding current after passing zero and blowing out arc. When the resistance current is large enough, the reigniting will not occurs, thus, it prevents intermittent arc over-voltage of grounding and resonance; Neutral point earth with high resistance can also limit the single-phase grounding fault current in power system, what's more, if the resistor-condenser current is greater than the capacitive current, the sensitivity of zero sequence protection will be improved, acting on the breaker to trip, meeting the requirements of relay protection.

Modern marine high voltage power system generally adopts neutral point earth with high resistance. [1]

III. THE CALCULATION OF SINGLE PHASE GROUNDING CURRENT FOR DIFFERENT TYPES OF NEUTRAL POINT GROUNDING METHOD

In order to discuss the single phase grounding current for various earth methods in power system, researchers can suppose the neutral point earth by paralleling resistors and inductors, the distributed capacitance to ground of every phase is C in power system. Phase A is regarded as a referenced one, when earth fault happens, there is a

grounding resistance R_d around grounding point, R_N is neutral point grounding resistance, L_N is neutral point grounding inductance, as the Fig. 1 shows.

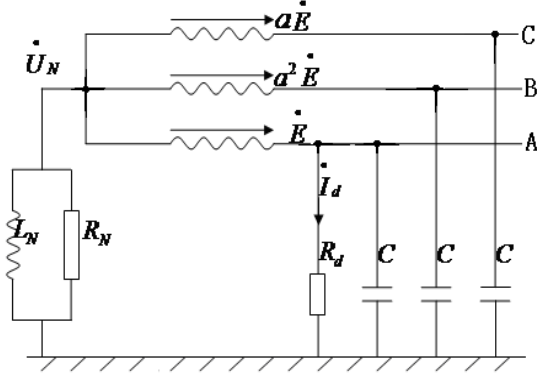


Figure 1. The single phase grounding diagram of power system

Supposing the voltage of three phases is balanced before earth happened, after that, there will be a voltage U_N between neutral point and ground, this moment the three phase voltages referring to ground are:

$$\begin{cases} \dot{U}_A = \dot{U}_N + \dot{E} \\ \dot{U}_B = \dot{U}_N + a^2 \dot{E} \\ \dot{U}_C = \dot{U}_N + a \dot{E} \end{cases} \quad (1)$$

Where, $a = e^{j120^\circ}$, $a^2 = e^{j240^\circ}$.

According to Kirchhoff's Current Laws, take the ground as a node, and then the current relation that passes through the ground is:

$$\begin{aligned} \dot{U}_N (g_N - jb_N) + (\dot{U}_N + \dot{E})(g_d + j\omega C) + \\ (\dot{U}_N + a^2 \dot{E})j\omega C + (\dot{U}_N + a \dot{E})j\omega C = 0 \end{aligned} \quad (2)$$

Where, $b_N = 1/(\omega L_N)$ is the neutral point grounding susceptance, $g_N = 1/R_N$ is the neutral point grounding conductance, $g_d = 1/R_d$ is the earth point conductance, therefore, the neutral point voltage referring to ground:

$$\dot{U}_N = \frac{-\dot{E}g_d}{(g_d + g_N) + (j3\omega C - jb_N)} \quad (3)$$

The current that pass through the earth point:

$$\dot{I}_d = (\dot{U}_N + \dot{E})g_d = \dot{E}g_d \frac{g_N + j3\omega C - jb_N}{g_N + g_d + j3\omega C - jb_N} \quad (4)$$

Equation (4) is commonly used to calculate earth current for different grounding methods. It will be discussed in following several parts respectively.

(1) When single phase metallic earth happens in the way that neutral point disconnect to earth, $g_d = \infty$, $g_N = 0$, $b_N = 0$, the grounding current which passes the earth point: $\dot{I}_d = \dot{E}j3\omega C$, it is only composed of distributed

capacitive current, and this current leads 90° to the voltage of the earth phase.

(2) When single phase metallic earth happens in the way that neutral point grounding with Petersen-coil, $g_d = \infty$, $g_N = 0$, the current which passes the earth point: $\dot{I}_d = j(3\omega C - 1/(\omega L_N))\dot{E}$. The grounding current includes inductive and capacitive current, and the inductive current of reactor is utilized to compensate capacitive current of power net, which can enormously decrease the grounding current. If researchers reasonably choose Petersen-coil and make $3\omega C = 1/(\omega L_N)$, that's to say $\dot{I}_d = 0$, we can realize complete compensation, the complete compensation is very useful to extinguish electric-arc.

(3) When single phase metallic earth happens in the way that neutral point grounding with high resistance, $g_d = \infty$, $b_N = 0$, the current which passes the earth point: $\dot{I}_d = \dot{E}(g_N + j3\omega C)$, the grounding current consists of capacitive current and resistive current, which makes earth fault current to be capacitive, it can reduce the phase angle between the earth fault current and it is voltage. Obviously, the resistive current is relative to neutral grounding resistance R_N , the more R_N is, the lower resistive current is, and vice versa.

IV. THE ANALYSIS OF NEUTRAL POINT GROUNDING WITH HIGH RESISTANCE FOR MARINE HIGH VOLTAGE POWER SYSTEM

Owing to the extremely high demand of insulation technology for marine high voltage power system, and considering the cost of insulation for high voltage power system, human safety .etc, especially the particularity of marine high voltage power system, ship grounding is actually connect to hull, and the hull itself is a good conductor, it may not only endanger human safety easily, but also damage low-voltage devices if there is a closed circuit between the high voltage system and low voltage system. In this case, the requirements of neutral point grounding technology for marine high voltage power system are not a bit high, and it is very complex to deal with, therefore, the study on this technology attracts a wide attention.

