

COOLING SYSTEM AND CONTROL METHOD FOR COOLING SYSTEM

TECHNICAL FIELD

[0001] The present disclosure relates to a cooling system and a control method for the
5 cooling system.

BACKGROUND

[0002] A power cable system using a superconducting cable cools the superconducting cable
by circulating a cryogenic coolant, such as liquid nitrogen, along the axis direction of the
10 superconducting cable to maintain a superconducting state. In case where an excessive
current not less than a rated current flows to a power system and transition to a normal
conducting state is made, such as in case of an unexpected accident, 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
15 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 an
20 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.

25 Citation List

Patent Literature

[0004]

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

SUMMARY

Technical Problem

5 [0005] A superconducting cable is cooled to a cooling temperature with a safety margin from the critical temperature so as not to exceed the critical temperature during operation. Meanwhile, a superconducting current limiting element constituting a superconducting current limiter is cooled to a temperature close to the critical temperature, because the superconducting current limiting element needs to immediately make transition to suppress a
10 short-circuit current not less than a rated current when the short-circuit current occurs in the superconducting cable. Thus, 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
15 in cost.

[0006] The present disclosure was made in view of the above problems, and an object of the present disclosure is to decrease a cost of the cooling system, while cooling the superconducting cable and the superconducting current limiter to a superconducting state at temperatures suitable for the superconducting cable and the superconducting current limiter,
20 respectively, when the superconducting cable and the superconducting current limiter are used in combination.

Solution to Problem

[0007] In order to achieve the above object, a cooling system according to the present
25 disclosure is a cooling system for a superconducting cable and a superconducting current limiter electrically connected to the superconducting cable, the cooling system including a refrigerator, a circulation passage for supplying a first refrigerant cooled by the refrigerator to the superconducting cable, and returning the first refrigerant to the refrigerator, a branch

passage disposed so as to branch from the circulation passage, bypass the superconducting cable, and go through the superconducting current limiter, and a condenser disposed on the branch passage, for condensing a second refrigerant, which is vaporized in the superconducting current limiter, by cooling the second refrigerant with the first refrigerant.

- 5 [0008] Further, a control method for a cooling system according to the present disclosure is a control method for a cooling system for a superconducting cable and a superconducting current limiter electrically connected to the superconducting cable, the cooling system including a refrigerator, a circulation passage for supplying a first refrigerant cooled by the refrigerator to the superconducting cable, and returning the first refrigerant to the refrigerator,
- 10 a branch passage disposed so as to branch from the circulation passage, bypass the superconducting cable, and go through the superconducting current limiter, and a condenser disposed on the branch passage, for condensing a second refrigerant, which is vaporized in the superconducting current limiter, by cooling the second refrigerant with the first refrigerant, the condenser being disposed in a gas phase portion of a refrigerant tank or a space
- 15 communicating with the gas phase portion, the refrigerant tank storing the second refrigerant for cooling a superconducting current limiting element included in the superconducting current limiter, and including 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
- 20 the refrigerant tank or the space communicating with the gas phase portion, and a flow rate control step of controlling the first refrigerant flowing into the condenser, in accordance with the pressure value.

Advantageous Effects

- 25 [0009] With a cooling system according to the present disclosure, since a dedicated refrigerator for a superconducting current limiter is unnecessary when a superconducting cable and the superconducting current limiter are used in combination, it is possible to simplify and decrease a cost of the cooling system, as well as to cool the superconducting

cable and the superconducting current limiter to a superconducting state at temperatures suitable for the superconducting cable and the superconducting current limiter, respectively. Further, with a control method for the cooling system according to the present disclosure, it is possible to control a cooling temperature of the superconducting current limiter to a temperature close to a transition temperature, making it 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.

BRIEF DESCRIPTION OF DRAWINGS

10 [0010] FIG. 1 is a system diagram of a power cable system using a superconducting cable and a superconducting current limiter in combination according to an embodiment.

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

15 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.

DETAILED DESCRIPTION

20 [0011] 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.

25 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.

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
5 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.

10 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.

