Universe Scientific Publishing

ORIGINAL ARTICLE

The Research of High Voltage Auxiliary Power System Neutral Point Grounding Modes between the Nuclear Power Plant and Conventional Fossil Fuel Power Plant

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ABSTRACT Currently, in power plants, the application of the extinction coil in high voltage auxiliary power system neutral point is less experienced. A research done on nuclear power plant and conventional fossil fuel power plant proved that using an auxiliary power system's different characteristics was leading to different demands of the grounding modes. Thus, this research was done by selecting the grounding mode of high voltage auxiliary power system neutral point on the main nuclear power plants and the partial fossil fuel power plants together with the calculation of practical engineering, and optimal design schemes. The high voltage auxiliary power system neutral point grounding modes have been induced in the large-scale into the nuclear power plant and the conventional fossil fuel power plant. Methods in determining the neutral point grounding modes are used by analyzing the principles commonly used grounding modes and requirements of related codes. First, choose the suitable grounding mode according to the calculation result of capacitive current. Then, choose more conducive grounding mode to the operation of power plant according to the operation of technology equipment. The power is required from the configuration, connection of auxiliary power and the cut from the accident of auxiliary power. As some power plants which are under-construction will be putting into operation one after another, the whole set of perfect security arrangements and operating experiences will also be accumulated inevitably. As a conclusion, high voltage auxiliary power system neutral point grounding modes directly affect the running of the auxiliary power system and even affect the security of the nuclear safety and the operation of the power plant. I hope this article can play a role for reference on the selection of the auxiliary power system grounding modes.

KEYWORDS
Nuclear power plant
Fossil fuel
Neutral point
Grounding mode
Nuclear safety
Capacitive current

1. Introduction

The development of nuclear power as a clean and high-efficiency energy has been stagnated due to the influences of Fukushima incident in Japan. Moreover, the continuous deepening of development progress of China's industrialization, the environment in some regions is further deteriorated. As a result, the environmental protection pressure is quickly increases. For example, the large-area haze of China in 2013 was an ironclad proof. Reestablishment of nuclear power represents the general trend. However, after restarting the approval of nuclear power plant projects, the access threshold has been improved. The technical and safety indexes are required to reach same level of international generation-3 nuclear power units. Currently, M310 units have been mostly put into operation in China. Also, WWER-1000 improved type, AP1000 and other relevant generation-3 units are under construction. Recently, China has successfully developed the only 1,000 MW generation-3 nuclear power brand of

doi: 10.18686/wcj.v4i4.3
Received: September 16, 2015; Accepted: November 4, 2015; Published online: December 28, 2015

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"Hualong One" with autonomous and complete intellectual property.

The grounding mode of high voltage auxiliary power system of power plant involves important issues of power plant such as safe operation of the plant and continuity of power supply. Meanwhile, in terms of professional technology, it is also involves many professional fields such as overvoltage and insulation coordination, relay protection and grounding design of auxiliary power system. Currently, the high voltage auxiliary power system neutral point grounding modes of nuclear power units is put into operation or under construction in China. However, conventional fossil fuel power plants are differing from each other. The capacity of power plant is continuously improved. In addition, the auxiliary power capacity current becomes increasingly big with the influence on safe operation of auxiliary power is increases. Although neutral point grounding mode is already stipulated in certain specifications, it is still controversial as to select the most suitable grounding mode and implementation scheme for operation of power plant. Besides, resistance value of resistance grounding mode shall be determined through analysis and calculation of actual projects by comprehensive consideration of various factors [1].

Through induction and sorting of principle and method for determination of high voltage auxiliary power system neutral point of power plant below, the high voltage auxiliary power system neutral point grounding modes of nuclear power plant and conventional fossil fuel power plant have been studied. The design requirements have been absorbed and optimized. Moreover, measures improving equipment safety and power supply reliability have been analyzed so as to realize application in the subsequent design of domesticated nuclear power plants and provide reference for selection of high voltage auxiliary power system neutral point grounding mode of nuclear power plant in the future.

2. Principle for determination of neutral point grounding methods

Most faults of high voltage auxiliary power system of power plant are resulting from single-phase grounding. Generator shutdown accidents therefore occur frequently and equipment such as circuit breaker, switch cabinet, mutual inductor, transformer and cable are often burnt. If the situation is even worse, major accidents such as burning of bus and shutdown of unit for several hours can be happened. Furthermore, the direct economic losses are also affected. With the increase of capacity of unit of power plant, the high voltage auxiliary power load increases and the quantity of high voltage cables also increase. Therefore, it results in the increase of single-phase grounding fault current of high voltage auxiliary system. Besides, it also directly influences safety, reliability and continuity of power plant, insulation level of equipment and degree of damage of single-phase ground capacitive current against equipment [2].

Since the heat-resisting capacity of power equipment in auxiliary power system of power plant is relatively low, amplitude of fault current upon single-phase grounding shall be restricted to prevent burn. Meanwhile, equipment suffering from unrecoverable faults shall be forced to exit from operation as soon as possible to prevent equipment damage or worsening of faults. In order to ensure reliable operation of equipment, the recoverable faults shall be automatically eliminated to prevent the compromise of power supply reliability due to unnecessary trip. When unrecoverable faults take place, the faulty equipment shall be isolated as soon as possible to avoid influence of normal power supply. Therefore, it is very important to identify and isolate grounded faulty branch circuits.

Basic principles for determination of selection of auxiliary power system neutral point grounding points of power plant are shown as follow based on the factors above:

(1) The influence of single-phase grounding fault on continuous power supply is minimal and the auxiliary equipment can continuously run for a relatively long period.

(2) In case of single-phase grounding fault, the overvoltage multiple of sound phase is relatively low. Therefore the insulation level of auxiliary power system is not damaged and phase fault is not developed.

(3) In case of single-phase grounding fault, the hazard of fault current towards motor and cable is minimized and it also benefits realization of sensitive and selective grounding protection.

(4) Reduce the mutual influence of auxiliary equipment as much as possible.

(5) The grounding equipment is easy to order, grounding protection is simple and the investment is not huge.

