

COOLING SYSTEM FOR SUPERCONDUCTING CURRENT LIMITER,
SUPERCONDUCTING CURRENT LIMITER, AND CONTROL METHOD FOR
COOLING SYSTEM FOR SUPERCONDUCTING CURRENT LIMITER

5 TECHNICAL FIELD

[0001] The present disclosure relates to a cooling system for a superconducting current limiter, the superconducting current limiter, and a control method for the cooling system for the superconducting current limiter.

10 BACKGROUND

[0002] A power cable system using a superconducting cable cools the superconducting cable by circulating a cryogenic refrigerant, such as liquid nitrogen, along the axis direction of the superconducting cable to maintain a superconducting state. For example, in case of an unexpected accident where an excessive current not less than a rated current flows to a power system and transition to a normal conducting state is made, a current limiter having a function of instantly interrupting a current is necessary. Conventionally, however, an example in which the superconducting cable and the current limiter are used in combination has not been found very much.

[0003] Patent Document 1 (in particular, FIG. 35) discloses a cooling system for combining a superconducting cable and a superconducting current limiter, and maintaining these at a temperature not higher than a SN transition temperature (critical temperature). The superconducting current limiter is a device for suppressing a current through the use of electric resistance that occurs when a superconducting state is broken and transition to a normal conducting state takes place. Patent Document 2 discloses an example with a dedicated refrigerator for cooling a superconducting current limiting element constituting a superconducting current limiter.

Citation List

Patent Literature

[0004]

Patent Document 1: WO99/62127A (FIG. 35)

Patent Document 2: JP2007-317884A

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SUMMARY

Technical Problem

[0005] The superconducting current limiter needs to immediately recover to a superconducting state when the superconducting state is broken and transition to a normal
10 conducting state is made. A cooling load is instantaneously increased when the superconducting current limiter recovers from the normal conducting state to the superconducting state. Thus, against the instantaneous increase in cooling load, the immediate recovery has to be made possible.

[0006] The superconducting cable is cooled to a cooling temperature lower than the critical
15 temperature with a safety margin from the critical temperature so as not to exceed the critical temperature during operation. Meanwhile, the superconducting current limiter is cooled to a temperature close to the critical temperature, because a superconducting current limiting element needs to immediately make transition to suppress a short-circuit current not less than a rated current when the short-circuit current occurs in the superconducting cable. Thus,
20 since the cooling temperatures for the superconducting cable and the superconducting current limiting element are different, it is generally considered that there is no other choice but to provide a dedicated refrigerator for each of them even if they are used in combination. Consequently, a cooling system may be complicated and increased in cost.

[0007] The present disclosure was made in view of the above problems, and an object of the
25 present disclosure is to allow for immediate recovery at a low cost and in transition of the superconducting current limiter.

Solution to Problem

[0008] In order to achieve the above object, a cooling system for a superconducting current limiter according to the present disclosure includes a condenser disposed in a gas phase portion of a refrigerant tank or a space communicating with the gas phase portion, the refrigerant tank storing a first refrigerant for cooling a superconducting current limiting element, and a liquid return channel for returning a condensate liquid liquefied by the condenser to a liquid phase portion of the refrigerant tank.

[0009] Further, a superconducting current limiter according to the present disclosure includes a superconducting current limiting element, a refrigerant tank storing a first refrigerant for cooling the superconducting current limiting element, and the cooling system for the above-described superconducting current limiter described above.

[0010] Furthermore, a control method for a cooling system for a superconducting current limiter according to the present disclosure is a control method for a cooling system for a superconducting current limiter, the cooling system including a condenser disposed in a gas phase portion of a refrigerant tank or a space communicating with the gas phase portion, the refrigerant tank storing a first refrigerant for cooling a superconducting current limiting element, and a liquid return channel for returning a condensate liquid liquefied by the condenser to a liquid phase portion of the refrigerant tank, the control method including a pressure detection step of detecting a pressure value in the gas phase portion of the refrigerant tank or the space communicating with the gas phase portion, and a flow rate control step of controlling a flow rate of the second refrigerant flowing into the condenser, in accordance with the pressure value.

Advantageous Effects

[0011] With a superconducting current limiter and a cooling system according to the present disclosure, since a dedicated refrigerator for the superconducting current limiter is unnecessary, allowing for simplification and a low cost, as well as immediate recovery after transition, and by controlling a recondensation amount of the first refrigerant in a condenser, it is possible to cool the superconducting current limiter to a desired temperature suitable for

cooling the same. Further, with a control method for the cooling system for the superconducting current limiter, it is possible to increase responsiveness of the superconducting current limiter when a short-circuit current not less than a rated current flows to a superconducting cable.