[0012] FIG. 1 is a system diagram of a cooling system 10 according to an embodiment. The cooling system 10 is a cooling system applied to a power cable system in which a
15 superconducting cable 12 and a superconducting current limiter 16 electrically connected to a terminal 14 of the superconducting cable 12 are used in combination, for cooling the superconducting cable 12 and the superconducting current limiter 16 to superconducting states suitable for respective cooling temperatures. The cooling system 10 includes a circulation passage 18 and a branch passage 22. The circulation passage 18 is provided with
20 a refrigerator 20 and a refrigerant pump 26. A refrigerant r1 (first refrigerant) cooled by the refrigerator 20 to an extremely low temperature suitable for a cooling temperature of the superconducting cable 12 circulates through the circulation passage 18 and the branch passage 22 by the refrigerant pump 26.

[0013] The circulation passage 18 includes a forward passage 18 (18a) formed in the
25 superconducting cable 12 from the terminal 14 along the axis direction of the superconducting cable 12, and a backward passage 18 (18b) separating from the superconducting cable 12 at another end of the superconducting cable 12 and returning to the refrigerator 20. The refrigerant r1 cooled by the refrigerator 20 flows through the forward passage 18 (18a), and

cools the superconducting cable 12 to a temperature less than a SN transition temperature to be held in a superconducting state. The branch passage 22 is arranged so as to branch from the circulation passage 18 upstream of the superconducting cable 12, go through the superconducting current limiter 16, bypass the superconducting cable 12, and return to the refrigerator 20.

[0014] FIGs. 2 and 3 are cross-sectional views of the cooling system for the superconducting current limiter 16 according to some embodiments, in the cooling system 10. As shown in FIG. 2 or 3, the branch passage 22 is provided with a condenser 30 (30a, 30b) constituting the cooling system for the superconducting current limiter 16. A refrigerant r2 (second refrigerant) used to cool the superconducting current limiter 16 has, for example, a temperature close to a boiling point under atmospheric pressure in order to cool the superconducting current limiter 16 to a temperature close to the critical temperature. Therefore, the refrigerant r2 partially evaporates during the operation of the superconducting current limiter 16. The condenser 30 causes the refrigerant r2 vaporized in the superconducting current limiter 16 to exchange heat with the refrigerant r1 to be cooled and recondensed.

[0015] The superconducting current limiter 16 includes a superconducting current limiting element 50, and a refrigerant tank 52 storing the refrigerant r2 for cooling the superconducting current limiting element 50. The superconducting current limiting element 50 is immersed in the refrigerant r2 stored in the refrigerant tank 52. The superconducting cable 12 is held at a low temperature with a safety margin from the critical temperature by the refrigerant r1 so as not to exceed the critical temperature. Meanwhile, the superconducting current limiter 16 is cooled to a temperature close to the critical temperature by the refrigerant r2 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 12. Therefore, the cooling temperatures of the superconducting cable 12 and the superconducting current limiter 16 are different.

[0016] According to the above embodiment, in the condenser 30, since the refrigerant r2

evaporating in the refrigerant tank 52 is cooled and recondensed with the refrigerant r1 and the recondensed refrigerant r2 serves to cool the superconducting current limiter 16, there is no need for a dedicated refrigerator for cooling the superconducting current limiter 16. Further, a gas phase portion G of the refrigerant r2 is in the saturated condition, making it possible to uniquely control a temperature (saturation temperature) in a liquid phase portion L of the refrigerant r2 by controlling a pressure (saturation pressure) in the gas phase portion G of the refrigerant r2. Since it is possible to control the temperature in the liquid phase portion L of the refrigerant r2, it is possible to cool the superconducting current limiting element 50 cooled by the refrigerant r2 to the temperature close to the critical temperature. Thus, the refrigerator for cooling the superconducting current limiting element 50 is unnecessary despite the difference in cooling temperature between the superconducting cable 12 and the superconducting current limiter 16, and with just one refrigerator for cooling the superconducting cable 12, it is possible to cool the superconducting cable 12 and the superconducting current limiter 16 to the cooling temperatures suitable therefor, respectively.