3. Requirements of procedures and specifications

3.1. Nuclear power plant

3.1.1. NB/T20051-2011 Design specification of auxiliary power system of nuclear power plant

The neutral point grounding point of medium voltage auxiliary system of pressured water reactor nuclear power plant is stipulated in 5.2.2.2.1 of this specification. When the grounding capacitive current of medium voltage auxiliary power system is 10 A and below, neutral point not-grounding mode shall be better adopted to facilitate continuous operation. Besides, operation with single-phase grounding fault within a restricted time limit is allowed. In order to win sufficient time for troubleshooting, the insulation of the system shall be continuously monitored at this point. When the grounding capacitive current exceeds 10 A, under the condition that safety and availability of nuclear power plant is fulfilled, other grounding mode can also be adopted. This specification is formulated by referring to (RCC-E-2002) *Design and Construction Rules for Electrical Components of Nuclear Islands of Pressurized Water Reac-*

tor Nuclear Power Plant and is prepared based on domestic nuclear power plant design, construction and operation experience. It is suitable for nuclear power plant designed by referring to 900 MW series pressurized water reactor nuclear power plant of France.

3.2. Fossil fuel power plant

3.2.1. GB 50660-2011 Code for design of large and medium-sized fossil fired power plant

It is stipulated in 16.3.2 of this code that the following modes can be adopted as high voltage auxiliary power system neutral point grounding mode of fossil fuel power plant:

(1) Non-grounding mode and grounding mode via resistance can be adopted as high voltage auxiliary power system neutral point grounding modes of fossil fuel power plant.

(2) When the grounding capacitive current of high voltage auxiliary power system is below 10 A, either non-grounding mode or grounding mode via high resistance can be adopted for the neutral point. When the grounding mode via high resistance is adopted, the ground resistance value can be selected in a reasonable way to control the total current of single-phase grounding fault as less than 10 A. The protection shall act and alarm.

(3) When the grounding capacitive current of high voltage auxiliary power system is above 7 A, resistance grounding mode can be adopted for neutral point. The ground resistance shall be selected in a way to make sure that the resistive current is not less than the capacitive current in case of single-phase grounding fault and the total current value of single-phase grounding fault makes the protection device acts tripping accurately and sensitively [3].

3.2.2. DL/T620-1997 Overvoltage protection and insulation coordination for AC electrical installations

It is stipulated in 2.1 of this specification:

(1) Design of system with high resistance grounding shall comply with the criterion of $R0 \leq X_{C0}$ so as to restrict transient overvoltage generated due to arch grounding fault. The grounding fault current is usually less than 10 A. R_0 refers to equivalent zero sequence resistance of the system, while X_{C0} refers to distribution capacitive resistance of each phase of the system against ground.

(2) In order to acquire sufficient current for quick and selective relay protection, grounding fault current is usually adopted as 100 - 1,000 A for system with low resistance grounding. As for a general system, the criterion of restriction of transient overvoltage is $(R0/X0) \geq 2$ where X0 refers to equivalent zero sequence inductive reactance of the system.

The foregoing is also consistent with the requirements of *Technical rule for designing auxiliary power system of fossil fuel power plants* (DL/T5153-2002).

4. Method for determination of neutral point grounding modes

4.1. Calculation of capacitive current

During determination of neutral point ground mode, current flowing through neutral point upon single-phase grounding shall be calculated first. Below is the general calculation method: Calculate single-phase grounding capacitive current of power supply network connected to one station transformer or auxiliary transformer with biggest capacity and then determine grounding mode, select equipment and set relay protection on this basis [4].

The capacitance of high voltage auxiliary power system is mainly cable capacitance. The total capacitance of cable is calculated according to capacitance of each phase against ground of different cable sections. Multiple the total capacitance of cable obtained with 1.25 to obtain the total approximate value of capacitance of the whole system (including capacitance of auxiliary transformer winding, motor and power distribution device). The single-phase grounding capacitive current can be obtained using Formula (1):

$$I_c = \sqrt{3}U_e\omega C \times 10^{-3} \quad (1)$$

Where, $\omega = 2\pi f_e$

Where, I_c——Single-phase grounding capacitive current (A);

U_e——Rated line voltage of auxiliary power system (kV);

ω——Angular frequency;

f_e——Rated frequency (Hz);

C——Capacitance of each phase of auxiliary power system against ground (C)

Approximate value of single-phase grounding capacitive current of 6-10 kV cable can also be obtained using the following formula:

6 kV cable line:

$$I_c = \frac{95+2.84S}{2200+6S}U_e \quad (2)$$

10 kV cable line:

$$I_c = \frac{95+1.44S}{2200+0.23S}U_e \quad (3)$$

Where, S represents cable section (mm^2).

4.2. Selection as per calculation result of capacitive current

High voltage auxiliary power system neutral point grounding mode fulfilling the requirement shall be selected according to calculation result of the abovementioned capacitive current first. The comparison of grounding modes is shown in Table 1.

4.3. Comparative study

Due to limitation of data and space, only comparative study of high voltage auxiliary power grounding modes of M310, WWER and AP1000 nuclear power units already built and under construction in China at present as well as conventional thermal power generating units with capacity

Table 1. Comparison of various neutral point grounding modes.

Characteristic	Ineffective grounding mode			Effective grounding mode	
	Not grounded	High resistance grounding (grounding current: $I_R \leq 10$ A)	Arc extinction coil grounding	Medium resistance grounding (10 A < I_R < 300A)	Low resistance grounding (300A < I_R < 1000 A)
Continuity of power supply	Good	Good	Good	Relatively good	Poor
Influence of dynamic and thermal stability of short-circuit current on equipment and threat against personal safety	Small	Small	Small	Relatively big	Big
Grounding steady-state overvoltage (not fault phase)	√3 p.u.	√3 p.u.	√3 p.u.	Less than √ 3 p.u.	Close to p.u.
Grounding maximum transient overvoltage (not fault phase)	3.5 p.u	2.5 p.u.	3.2 p.u. (2.5 p.u. Automatic arc suppression)	Less than 2.5 p.u.	Close to p.u.
Relay protection coordination	Difficult	Best	Poor	Good	Good
First fault	Not tripping	Not tripping	Not tripping	Tripping	Tripping
Scope of application (capacitive current)	Ic < 10 A	Ic < 7 A	Ic > 10 A	7 A < Ic < 100 A (enterprise standard of power company of a certain company [5])	Ic > 100 A (enterprise standard of power company of a certain company [5])
Investment	Little	Relatively huge	Relatively huge	A lot	A lot

Table 2. High voltage auxiliary power system neutral point grounding modes of domestic nuclear plants and fossil fuel power plants.