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BRIEF DESCRIPTION OF DRAWINGS

[0012] FIG. 1 is a system diagram where a superconducting current limiter is applied to a power cable system using a superconducting cable according to an embodiment.

FIG. 2 is a cross-sectional view of the cooling system for the superconducting current limiter according to an embodiment.

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FIG. 3 is a cross-sectional view of the cooling system for the superconducting current limiter according to an embodiment.

FIG. 4 is a flowchart of a control method for the cooling system for the superconducting current limiter according to an embodiment.

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DETAILED DESCRIPTION

[0013] Some embodiments of the present invention will be described below with reference to the accompanying drawings. It is intended, however, that unless particularly specified, dimensions, materials, shapes, relative positions and the like of components described or shown in the drawings as the embodiments shall be interpreted as illustrative only and not intended to limit the scope of the present invention.

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For instance, an expression of relative or absolute arrangement such as “in a direction”, “along a direction”, “parallel”, “orthogonal”, “centered”, “concentric” and “coaxial” shall not be construed as indicating only the arrangement in a strict literal sense, but also includes a state where the arrangement is relatively displaced by a tolerance, or by an angle or a distance whereby it is possible to achieve the same function.

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For instance, an expression of an equal state such as “same”, “equal”, and “uniform” shall not be construed as indicating only the state in which the feature is strictly equal, but

also includes a state in which there is a tolerance or a difference that can still achieve the same function.

Further, for instance, an expression of a shape such as a rectangular shape or a tubular shape shall not be construed as only the geometrically strict shape, but also includes a shape with unevenness or chamfered corners within the range in which the same effect can be achieved.

On the other hand, an expressions such as “comprising”, “including”, “having”, “containing”, and “constituting” one constitutional element are not intended to be exclusive of other constitutional elements.

[0014] FIG. 1 is a system diagram where a superconducting current limiter is applied to a power cable system using a superconducting cable according to an embodiment. A power cable system 10 includes a refrigerator 20, a reservoir 22, and a refrigerant pump 24 on a circulation passage 12 where a refrigerant r2 (second refrigerant) circulates. The refrigerant r2 such as liquid nitrogen cooled to an extremely low temperature circulates through the circulation passage 12. A part of the circulation passage 12 is disposed along the axis direction of the superconducting cable 16, and the superconducting cable 16 is cooled to a superconducting state by the refrigerant flowing through the circulation passage 12. A branch passage 14 branches from the circulation passage 12 upstream of the superconducting cable 16. The branch passage 14 bypasses the superconducting cable 16, goes through a superconducting current limiter 18, and is connected to the reservoir 22.

[0015] For example, in case of an unexpected accident where an excessive current not less than a rated current flows to a power system, and a superconducting state of the superconducting cable 16 and the superconducting current limiter 18 is broken and makes transition to a normal conducting state, the superconducting current limiter 18 suppresses or interrupts a current flowing through the superconducting cable 16 by using electric resistance caused in the transition.

[0016] As shown in FIG. 2 or 3, the superconducting current limiter 18 according to an embodiment includes a superconducting current limiting element 50, a refrigerant tank 52

where a refrigerant r1 (first refrigerant) for cooling the superconducting current limiting element 50 is stored, and a cooling system 30 for the superconducting current limiter 18. The superconducting current limiting element 50 is cooled by being immersed in a liquid phase portion L of the refrigerant r1.

5 [0017] As shown in FIG. 2 or 3, the cooling system 30 (30a, 30b) for the superconducting current limiter according to some embodiments includes a condenser 31 (31a, 31b) which is disposed in a gas phase portion G of the refrigerant r1 formed in the refrigerant tank 52 or a space S communicating with the gas phase portion G. During the operation of the superconducting current limiter 18, the refrigerant r1 for cooling the superconducting current
10 limiter 18 is partially evaporated by heat received from the superconducting current limiting element 50. In the condenser 31, the refrigerant r2 and the evaporated refrigerant r1 exchange heat, cooling and condensing the refrigerant r1. A liquefied condensate liquid is returned to the liquid phase portion L of the refrigerant tank 52 through a liquid return channel 32. Thus immediately returning the refrigerant r1 recondensed by the condenser 31 from the
15 liquid return channel 32 to the refrigerant tank 52, it is possible to increase the recondensation amount in the condenser 31. Therefore, it is possible to efficiently perform recondensation, allowing for immediate recovery against the cooling load instantaneously increased in transition.