A. The calculation of grounding current for marine high voltage power system

It is popular to adopt high resistance grounding of neutral point for marine high voltage power system, generally the resistance is bigger than 500Ω .

The principle for the selective design of resistive current I_R :

(1) The resistive current of earth point is not lower than 1 to 1.5 times capacitive current as required, that's to say $I_R \geq (1 \sim 1.5)I_C$, to make sure that intermittent arc-grounding over-voltage will not happen. Such being the case, the over-voltage will not exceed 2.6 times phase voltage in general, and it is also the over-voltage which generator can endure. The standard of withstanding voltage is 1.5 times rated line voltage for common marine alternating current generator, the same as 2.6 times phase voltage. In that case, the grounding over-voltage which is lower than 2.6 times phase voltage is seemed to be a safe one. In other words,

the over-voltage of marine alternating current generator is not advisable to be more than 2.6 times phase voltage.

I_C is total capacitive current of power system, there will appear capacitance between all high voltage cable and ground, and this type of capacitance is called distributed capacitance. The capacitive current is sum of leakage current which produced by distributed capacitance, so it is relative to the specification and length of cable, researchers can get know the capacitive current or capacitance per unit length from related manuals, and then multiply it by actual length of cable in specific ship to calculate the total capacitive current.

The resistive current of earth point:

$$I_R = U_N / R_N = U_e / (\sqrt{3} R_N)$$

Where, U_N is the voltage between neutral point and ground, U_e is rated line voltage.

The total capacitive current of power system:

$$I_C = 3\omega C U_e / \sqrt{3}.$$

(2) $I_d \geq 3A$, to ensure the sensitivity of grounding protection for generator.

The insertion of R_N will increase the single-phase grounding fault current by $\sqrt{2}$ times or more, and change to be resistive and capacitive coexisted current from pure capacitive current, the total single-phase grounding fault current $I_d = \sqrt{I_R^2 + I_C^2}$.

(3) $I_d \leq (10 \sim 15) A$, to reduce the burning damage to the core of generator when the stator winding appears single-phase grounding fault in generator.

(4) According to the Rules for Classification of Sea-going Steel Ships(2006):when power system adopts neutral point grounding, the grounding fault current should never more than full-load current of most one generator in the switchboard or the subsection of switchboard, and not lower than 3 times of the minimum acting current of the grounding fault protection device:

$$I \leq I_d / 3$$

B. The selection and calculation of the resistance of grounding reactor for marine high voltage power system

The selection of reactor should according to the technology condition, such as nominal voltage, the most running voltage, frequency, current, resistance value, level of protection, type of cooling, the flowing time, the insulation level, what's more, researchers should check it with environmental condition, for example, environmental temperature, relative humidity. The following parts will put key point on the selection and calculation of reactor. The selection and calculation of resistance of reactor R_N depend on the capacitive current I_C and the choice of resistive current I_R , according to $I_R \geq I_C$,

And then: $U_e / (\sqrt{3} R_N) \geq 3\omega C U_e / \sqrt{3}$, So,

$$R_N \leq 1 / (3\omega C)$$

Take safe margin into account: generally $I_R = 1.5 I_C$, So,

$$R_N = 1 / (4.5\omega C) = 1 / (9\pi f C)$$

When the electric arc is connected to the ground, in the process of arc lighting and extinguishing, the marine high voltage power system will accumulate redundant electric charge, and intensify the oscillation, and then produce a high over-voltage. If researchers can dissipate the charge by the neutral point grounding reactor before a period that electric arc relights from crushing out (about a half fundamental frequency cycle), and the over-voltage will greatly reduces. The capacitor between high-voltage cable and ground for marine high voltage power system discharges to neutral point grounding resistance R_N follows the exponential function principle $f(t) = e^{-t/T}$, if $R_N = 1 / (3\omega C)$, the time constant of discharging $T = 3R_N C = 1 / \omega = 1 / (2\pi f)$, if it is equal to a half fundamental frequency cycle, in other words, when $t = 1 / (2f)$, $f(t) = e^{-t/T} = e^{-\pi} = 0.04$, this indicates in the half fundamental frequency cycle, the charge of the high-voltage cable reduce to 0.04 from 1, obviously, 96% have been discharged, so there will not appears a very high over-voltage any longer in general.

If $R_N = 1 / (4.5\omega C) = 1 / (9\pi f C)$, the time constant of discharging $T = 3R_N C = 1 / (3\pi f)$, when $t = 1 / (2f)$, $f(t) = e^{-t/T} = e^{-1.5\pi} = 0.009$, this indicates in the half fundamental frequency cycle, the charge of the high-voltage cable reduce to 0.009 from 1, more than 99% electric charge have been discharged, so there will not appear a high over-voltage any more. [8-10]

V. CONCLUSIONS

With the constantly increase of capacity of marine power system, high voltage power system has been a necessary choice for huge marine power system. Marine high voltage power system is a new area in domestic navigation, there are so much different in technology, maintenance, management mode comparing to traditional low power system, recently, it is in the beginning step for domestic marine high voltage power system. Especially, with the spreading and using of marine high voltage power system, the technology of neutral point grounding has attracted great attention of ship designers. The type of neutral point grounding is a key technology and hot point for marine high voltage power system.

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