Type of power plant	Name of project	Grounding mode
Fossil fuel power plant	200 MW and below	Not grounded or arc extinction coil grounding
	300 MW and above	Grounding via resistance
Nuclear power plant	Phase I of Qinshan Nuclear Power Plant, Daya Bay Nuclear Power Plant, Phase I of Lingao Nuclear Power Plant, Expansion Project of Phase II of Qinshan Nuclear Power Plant and Phase II of Lingao Nuclear Power Plant	Not grounded
	Phase I of Tianwan Nuclear Power Plant and Sanmen Nuclear Power Plant	Grounding via resistance
	Phase I of Fuqing Nuclear Power Plant and Fangjiashan Nuclear Power Plant	Not grounded under normal condition and input of arc extinction coil upon single-phase grounding

of 300 MW and above are carried out.

5. Analysis of current situation

The high voltage auxiliary power system neutral point grounding modes of domestic nuclear plants and fossil fuel power plants are shown in Table 2.

5.1. Comparative study

We can see from Table 3 that grounding mode fulfilling the requirement is selected according to calculation result of capacitive current first. If the capacitive current is below 10 A, non-grounding mode may be adopted. If the capacitive current is above 10 A, only arc extinction coil or resistance grounding mode can be adopted. Troubleshooting measures adopted under different grounding modes against single-phase grounding fault differ. Non-grounding mode, high resistance grounding mode and arc extinction coil grounding mode are only alarmed but do not tripper upon the occurrence of the first single-phase grounding fault. However resistance grounding mode is directly trips in which directly affects the auxiliary power operation mode, nuclear and operation safety of the whole nuclear power plant as well as fossil fuel power plant. In the authors' own opinion, selection of a more suitable grounding mode is closely related to requirements of configuration and operation mode of process equipment of power plant for power supply, lead-in of auxiliary power supply and switching result of auxiliary power accident. The typical wiring diagrams of high voltage auxiliary power systems of M310 reactor-type, WWER1000 and AP1000 nuclear plants and thermal power generating units with capacity of 300 MW and above are shown in attached Figure 1 to Figure 4.

5.2. Requirements of process equipment configuration and operation mode for power supply

The biggest difference between nuclear power plant and conventional fossil fuel power plant is the classification of load. Nuclear power plant has nuclear safety equipment and safety related equipment where it shall fulfill the requirements of "defense in depth". Emergency shutdown of reactor, isolation of containment, emergency cooling of reactor core, waste heat exhaust and special safety facilities in preventing abundant diffusion of radioactive substances to surrounding environment are shall be set up. On the contrary, fossil fuel power plant only has equipment safety related equipment without nuclear safety equipment [5].

(1) M310 and WWER1000

Medium voltage power load in special safety facilities exists in M310 and WWER1000 reactor types. Reliable power supply of these loads shall be guaranteed under any working condition (loss of power in whole plant and accident beyond design basis). After normal power supply fails, emergency diesel engine shall provide power supply for emergency loads such as special safety facilities. Upon emergency treatment of M310, the emergency diesel engine power system is neutral point non-grounding system which acts on signals but does not tripper upon occurrence of the first single-phase grounding fault. It shall ensure continuous power supply for a certain period. High resistance grounding is adopted in WWER emergency diesel engine power system. It acts same as that of M310 upon occurrence of the first single-phase grounding fault. It is also acts on signal. We can see from the setting above that M310 and WWER reactor types shall strive to maintain continuous operation of medium voltage auxiliary power and ensure operation of nuclear safety system. In case of loss of normal power supply, the emergency power supply system shall be still capable of satisfying the demand of continuous power supply and guaranteeing nuclear safety.

(2) AP1000

Guarantee of safety functions such as cooling of reactor core, isolation of containment and waste heat exhaust of AP1000 are no longer rely on AC power supply system inside and outside the plant. Compared with M310 and WWER1000 reactor types, AP1000 has no emergency medium voltage load. Except safety related function that execute the cut-off of main pump power supply upon shutdown of main pump circuit breaker, the other AC power supply systems are all at non-safety level.

(3) Thermal power

Conventional fossil fuel power plant has no nuclear safety related function requirements. Two buses are usually adopted for each unit with capacity of 300MW and above. Also, two auxiliary engines are connected to these two buses respectively. Table 2 has reflected the output condition of unit under the condition that a certain 2 × 300 MW unit cuts off a certain circuit on 6 kV bus section. We can see from Table 3, that the output of the unit will not be influenced if one of most circuits on 6 kV bus trips due to single-phase grounding faults. Load shedding of unit is required only upon cut-off of a minority of loads such as draught fan. Besides, with the continuous expansion of capacity of power grid, the fluctuation of output of the unit within a certain range almost has no influenced on the system. However, sudden accidental shutdown of unit with capacity of 300 MW and above has a relatively big impact on the system.

Table 3. Unit output under cut-off of 6 kV load of single loop.

Name of loop	Unit output/%
Circulating water pump	60 in summer and 100 in winter
Condensate pump	100
Coal mill and mill exhauster	100
Belt conveyor	100
Induced draft fan, forced draught fan and primary air fan	70
Booster pump	100
Opening-type water pump	100
Mortar pump	100
Low voltage power supplies of main powerhouse and auxiliary workshop	100

Through integration of analysis above, M301 unit has the highest requirement for reliability of medium voltage auxiliary power supply in case of single-phase grounding fault regarding requirements of configuration and operation mode of process equipment for power supply under the condition that defense in depth of nuclear safety and equipment safety are guaranteed. Non-grounding mode or arc extinction coil grounding is adopted for neutral point grounding mode. That the grounding fault acts on signal benefits power supply of nuclear safety facilities. The emergency diesel engine power supply system is neutral point non-grounding system upon emergency. It can fulfill the requirement for continuous power supply upon occurrence of single-phase grounding fault. WWER also has relatively high requirement for reliability of medium voltage auxiliary power supply. Although neutral point resistance grounding mode is adopted during normal operation and the grounding protection acts on tripping, the reliability also fulfills the requirement since high resistance grounding is adopted in emergency diesel engine. AP1000 medium voltage AC system has no nuclear safety requirement. Neutral point resistance grounding mode is adopted and the grounding protection acts on tripping. As a result, it has no influence or very small influence on nuclear safety. Conventional fossil fuel power plants with capacity of 300 MW and above only have equipment safety requirements. Neutral point resistance grounding mode is adopted and the grounding protection acts on tripping. The tripping of some circuits has a certain influence on output of power plant. However, it can ensure equipment safety better compared with non-grounding single-phase grounding which can trigger short-circuit fault of bus to result in shutdown of the unit [6].