[0018] Further, the cooling system 30 is basically constituted by the condenser 31 and the
20 liquid return channel 32, and does not need a dedicated refrigerator for the superconducting current limiter, allowing for simplification and a low cost. Furthermore, regulating the flow rate of the refrigerant r2 for cooling the refrigerant r1 in the condenser 31, it is possible to control the recondensation amount of the refrigerant r1. Since the gas phase portion G or the communication space S is in the saturated condition, it is possible to control the pressure
25 (saturation pressure) of the gas phase portion G or the communication space S by controlling the recondensation amount of the refrigerant r1, and it is further possible to control the temperature (saturation temperature) of the gas phase portion G or the communication space S by controlling the pressure of the gas phase portion G or the communication space S. Thus,

it is possible to control the liquid phase portion L of the refrigerant r1 to the temperature suitable for cooling the superconducting current limiter 18.

[0019] In the power cable system 10, the superconducting cable 16 is held at a cooling temperature with a safety margin from the critical temperature so as not to exceed the critical temperature. Meanwhile, the superconducting current limiter 18 is cooled to a temperature close to the critical temperature in order to immediately interrupt a short-circuit current not less than a rated current when the short-circuit current occurs in the superconducting cable 16. Therefore, the cooling temperatures of the superconducting cable 16 and the superconducting current limiter 18 are different. Accordingly, it is generally considered that there is no other choice but to provide a dedicated refrigerator for each of the superconducting cable 16 and the superconducting current limiter 18 even if they are used in combination. By contrast, according to the present embodiment, it is possible to control the refrigerant r2 to the cooling temperature suitable for the superconducting cable 16 by the refrigerator 20, as well as it is possible to control the refrigerant r1 to the cooling temperature suitable for the superconducting current limiter 18.

[0020] If the short-circuit current not less than the rated current flows to the superconducting cable 16, the superconducting current limiting element 50 included in the superconducting current limiter 18 makes transition and is heated by electrical resistance arising from the transition, raising the pressure of the refrigerant r1 for cooling the superconducting current limiting element 50. With respect to the pressure rise of the refrigerant r1, the flow rate of the refrigerant r2 flowing into the condenser 31 is increased to prevent a temperature rise of the refrigerant r1. In this case as well, since the power cable system 10 shown in FIG. 1 includes the reservoir 22, it is possible to return the flow rate of the refrigerant r2 needed for the cooling load of the superconducting cable 16 from the condenser 31 to the reservoir 22, without being influenced by the flow rate and a fluid pressure of the refrigerant r2 flowing into the reservoir 22 through the superconducting cable 16.

[0021] In an embodiment, the reservoir 22 is disposed at a junction of the circulation passage 12 and the branch passage 14. Then, the refrigerant r2 of the branch passage 14 is

returned to a gas phase portion of the reservoir 22. If the circulation passage 12 merges into the branch passage 14 upstream of the reservoir 22, the refrigerant r2 may flow back to the branch passage 14 from the circulation passage 12 where the flow rate of the refrigerant r2 is high. According to the present embodiment, since the refrigerant r2 flowing through the branch passage 14 is returned to the gas phase portion of the reservoir 22, there is no risk of the flowback.

[0022] In the embodiment shown in FIG. 2, since the condenser 31 (31a) is disposed in the gas phase portion G of the refrigerant tank 52, the condensate liquid of the refrigerant r1 reliquefied by the condenser 31 (31a) directly falls by gravity to a liquid level of the liquid phase portion L from the gas phase portion G. Therefore, in the present embodiment, the liquid return channel 32 can be regarded as being formed in the gas phase portion G. Since the condenser 31 (31a) is disposed in the gas phase portion G, a housing and the like are unnecessary. Therefore, it is possible to simplify and decrease the cost of the cooling system 30 (30a).

[0023] For example, liquid nitrogen is used as the refrigerant r1 and the refrigerant r2. For example, liquid nitrogen at a temperature 67K suitable for cooling the superconducting cable 16 is supplied to the superconducting cable 16 and the condenser 31. In the superconducting current limiter 18, when the refrigerant tank 52 is held at, for example, the atmospheric pressure, the liquid phase portion L of the refrigerant r1 is controlled to a temperature close to 77K which is the boiling point of liquid nitrogen.