5.2.1. Connection of auxiliary power

The power supply of auxiliary equipment of M310 reactor-type unit is only provided by main single power supply outside the plant. The power supply of standby load is provided by main and auxiliary power supplies outside the plant; one loop of power supply is led from main and auxiliary power supplies outside the plant to WWER1000 and AP1000 unit loads. The power supply of load continuously supplying power during shutdown is provided by backup diesel generator unit besides main while auxiliary power supplies outside the plant. It has higher reliability than M310 for unit and standby loads and emergency load. One loop of power supply is led from high voltage auxiliary transformer and high voltage starting/backup transformer to the unit loads of thermal power generating units with capacity of 300 MW and above. As for security load required to continuously supply power during shutdown, besides the abovementioned two power suppliers, diesel engine generating unit is also used for power supply. It has higher reliability than M310 for power supply of unit and security load. The power supply of auxiliary equipment of M310 unit is singular. During fault of high voltage auxiliary transformer of WWER, although it can be switched to auxiliary power supply, shutdown is still needed. AP1000 unit load shall have at least two power suppliers. Possibility of continuous operation is needed in case of fault. As for fossil fuel power plant, the unit load has two power suppliers. In case of a fault, the faulty power supply can be switched to the other normal power supply for continuous operation. If viewed from guarantee of continuous and stable operation of power plant, operational safety of main equipment and improvement of annual operation duration of power plant, M310 unit has highest requirement for continuity of power supply. In the authors' opinion, it is also a reason why different grounding modes apply to high voltage auxiliary neutral point of various types of units.

5.2.3. Results of switching of auxiliary power accident

Double-reactor layout is adopted for M310 and WWER1000 reactor types. Four high voltage auxiliary transformers and two auxiliary transformers are set up in two units. The capacity of auxiliary transformer of M310 is less than the high voltage auxiliary transformer of single unit. The capacity of auxiliary transformer of WWER1000 is basically same as capacity of single high voltage auxiliary transformer. Single-reactor layout is adopted for AP1000 reactor type. Two high voltage auxiliary transformers and two auxiliary transformers are set up. Capacity and quantity of auxiliary transformers and high voltage auxiliary transformers are the same.

When the working power supply of M310 reactor type is slowly switched to auxiliary power supply due to fault, the reactor of the unit shall be shut down. When WWER1000 reactor type is switched to standby power supply, shutdown load shedding of steam turbine generator is implemented. However, auxiliary load needed for 40% power of the reactor can be maintained. Only the unit is shutdown (the reactor is not shut down). According to the operation mode of AP1000 learned at present, when the power supply is switched to auxiliary power supply, the unit is able to generating electricity with load. However, no operational experience has been obtained in reality. It shall be still further implemented during actual project implementation. Thermal power generating unit usually trips and cuts off faulty equipment at once during occurrence of single-phase grounding fault. Even if the medium voltage bus losses power, the auxiliary power can also be quickly switched to standby power supply through quick-switching device. Under the precondition that the equipment safety is ensured, the operation of power plant or load-down operation is basically not affected. It is thus clear that M310 directly enters reactor shutdown status when it is switched to auxiliary power supply in case of high voltage auxiliary power fault. Thus, it is very important and necessary to maintain continuity of working power supply. On the contrary, WWER and AP1000 do not directly shut down the reactor after switching of auxiliary power supply. Power operation can be resumed as soon as possible. The requirement of WWER and AP1000 for continuity of power supply is not higher than that of M310. Resistance grounding mode is also applicable in which is selected in thermal power generating units. The auxiliary power supply is quickly switched after occurrence of single-phase grounding fault. Equipment safety demand and the demand of continuous operation of power plant shall be both satisfied [7].

5.2.4. Brief summary

If analyzed from the three aspects mentioned above, when single-phase grounding fault occurs, M310 shall be better maintained continuous operation for a certain period so as to eliminate the fault as soon as possible. WWER and AP1000 are immediately trip to protect equipment safety after the occurrence of single-phase grounding fault. Meanwhile, they have relatively small or no influence on nuclear safety. In addition, thermal power generating unit immediately trips after the occurrence of single-phase grounding fault of separate loop. It has also no influence or relatively small influence on output of power plant. Therefore, the demand of equipment safety is mainly satisfied.

6. Engineering application

A Comparative study of high voltage auxiliary power system neutral point grounding modes of nuclear power plant and conventional fossil fuel power plant is carried out for actual projects one by one. Also, design optimization schemes are put forward. Phase I of Fuqing Nuclear Power Plant is used for nuclear power M310 unit while Tianwan

3# and 4# Nuclear Plants are used for WWER unit. Meanwhile, Phase I of Sanmen Nuclear Power Plant is used for AP1000. As for thermal power generating unit, 300–1000 MW units designed by multiple power design institutes are used as exampled.

6.1. Non-grounding mode and arc extinction coil grounding mode

(1) Grounding Scheme

In Phase I of Fuqing Nuclear Power Plant, upon power supply of high voltage auxiliary transformer A and auxiliary transformer, the capacitive current of auxiliary power system will approach 13 A and 17 A respectively. According to the requirements of RCC-E, neutral point non-grounding mode shall be adopted to realize the purpose of operation for a certain period with grounding fault. However, relatively big risk is exists. According to research findings of the test of arc self-extinguishing characteristic of China Electric Power Research Institute on single-phase grounding fault, it has indicated that arc can hardly distinguish when capacitive current exceeds 10 A under neutral point non-grounding mode. The requirement of liability is no longer fulfilled. Besides, once single-phase grounding takes place, such big capacitive current will be possible soon developed from single-phase grounding into phase-to-phase short circuit. For example, 6 kV flat cable of the bucket wheel machine circuit of a certain 2 × 300 MW power plant was improperly dragged in which it was broken by the bucket wheel machine wheel on steel rail resulting instability grounding of phase A (it was found out that the yellow cable core wire was burnt on the site) and generate intermittent grounding arc. Meanwhile, the non-faulty phases B and C also had overvoltage. At this point, the insulation of supporting insulator of the vertical bus phase C corresponding to the primary fan circuit of switch cabinet in the testing position was weak. Thus, it went through breakdown under the action of overvoltage, to result in out-of-phase two-point grounding circuit (phases A and C) in the entire 6 kV IIA section system. Under the condition of two-point grounding, the bucket wheel machine circuit flows through relatively big fault current causing phase A fuse was burnt. Thus the contact acted on trips, and the grounding fault of the bucket wheel machine was cut off. However, the grounding fault of 6 kV phase C bus is still existed. Since the grounding fault of phase C bus couldn't be eliminated, metallic steam generated by arc began to diffuse from the fault point, in order to trigger phase-to-phase short circuit of static contact -on the bus side of switch cabinet. After phase-to-phase short circuit, the overcurrent protection of high voltage auxiliary transformer acts to trip the power incoming switch of 6 kV IIA section. As a result, the whole 6 kV IIA section bus lost power and the fault ended. The whole fault lasted for approximately 4–5 min. If viewed from the fault process, phase-to-phase short circuit triggered by single-phase grounding was the primary cause of fault development. If non-grounding mode was still adopted for faulty operation at this point, the reliable operation of medium voltage system could not be ensured. Due to the reason mentioned in 5.2.1., M310 had to run for a certain period with grounding fault due to the operation requirements of auxiliary power. The low resistance grounding mode couldn't fulfill the requirement. Therefore, the neutral point grounding mode was comprehensively reconstructed. It was finally determined that arc extinction coil (modulation type) grounding to compensate capacitive current and grounding line selection device were adopted for neutral point. The arc extinction coil was offline during normal condition, and quickly input upon single-phase grounding fault to compensate capacitive current. As for a permanent fault, fault line selection was conducted. Meanwhile, the protection of personal safety was greatly improved [8].

(2) Calculation of Capacity of Arc extinction coil

Overcompensation operation mode shall be better adopted. The capacity of arc extinction coil is usually calculated according to the following formula:

$$Q = 1.35 I_c \frac{U_e}{\sqrt{3}} \tag{4.1}$$

Where, Q——Compensation capacity (kVA);

U_e——Rated line voltage of auxiliary power system (kV);

I_c ——Capacitive current of auxiliary power system (A)

(3) Existing Problems

Although arc suppression grounding mode has its own advantages (e.g. slowdown of the rising speed of voltage resumption through compensation capacitive current, benefiting of the extinguishing of grounding arc, lowering the probability of occurrence of intermittent arc grounding overvoltage to automatically eliminate most instant grounding faults and capacity of faulty operation for 2 hours since arc extinction coil grounding and non-grounding system belongs to the category of ineffective grounding), it also has its inherent defects. When the neutral point is grounded via arc extinction coil, it is classified into overcompensation and under-compensation. The so-called overcompensation refers to compensation method adopted when the reactive current is greater than capacitive current. While, the under-compensation refers to compensation method adopted when the reactive current is less than capacitive current. In the practice, overcompensation is usually adopted to prevent the reduced of capacitive current during change of operation mode and also to ensure operation of arc extinction coil is at resonance point. When arc extinction coil approaches full compensation operation, displacement voltage of neutral point will be enlarged to result in the phenomenon of "virtual grounding". It is worth attention that arc extinction coil is seldom applied in an auxiliary power system of domestic and foreign power plants. It is learned that arc extinction coil was only used in a neutral point of auxiliary power of a 200 MW unit in Guangdong Province as well as small units with capacity of 100 MW and below. Therefore, the application of arc extinction coil is lack of extensive operational experience. During actual application process, the grounding mode operation is relatively complicated as well as the grounding protection. Issues of whether the arc extinction coil can be reliably and quickly input through contactor, the probability of fault of the device and displacement of neutral point shall be further learned and tracked.

(4) Design Optimization

If the capacitive current of auxiliary power medium voltage system exceeds 10A and it is expected to adopt neutral point non-grounding mode for operation, the following measures can be adopted to reduce the capacitive current below 10 A:

(i) Power loads not directly related to the production of power plant such as loads of office building and dormitory in plant front area shall be supplied by public power grid instead of auxiliary power.

(ii) Medium voltage cast bus made using new technology shall be used to replace the cable line so as to effectively lower capacitive current. This technology has already been successfully applied in some nuclear power plants of CGN at present.

(iii) As for medium voltage load of relatively long individual cable line, isolation transformer can be set up to reduce the capacitive current entering auxiliary power system.

6.2. Resistance grounding modes

(1) Detailed Classification

Traditional classification classified resistance grounding as high resistance grounding and low resistance grounding. In addition, with the development of resistance grounding technologies, three grounding modes, i.e. high resistance grounding mode, medium resistance grounding mode and low resistance grounding mode, are gradually developed. As for high resistance grounding, the grounding fault current is usually adopted as less than 10 A while for low resistance grounding, the grounding fault current is usually adopted as 100−1000 A. The definition of resistance in current range of 30−300 A is not given. It is classified according to relevant literatures as shown in Table 4. (system voltage as 6.3 kV):

Table 4. Classification of resistance grounding modes as per resistance.

Classification as per resistance	High resistance	Medium resistance	Low resistance
Range of resistance (Ω)	> 300	10~300	<10
Grounding fault current I_R(A)	$I_R < 10$	$10 < I_R < 600$	$600 < I_R < 1000$

(2) Calculation of Ground Resistance Values

China has not clearly stipulated the standardization of selection of neutral point resistance. Neutral point resistance value must be selected according to the specific conditions of power plant. Factors such as restriction of multiple of interval arc grounding overvoltage, sensitivity of relay protection, disturbance against communication line, contact voltage and step voltage shall be considered, analyzed, and compared. The principle of best comprehensive effect shall be selected.

Calculation formula of resistance value of neutral point of resistor directly connected to the system is shown as follows:

$$R_N = \frac{U_e}{\sqrt{3} I_R} \tag{4.1}$$

Where, R_N——Resistance value of resistor directly connected (kΩ);

U_e——Rated line voltage of bus of high voltage auxiliary power system (kV);

I_R——Ground resistive current (A) which shall be better not lower than ground capacitive current of the system.

(3) Selection of Ground Resistance of Neutral Point High Resistance Grounding Mode

Control the single-phase grounding fault current as less than 10 A.

It is usually selected as per $I_R = (1 \sim 1.5)\ I_C$. The ground resistance is determined as around 300~500 Ω if calculated according to medium voltage auxiliary voltage of 6.3 kV.