[0024] In an embodiment, as shown in FIG. 3, the condenser 31 (31b) is disposed above the refrigerant tank 52. Then, the liquid return channel 32 is configured to drop the condensate liquid condensed by the condenser 31 (31b) to the liquid phase portion L of the refrigerant tank 52. Since the condenser 31 (31b) is disposed above the refrigerant tank 52, the recondensed refrigerant r1 is automatically returned by gravity to the liquid phase portion L of the refrigerant tank 52. Thus, power for returning the recondensed refrigerant r1 to the refrigerant tank 52 is unnecessary.

[0025] In an embodiment, as shown in FIG. 3, the condenser 31 (31b) includes a housing 34

disposed above the refrigerant tank 52. Then, as the liquid return channel 32, the condenser 31 (31b) includes a communicating tube 35, which causes the inside of the housing 34 and the inside of the refrigerant tank 52 to communicate with each other, and is configured such that a lower end portion 35a of the communicating tube 35 protrudes downward relative to a ceiling surface 54 of the refrigerant tank 52. The refrigerant r1 recondensed by the condenser 31 (31b) falls to the lower end portion 35a down the communicating tube 35. Thus, the recondensed refrigerant r1 can fall, down the communicating tube 35, in the vicinity of the liquid level of the liquid phase portion L of the refrigerant r1 stored in the refrigerant tank 52. Going down the communicating tube 35, it is possible to avoid contact with the gas phase portion G, and thus it is possible to suppress re-evaporation in the middle of the falling. If the condenser 31 (31b) is not configured such that the lower end portion 35a of the communicating tube 35 protrudes downward relative to the ceiling surface 54 of the refrigerant tank 52, the condensate liquid may be revaporized.

[0026] The condenser 31 (31b) shown in FIG. 3 is disposed above the upper surface of the refrigerant tank 52 via the communicating tube 35. However, in another embodiment, the housing 34 may be disposed to be placed in contact with the upper surface of the refrigerant tank 52.

[0027] In an embodiment, as shown in FIGs. 2 and 3, the condenser 31 (31a, 31b) includes a heat exchanger 36 for exchanging heat between the refrigerant r1 and the refrigerant r2, and further includes a flow regulating valve 38 for controlling the flow rate of the refrigerant r2 supplied to the heat exchanger 36. In the present embodiment, controlling the opening degree of the flow regulating valve 38, it is possible to control the flow rate of the refrigerant r2 supplied to the heat exchanger 36. Thus, it is possible to control the condensation amount of the refrigerant r1 exchanging heat with the refrigerant r2. The refrigerant tank 52 is a vessel having an enclosed structure, and the inside of the refrigerant tank 52 is in a saturated condition. Thus, controlling the condensation amount of the refrigerant r1, it is possible to control the pressure (saturation pressure) of the refrigerant tank 52. Controlling the saturation pressure, it is possible to control the uniquely corresponding saturation temperature

from the saturation pressure. Thus, it is possible to control the refrigerant r1 to the temperature suitable for cooling the superconducting current limiting element 50.

[0028] In the embodiments shown in FIGs. 2 and 3, the heat exchanger 36 is constituted by a heat exchanger tube disposed in the gas phase portion G of the refrigerant tank 52 or the communication space S. The heat exchanger tube internally flows the refrigerant r2, the heat exchanger tube externally forms the gas phase portion G of the refrigerant r1, and the refrigerant r1 and the refrigerant r2 indirectly exchange heat via the heat exchanger tube. Thus, the gas phase portion G or the communication space S can form an enclosed space, making it possible to hold the saturated condition. Thus, it is possible to control the temperatures of the gas phase portion G and the communication space S by controlling the pressure of the gas phase portion G or the communication space S, making it possible to control the cooling temperature of the superconducting current limiting element 50 to the temperature close to the critical temperature.

[0029] In the embodiment shown in FIG. 2 or 3, the flow regulating valve 38 is disposed on the branch passage 14 upstream of the condenser 31. However, the flow regulating valve 38 may instead be disposed on the branch passage 14 downstream of the condenser 31.

Further, in an embodiment, as shown in FIGs. 2 and 3, a pipe constituting the circulation passage 12 and the branch passage 14 is coated with a heat insulating layer 44 so that heat does not penetrate from the outside. Moreover, the liquid level of the liquid phase portion L stored in the refrigerant tank 52 can be detected by a liquid level meter 56. Thus, it is possible to grasp a refrigerant liquid volume of the liquid phase portion L.