High resistance grounding mode requires capacitive current below 7 A. Currently, cable laying network is often adopted in high voltage auxiliary power in both nuclear power plant and conventional fossil fuel power plant. Therefore the capacitive current of medium and large-sized power plants basically exceeds 7 A. As a result, the high resistance grounding mode is basically inapplicable and it is thus not given unnecessary details.

(4) Selection of Medium Resistance and Low Resistance

$$I_R = U_{ph}/R_n \tag{4.2}$$

$$K = I_R/I_c \tag{4.3}$$

R_n——Resistance of neutral point;

U_{ph}——Rated phase voltage;

I_R——Single-phase grounding fault current of power grid refers to current flowing through R_n;

I_c——Capacitive current of power grid;

6.3. Selection according to requirement for restriction of arch grounding overvoltage

The principle of restriction of arc grounding overvoltage by neutral point ground resistance is the energy consumption action of resistance. When a single-phase grounding fault occurs, the duration from extinguishing of arc to re-striking at the fault point usually lasts for half a cycle. During this half a cycle, the electric charge in capacitance of non-faulty phase against ground will be released to the ground via neutral ground resistance R_n. The releasing speed of capacitive charge is related to value K (value R_n). Arc overvoltage declines accordingly with the increase of value K. However, the relationship between reduction of arc overvoltage multiple and value K is not a straight-line relation. When value K is greater than 4, the effect of reduction of arc overvoltage will not be obvious even if value K is continuously increased. Abundant tests and calculations conducted by many research institutions and scientific researchers at home and abroad indicate that intermittent arc overvoltage multiple can be restricted within 2.6 times when $I_R = I_c$. When $I_R = 4I_c$, intermittent arc overvoltage multiple can be restricted within 1.8 times. The requirement for restriction of arch overvoltage can be usually satisfied when $I_R = (1\sim4)\ I_c$ is selected [9].

6.4. Selection according to requirement for guarantee of relay protection sensitivity

If considered from the perspective of satisfaction of relay protection sensitivity, the bigger value K the better (i.e. the smaller R_n the better). However, current microcomputer protection usually has zero sequence protection function and the current starting value is quite small (0.01 A). As for power distribution system with medium resistance or low resistance grounding, the single-phase grounding fault current is much bigger than the capacitive current of each line against ground. The sensitivity requirement of zero sequence protection can usually be guaranteed.

6.5. Consideration from perspective of personal safety

When single-phase grounding fault occurs to neutral point via small resistance grounding power distribution grid, the grounding short-circuit current flowing through fault point is relatively big to result in rise of potential at the fault point and possibly lead to step voltage and contact voltage exceeding allowable values. If personnel get close to the fault point or contact the faulty electrical equipment at this point, casualties may be caused. Therefore, if considered from reduction of step voltage and contact voltage at fault point, the bigger the value of neutral point grounding resistance the better.

6.6. Consideration from perspective of reduction of grounding short-circuit current at fault point

The bigger the single-phase grounding short circuit current of fault point the worse the damage to the faulty equipment thus will become in case of fault. However, if considered from reduction of damage of single-phase grounding fault current against equipment, the bigger the value of neutral point ground resistance the better.

To sum up, the selection of vale of neutral point ground resistance is a comprehensive technical and economic issue. The best scheme shall be selected through comprehensive analysis and comparison of specific conditions and characteristics of each auxiliary power system.

Several years ago, High Voltage Specialized Committee of Chinese Society for Electrical Engineering organized the convening of neutral point ground technology seminars for multiple times. Experts attending the seminars basically formed a consensus that neutral point ground resistance with relatively big resistance value could be adopted under the precondition that lowering of intermittent arc grounding overvoltage was satisfied.

6.7. Determination of ground resistance value

In 6 kV and 10 kV auxiliary power systems, capacitive current usually seldom exceeds 40 A. Therefore, after ground resistance is connected to neutral point, the lower limit of resistive component of grounding current can be controlled at approximately 40 A. The specific value also depends on size of capacitive current of system and sensitivity requirement of protection device. It needs clarification that the allowable single-phase grounding current of the system is also restricted by duration of fault so as to prevent burning of iron core upon single-phase grounding taking place inside motor or transformer. To this end, the followings shall be satisfied: Single-phase grounding current is less than or equal to $100t^{-0.4}$. This formula indicates relationship between single-phase grounding current (A) and duration of arc t(s). If fault cut-off time is determined as 1, the single-phase grounding current of the system shall be less than 100 A. Whereas, for fault cut-off time is determined as 0.2~0.3 s, the single-phase grounding current of the system shall be less than 200 A. This value can be viewed as the upper limit of single-phase grounding current. Therefore, it is clear that single-phase grounding current determined for medium resistance grounding is suggested as 40~200 A. This current shall not be too big. In

Table 5. Resistance value/single-phase grounding current in resistance grounding mode.

Thermal power	Northwest Institute	Henan Xinyang Power Plant 2 × 300 MW	100 Ω/40 A (6 kV)
		Qinghai Huadian Datong Power Plant 2 × 300 MW	40 Ω/100 A (6 kV)
		Phase I of Shaanxi Fugu Power Plant 2 × 1000 MW	60 Ω/100 A (10 kV)
		Phase IV of Tianjin Zouxian Power Plant 2 × 1000 MW	60 Ω/100 A (10 kV)
	North China Institute	Tianjin Lingang Power Plant 2 × 350 MW	18.2 Ω/200 A (6 kV)
	Guangdong Institute	Shanwei Power Plant 2 × 600 MW	40 Ω/100 A (6 kV)
		Datang Chaozhou Sanbaimen Power Plant 4 × 600 MW	40 Ω/100 A (6 kV)
Nuclear power	Northeast Institute	Tianwan 3# and 4# 2 × 1000 MW	40 Ω/100 A (6 kV)
	East China Institute	Phase I of Sanmen Nuclear Power Plant 2 × 1250 MW	6.06 Ω/1000 A (10 kV)

the authors' opinion, value of grounding current as about 4 times of capacitive current can restrict intermittent arc overvoltage multiple within 1.8 times, which is very beneficial to safe operation of cable and equipment. Each power institute in China also determines resistive current mainly within the above mentioned range when adopting medium resistance grounding mode as shown in Table 5.