[0030] In an embodiment, as shown in FIG. 2 or 3, a pressure sensor 40 is provided for detecting a pressure in the gas phase portion G of the refrigerant tank 52 or the communication space S of the condenser 31 (31b). A detected value of the pressure sensor 40 is transmitted to a control part 42, and the control part 42 controls the opening degree of the flow regulating valve 38 based on the detected value of the pressure sensor 40. Since the gas phase portion G of the refrigerant tank 52 and the communication space S are in the saturated condition, it is possible to obtain the temperature (saturation temperature) of the gas

phase portion G or the communication space S by detecting the pressures (saturation pressures) of the gas phase portion G and the communication space S. Therefore, controlling the pressure of the gas phase portion G or the communication space S, it is possible to accurately control the refrigerant r1 to the temperature suitable for cooling the superconducting current limiting element 50.

[0031] In an embodiment, the control part 42 is configured to control the temperature of the refrigerant r1 to a temperature within a setting range close to the transition temperature of the superconducting current limiter 18. If the superconducting current limiter 18 is used in combination with the power cable system 10 using the superconducting cable 16, it is possible to increase responsiveness of the superconducting current limiter 18 when the short-circuit current not less than the rated current flows to the superconducting cable 16 and transition is made.

[0032] Further, since the superconducting current limiter 18 includes the cooling system 30 having the above configuration, immediate recovery is possible against the cooling load instantaneously increased in the transition of the superconducting cable 16, as well as it is possible to control the temperature in the liquid phase portion L of the refrigerant r1 by regulating the flow rate of the refrigerant r2 for cooling the refrigerant r1 in the condenser 31. Thus, it is possible to cool the superconducting current limiting element 50 to the desired temperature suitable for cooling the same.

[0033] As shown in FIG. 4, a control method for the cooling system for the superconducting current limiter according to an embodiment first detects a pressure value in the gas phase portion G of the refrigerant tank 52 or the communication space S (pressure detection step S10). Next, in accordance with the detected pressure value, the control method controls the flow rate of the refrigerant r2 flowing into the condenser 31 (flow rate control step S12). Thus, the gas phase portion G of the refrigerant tank 52 or the communication space S can have a target pressure, making it possible to control the cooling temperature of the superconducting current limiting element 50 to the temperature close to the transition temperature by the liquid phase portion L of the refrigerant tank 52. Thus, it is possible to

increase responsiveness of the superconducting current limiter 18 when the short-circuit current not less than the rated current flows to the superconducting cable 16.

[0034] Inside the refrigerant tank 52, the refrigerant r1 is maintained in the saturated condition. In an embodiment, the flow rate control step S12 includes controlling the flow rate of the refrigerant r2 flowing into the condenser 31, such that the refrigerant r1 in the refrigerant tank 52 has a target pressure P_g uniquely corresponding to a cooling target temperature T_g . Targeted at the pressure of the refrigerant r1 in the refrigerant tank 52 which is easy to control as a control parameter, the flow rate of the refrigerant r2 flowing into the condenser 31 is controlled such that the pressure of the refrigerant r1 becomes the target pressure P_g . Thus, it is possible to accurately perform control to obtain the cooling target temperature T_g of the refrigerant r1 uniquely corresponding to the target pressure P_g .

[0035] FIG. 4 describes an example of a method for controlling the pressure of the gas phase portion G or the communication space S by controlling the opening degree of the flow regulating valve 38 in the embodiment shown in FIG. 2 or 3. In FIG. 4, reference character V indicates an opening degree (%) of the flow regulating valve 38. In this control example, the target pressure P_g of the gas phase portion G or the communication space S is set within a range from a pressure width P1 to a pressure width P2.

The object of the pressure control is to cool a liquid temperature of the refrigerant r1, which is stored to cool the superconducting current limiting element 50 included in the superconducting current limiter 18, to the cooling target temperature T_g . If the cooling target temperature T_g of the refrigerant r1 is set within the range of $T1 \leq \text{cooling target temperature } T_g \leq T2$, it is possible to set the target pressure P_g of the pressure value corresponding to the saturation pressure within the range of $P1 \leq \text{target pressure } P_g \leq P2$. A temperature T1 is a lower limit value of the cooling target temperature T_g , and the pressure P1 is the pressure uniquely corresponding to the temperature T1 under the saturated condition. Further, a temperature T2 is an upper limit value of the cooling target temperature T_g , and the pressure P2 is the pressure uniquely corresponding to the temperature T2 under the saturated condition.

[0036] In FIG. 4, the relationship among a detected value P of the pressure sensor 40, the target pressure P_g (pressure widths P1-P2), and the pressure values P1, P2 at control, and the range of the opening degree V (%) of the flow regulating valve 38 are as follows.

Target pressure: $P1 \leq P_g \leq P2$

5 Condition below target pressure: $P < P1$

Condition above target pressure: $P2 < P$

$0 \leq V \leq 100$

[0037] First, the pressure value P of the gas phase portion G or the communication space S is detected by the pressure sensor 40 (step S10). Next, when the pressure value P is decreased to be below the target pressure P_g (pressure widths P1-P2) ($P < P1$) (step 12a), the pressure of the refrigerant r1 drops and the liquid temperature of the refrigerant r1 is low. Thus, the opening degree V of the flow regulating valve 38 is decreased to decrease the flow rate of the refrigerant r1 flowing into the condenser 31 (step S14a). When the pressure value P is stable within the range ($P1 \leq P_g \leq P2$) of the target pressure P_g (step S12b), the opening degree V of the flow regulating valve 38 is kept constant and is not changed (step S14b). When the pressure value P increases ($P2 < P$) (step S12c), the liquid temperature of the refrigerant r1 is increased by the pressure rise of the refrigerant r1. Thus, the opening degree V of the flow regulating valve 38 is increased to increase the flow rate of the refrigerant r2 flowing into the condenser 31 (step 14c). Performing such operation, it is possible to hold the pressure of the gas phase portion G or the communication space S at the target pressure P_g. Further, it is possible to set the target pressure P_g near the atmospheric pressure.

[0038] The contents described in the above embodiments would be understood as follows, for instance.

[0039] (1) A cooling system (30) for a superconducting current limiter according to an aspect includes a condenser (31 (31a, 31b)) disposed in a gas phase portion (G) of a refrigerant tank (52) or a space (S) communicating with the gas phase portion (G), the refrigerant tank (52) storing a first refrigerant (r1) for cooling a superconducting current limiting element (50), and a liquid return channel (32) for returning a condensate liquid

liquefied by the condenser (31) to a liquid phase portion (L) of the refrigerant tank (52).

[0040] With the above configuration, during the operation of the superconducting current limiter, the first refrigerant which is partially evaporated by heat received from the superconducting current limiting element is recondensed by the above-described condenser and the recondensed first refrigerant is immediately returned to the refrigerant tank from the above-described liquid return channel, making it possible to increase the recondensation amount. Therefore, it is possible to efficiently perform recondensation, allowing for immediate recovery against the cooling load instantaneously increased in transition.

[0041] Further, the cooling system according to the present disclosure is basically constituted by the above-described condenser and the above-described liquid return channel, and does not need a dedicated refrigerator for the superconducting current limiter, allowing for a low cost. Furthermore, regulating the flow rate of the second refrigerant for cooling the first refrigerant in the condenser, it is possible to control the temperature of the recondensed first refrigerant. Thus, it is possible to control the first refrigerant to the temperature suitable for cooling the superconducting current limiter.

[0042] (2) The cooling system (30) for the superconducting current limiter according to another aspect is the cooling system for the superconducting current limiter according to the above configuration (1), where the condenser (31) is disposed above the refrigerant tank (52), and the liquid return channel (32) is configured to drop the condensate liquid in the liquid phase portion (L) of the refrigerant tank (52).

[0043] With the above configuration, since the condenser is disposed above the refrigerant tank, the recondensed first refrigerant is automatically returned by gravity to the liquid phase portion of the refrigerant tank. Thus, power for returning the recondensed first refrigerant to the refrigerant tank is unnecessary.

[0044] (3) The cooling system (30) for the superconducting current limiter according to still another aspect is the cooling system for the superconducting current limiter according to the above configuration (2), where the condenser (31 (31b)) includes a housing (34) disposed above the refrigerant tank (52), and a communicating tube (35) causing the housing (34) and

the refrigerant tank (52) to communicate with each other, and the condenser (31 (31b)) is configured such that a lower end (35a) of the communicating tube (35) protrudes downward relative to a ceiling surface (54) of the refrigerant tank (52).

[0045] With the above configuration, the first refrigerant recondensed by the condenser falls,
 5 down the above-described communicating tube, to the vicinity of the liquid level of the liquid phase portion of the first refrigerant stored in the refrigerant tank. Going down the communicating tube, it is possible to avoid contact with the gas phase portion. Thus, it is possible to suppress re-evaporation in the middle of the falling.

[0046] (4) The cooling system for the superconducting current limiter according to yet
 10 another aspect is the cooling system (30) for the superconducting current limiter according to any one of the above configurations (1) to (3), where the condenser (31) includes a heat exchanger (36) for exchanging heat between the first refrigerant (r1) and the second refrigerant (r2), and a flow regulating valve (38) for controlling a flow rate of the first refrigerant (r1) supplied to the heat exchanger (36).