The resistance value of Phase I of Sanmen Nuclear Power Plant is determined as 6.06 Ω/1000 A except Sanmen Nuclear Power Plant which adopts neutral point low resistance grounding mode, nuclear power plants and thermal power are generating units that adopting resistance grounding above abundantly and adopt medium voltage grounding mode. The primary cause for adoption of low resistance grounding in Sanmen Nuclear Power Plant is that it is stipulated in IEEE 142 of the United States that 90% of windings of equipment adopting star connection such as transformer and motor shall be protected. 10% of windings away from neutral point still cannot be protected. The single-phase grounding current at this place is only around 10% of that at the outgoing terminal. It is close to 100 A. At this point, the sensitivity of single-phase grounding protection shall be guaranteed. The requirement can be satisfied only when the single-phase grounding fault current outside the electrical equipment reaches about 1,000 A. However, the domestic standard only raises the rotator grounding protection requirement not less than 90% in installation protection area of generator with capacity below 100 MW. The requirements for motor and transformer are both single-phase grounding protection, which is different from the requirements of American standard [10].

6.8. Design optimization

Since the single-phase grounding current is too big for low resistance grounding, the following problems will be caused:

(A) Burning: If single-phase grounding fault occurs at a certain place of cable duct or cable tunnel, current arc above 600 A may burn other adjacent cables and it will flee to other places along the duct or tunnel.

(B) Endangering of Personal and Equipment Safety: Ground potential of single-phase grounding point or voltage of motor shell would substantially rise. It is likely that insulation of contact voltage, step voltage and electronic weak current devices would exceed the standard.

(C) The resistor has a big volume; many consumables are used as well as the prices are high.

(D) Wrong actions possibly resulting in differential protection of transformer.

As for external fault resulting from single-phase grounding short circuit, the current circulates through the resistance of neutral point of transformer. When the current is too big to exceed the setting range of differential protection of transformers, the differential protection would act wrongfully to cut off the power supply at each side to result in an open circuit to worsen the accident. Therefore, the use of low resistance grounding mode shall be restricted.

In the authors' opinion, if AP1000 units are to be built in China in the future, the selection of neutral point ground resistance and grounding fault current may be further optimized. It must be based on domestic specifications and standards, power plant operation and progress of equipment domestication after introduction, digestion and absorption. For example, the grounding mode can be changed to medium resistance grounding or arc extinction coil grounding.

7. Conclusion

High voltage auxiliary power system neutral point grounding modes of nuclear power plant and fossil fuel power plant directly affect operation mode of auxiliary power and even influence nuclear safety and operational safety of the whole nuclear power plant and fossil fuel power plant. Grounding mode fulfilling the requirement of specification shall be selected first according to calculation result of capacitive current. Then, a grounding mode better benefiting power plant operation shall be selected according to requirements of configuration and operation mode of process equipment of power plant for power supply, lead-in of auxiliary power supply and auxiliary power accident switching result. This is because different things shall not be treated as the same.

It is expected to have a certain inspiring and reference effect on the selection of grounding mode of nuclear power units in the future through analysis and study of high voltage auxiliary power system neutral point ground modes of domestic large nuclear power plant and fossil fuel power plant.

The application of arc extinction coil in auxiliary power neutral point of power plant is still lack of experience. With the successive commissioning of nuclear power plants under construction in recent two years, a complete set of safety measures and operation experience will be inevitably and gradually accumulated.

Conflicts of interest

These authors have no conflicts of interest to declare.

Authors' contributions

These authors contributed equally to this work.