[0047] With the above configuration, since the flow rate of the second refrigerant supplied to
 15 the above-described heat exchanger can be controlled by the above-described flow regulating valve, it is possible to control the recondensation amount of the first refrigerant in the condense by controlling the flow rate of the second refrigerant. Thus, it is possible to control the saturation pressure of the refrigerant tank in the saturated condition and the
 20 saturation temperature uniquely corresponding to the saturation pressure. Thus, it is possible to control the liquid phase portion of the first refrigerant to the temperature suitable for cooling the superconducting current limiter.

[0048] (5) The cooling system (30) for the superconducting current limiter according to yet
 another aspect is the cooling system for the superconducting current limiter according to the
 25 above configuration (4), the cooling system including a pressure sensor (40) for detecting a pressure in the gas phase portion (G) of the refrigerant tank (52) or the space (S) communicating with the gas phase portion (G), and a control part (42) for controlling an opening degree of the flow regulating valve (38) based on a detected value of the pressure

sensor (40).

[0049] With the above configuration, controlling the opening degree of the flow regulating valve based on the detected value of the above-described pressure sensor, it is possible to control the saturation pressure of the gas phase portion in the saturated condition or the space communicating with the gas phase portion. Controlling the saturation pressure, it is possible to accurately control the saturation temperature of the first refrigerant in the refrigerant tank. Thus, it is possible to accurately control the liquid phase portion of the first refrigerant to the temperature suitable for cooling the superconducting current limiting element.

[0050] (6) The cooling system (30) for the superconducting current limiter according to yet another aspect is the cooling system for the superconducting current limiter according to the above configuration (5), where the control part (42) is configured to control a temperature of the first refrigerant (r1) to a temperature within a setting range close to a transition temperature.

[0051] With the above configuration, if the superconducting current limiter is used in combination with the power cable system using the superconducting cable, it is possible to increase responsiveness of the superconducting current limiter when the short-circuit current not less than the rated current flows to the superconducting cable and transition is made. Further, as described above, it is possible to cool the superconducting cable to the temperature suitable for the superconducting cable by the second refrigerant, as well as by regulating the flow rate of the second refrigerant for cooling the first refrigerant in the condenser, it is possible to control the temperature of the recondensed first refrigerant and to control the first refrigerant to the temperature suitable for cooling the superconducting current limiter.

[0052] (7) A superconducting current limiter (18) according to an aspect includes a superconducting current limiting element (50), a refrigerant tank (52) storing a first refrigerant (r1) for cooling the superconducting current limiting element (50), and the cooling system (30) according to any one of the above configurations (1) to (6).

[0053] With the above configuration, since the superconducting current limiter includes the cooling system having the above configuration, it is possible to efficiently recondensate the

first refrigerant evaporated in the condenser. Thus, immediate recovery is possible after the transition, as well as it is possible to control the temperature in the gas phase portion of the first refrigerant by regulating the flow rate of the second refrigerant for cooling the first refrigerant in the condenser, making it possible to cool the superconducting current limiter to the desired temperature suitable for cooling the same.

[0054] (8) A control method for a cooling system for a superconducting current limiter according to the present disclosure is a control method for a cooling system for a superconducting current limiter, the cooling system including a condenser (31) disposed in a gas phase portion (G) of a refrigerant tank (52) or a space (S) communicating with the gas phase portion (G), the refrigerant tank (52) storing a first refrigerant (r1) for cooling a superconducting current limiting element (50), and a liquid return channel (32) for returning a condensate liquid liquefied by the condenser (31) to a liquid phase portion (L) of the refrigerant tank (52), the control method including a pressure detection step (S10) of detecting a pressure value in the gas phase portion (G) of the refrigerant tank (52) or the space (S) communicating with the gas phase portion (G), and a flow rate control step (S12) of controlling a flow rate of the second refrigerant (r2) flowing into the condenser (31), in accordance with the pressure value.

[0055] With the above configuration, since the gas phase portion of the refrigerant tank or the space communicating with the gas phase portion can have a target pressure, it is possible to control the cooling temperature of the superconducting current limiter to the temperature close to the transition temperature by the liquid phase portion of the refrigerant tank. Thus, it is possible to increase responsiveness of the superconducting current limiter when the short-circuit current not less than the rated current flows to the superconducting cable.