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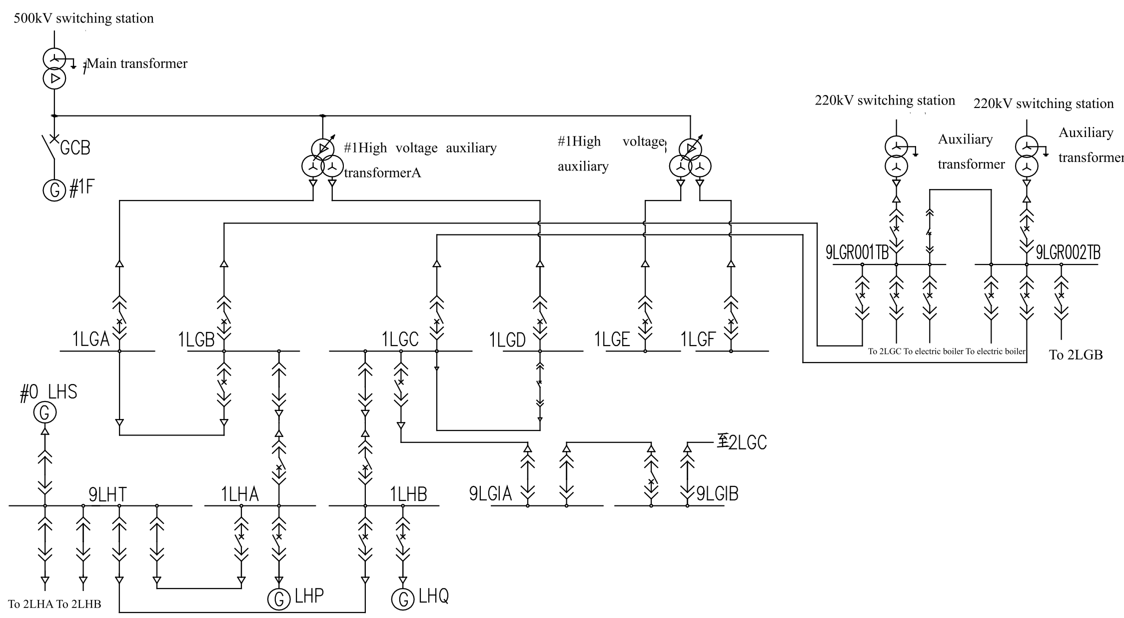
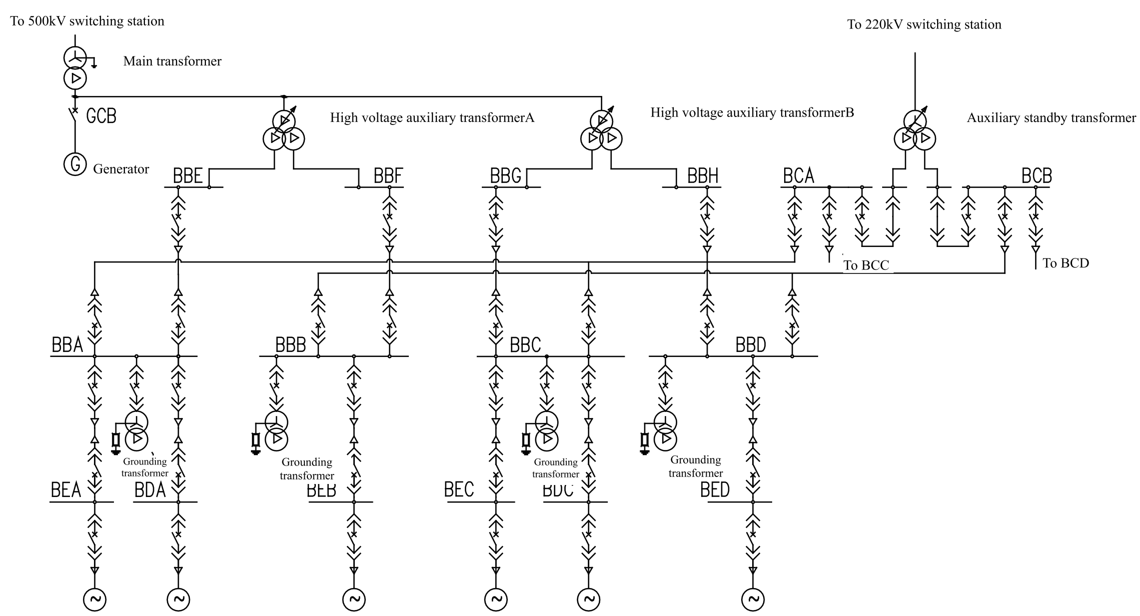
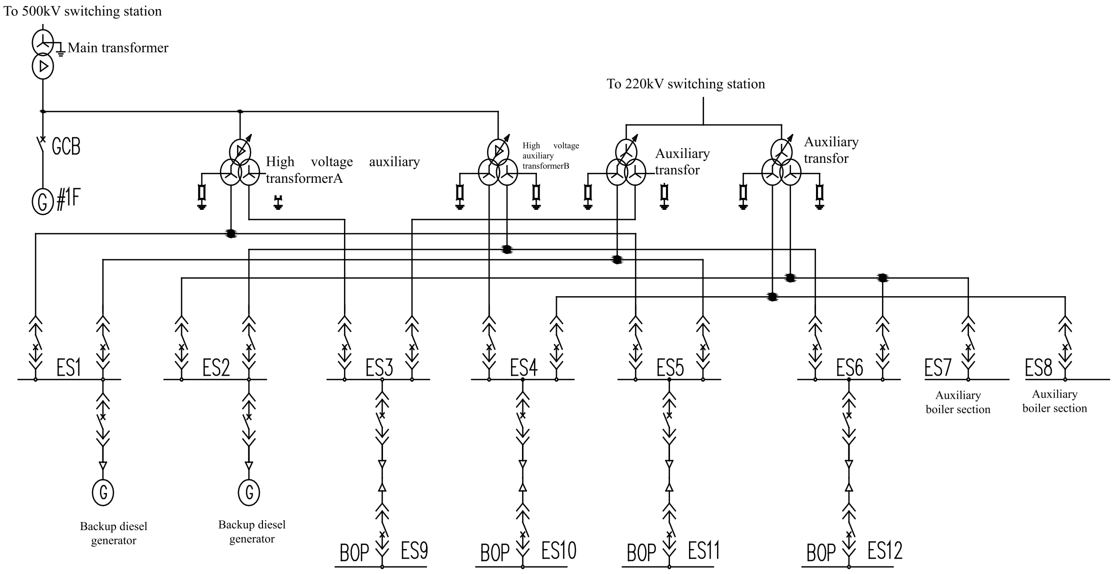


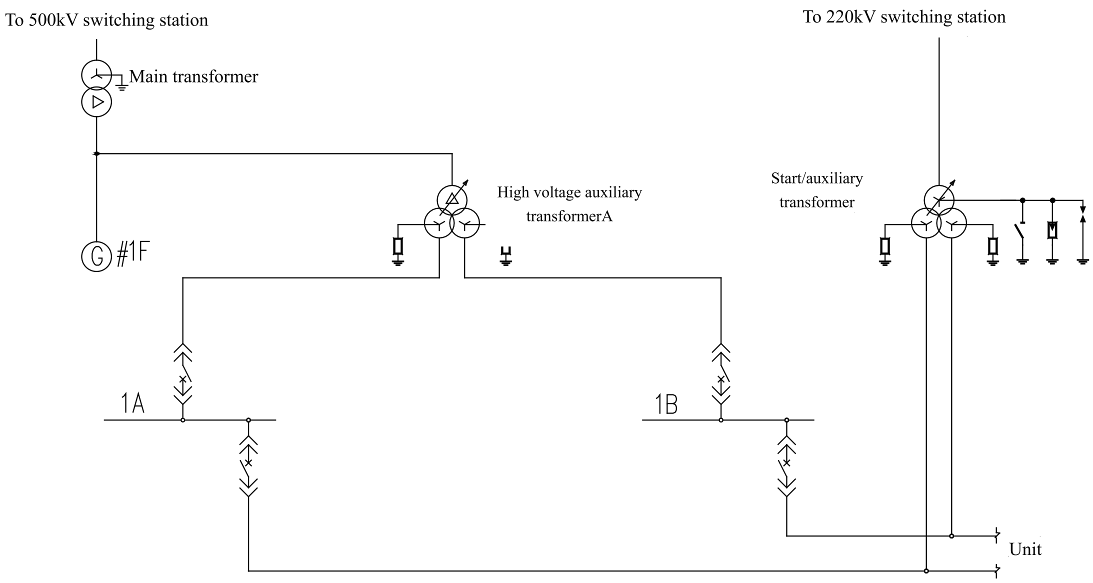
Attached Figure 1. Typical Wiring Diagram of M310 Reactor Type High Voltage Auxiliary Power.



Attached Figure 2. Typical Wiring Diagram of WWER1000 Reactor Type High Voltage Auxiliary Power.



Attached Figure 3. Typical Wiring Diagram of AP1000 Reactor Type High Voltage Auxiliary Power.



Attached Figure 4. High Voltage Auxiliary Power of Thermal Power Generating Unit of 300MW and Above.