[0056] (9) The control method for the cooling system for the superconducting current limiter according to an aspect is the control method for the cooling system according to the above configuration (8), where the refrigerant tank (52) is configured to internally maintain the first refrigerant (r1) in a saturated condition, and the flow rate control step (S12) includes controlling the flow rate of the second refrigerant (r2) flowing into the condenser (31), such

that the first refrigerant (r1) in the refrigerant tank (52) has a target pressure P_g uniquely corresponding to a cooling target temperature T_g .

[0057] With the above configuration, targeted at the pressure of the first refrigerant in the refrigerant tank which is easy to control as a control parameter, the flow rate of the second
 5 refrigerant flowing into the condenser is controlled such that the pressure becomes the target pressure P_g . Thus, it is possible to accurately perform control to obtain the cooling target temperature T_g of the first refrigerant uniquely corresponding to the target pressure P_g .

Reference Signs List

10	[0058]	
10		Power cable system
12		Circulation passage
14		Branch passage
16		Superconducting cable
15	18	Superconducting current limiter
	20	Refrigerator
	22	Reservoir
	24	Refrigerant pump
	30 (30a, 30b)	Cooling system
20	31 (31a, 31b)	Condenser
	32	Liquid return channel
	34	Housing
	35	Communicating tube
	35a	Lower end portion
25	36	Heat exchanger
	38	Flow regulating valve
	40	Pressure sensor
	42	Control part

	44	Heat insulating layer
	50	Superconducting current limiting element
	52	Refrigerant tank
	54	Ceiling surface
5	56	Liquid level meter
	r1	Refrigerant (first refrigerant)
	r2	Refrigerant (second refrigerant)
	G	Gas phase portion
	L	Liquid phase portion
10	S	Communication space

CLAIMS

1. A cooling system for a superconducting current limiter, comprising:
 - a condenser disposed in a gas phase portion of a refrigerant tank or a space
 - 5 communicating with the gas phase portion, the refrigerant tank storing a first refrigerant for cooling a superconducting current limiting element; and
 - a liquid return channel for returning a condensate liquid liquefied by the condenser to a liquid phase portion of the refrigerant tank.
- 10 2. The cooling system for the superconducting current limiter according to claim 1, wherein the condenser is disposed above the refrigerant tank, and wherein the liquid return channel is configured to drop the condensate liquid in the liquid phase portion of the refrigerant tank.
- 15 3. The cooling system for the superconducting current limiter according to claim 2, wherein the condenser includes:
 - a housing disposed above the refrigerant tank; and
 - a communicating tube causing the housing and the refrigerant tank to
 - communicate with each other, and
 - 20 wherein the condenser is configured such that a lower end of the communicating tube protrudes downward relative to a ceiling surface of the refrigerant tank.
4. The cooling system for the superconducting current limiter according to any one of claims 1 to 3,
- 25 wherein the condenser includes:
 - a heat exchanger for exchanging heat between the first refrigerant and the second refrigerant; and
 - a flow regulating valve for controlling a flow rate of the second refrigerant

supplied to the heat exchanger.

5. The cooling system for the superconducting current limiter according to claim 4, comprising:

5 a pressure sensor for detecting a pressure of the gas phase portion or the space communicating with the gas phase portion; and

a control part for controlling an opening degree of the flow regulating valve based on a detected value of the pressure sensor.

10 6. The cooling system for the superconducting current limiter according to claim 5, wherein the control part is configured to control a temperature of the first refrigerant to a temperature close to a transition temperature of the superconducting current limiter.

7. A superconducting current limiter, comprising:

15 a superconducting current limiting element;

a refrigerant tank storing a first refrigerant for cooling the superconducting current limiting element; and

the cooling system for the superconducting current limiter according to any one of claims 1 to 6.

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8. A control method for a cooling system for a superconducting current limiter, the cooling system including:

a condenser disposed in a gas phase portion of a refrigerant tank or a space communicating with the gas phase portion, the refrigerant tank storing a first refrigerant for

25 cooling a superconducting current limiting element; and

a liquid return channel for returning a condensate liquid liquefied by the condenser to a liquid phase portion of the refrigerant tank,

the control method comprising:

a pressure detection step of detecting a pressure value in the gas phase portion of the refrigerant tank or the space communicating with the gas phase portion; and

a flow rate control step of controlling a flow rate of the second refrigerant flowing into the condenser, in accordance with the pressure value.

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9. The control method for the cooling system for the superconducting current limiter according to claim 8,

wherein the refrigerant tank is configured to internally maintain the first refrigerant in a saturated condition, and

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wherein the flow rate control step includes controlling the flow rate of the second refrigerant flowing into the condenser, such that the first refrigerant in the refrigerant tank has a target pressure P_g uniquely corresponding to a cooling target temperature T_g .