[0017] For example, liquid nitrogen is used as the refrigerant r1 and the refrigerant r2. For example, liquid nitrogen of 67K according to the cooling temperature of the superconducting cable 12 is supplied to the superconducting cable 12 and the condenser 30 by the refrigerator 20. If the superconducting current limiter 16 is held at the atmospheric pressure, the liquid phase portion L of the refrigerant r2 is controlled to a temperature close to 77K which is the boiling point of liquid nitrogen.

[0018] In an embodiment, as shown in FIG. 1, the superconducting current limiter 16 is electrically connected to the terminal 14 of the superconducting cable 12, as well as electrically connected to a power system such as a power transmission equipment 24.

[0019] In an embodiment, as shown in FIG. 1, the circulation passage 18 is provided with a reservoir 28 for recovering the refrigerant r1 having passed through the superconducting cable 12 and the superconducting current limiter 16. When the short-circuit current not less than the rated current flows to the superconducting cable 12, the superconducting current limiting element 50 included in the superconducting current limiter 16 makes transition and is heated

by electrical resistance arising from the transition. With respect to a pressure rise of the refrigerant r2 caused by a temperature rise of the superconducting current limiting element 50, the flow rate of the refrigerant r1 flowing into the condenser 30 is increased to prevent a temperature rise of the refrigerant r2. In this case as well, since the present embodiment includes the reservoir 28, it is possible to return the flow rate of the refrigerant r1 needed for cooling load from the condenser 30 to the reservoir 28, without being influenced by the flow rate and a fluid pressure of the refrigerant r1 flowing into the reservoir 28 through the superconducting cable 12.

[0020] In an embodiment, the reservoir 28 is disposed at a junction of the circulation passage 18 and the branch passage 22. Then, the refrigerant r1 of the branch passage 22 is returned to a gas phase portion of the reservoir 28. If the circulation passage 18 merges into the branch passage 22 upstream of the reservoir 28, the refrigerant r1 may flow back to the branch passage 22 from the circulation passage 18 where the flow rate of the refrigerant r1 is high. According to the present embodiment, since the circulation passage 18 and the branch passage 22 are connected to the reservoir 28, and the branch passage 22 is returned to the gas phase portion of the reservoir 28, there is no risk of the flowback.

[0021] In an embodiment, as shown in FIG. 2 or 3, the condenser 30 (30a, 30b) is disposed in the gas phase portion G of the refrigerant tank 52 storing the refrigerant r2 or a space S communicating with the gas phase portion G. In the embodiment shown in FIG. 2, the condenser 30 (30a) is disposed in the gas phase portion G of the refrigerant tank 52, and in the embodiment shown in FIG. 3, the condenser 30 (30b) is disposed in the space S communicating with the gas phase portion G. The condenser 30 (30a) further includes a liquid return channel 32 for returning a condensate liquid of the refrigerant r2 liquefied by the condenser 30 to the liquid phase portion L of the refrigerant tank 52.

[0022] The superconducting current limiter 16 needs to immediately recover to the superconducting state when making transition from the superconducting state to the normal conducting state, and the cooling load is instantaneously increased at the time of the recovery. Therefore, for the immediate recovery of the superconducting current limiter 16, the

refrigerant r2 vaporized by the condenser 30 needs to be recondensed efficiently. According to the present embodiment, the refrigerant r2 recondensed by the condenser 30 is immediately returned to the refrigerant tank 52 through the liquid return channel 32, making it possible to efficiently recondense the refrigerant r2.

5 [0023] In the embodiment shown in FIG. 2, since the condenser 30 (30a) is disposed in the gas phase portion G of the refrigerant tank 52, the condensate liquid reliquefied by the condenser 30 (30a) 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 30 (30a) is
10 disposed in the gas phase portion G, a housing and the like are not unnecessary. Therefore, it is possible to simplify and decrease the cost of the condenser 30 (30a).

[0024] In an embodiment, as shown in FIG. 3, the condenser 30 (30b) is disposed above the refrigerant tank 52. Then, the liquid return channel 32 is configured to drop the condensate liquid condensed by the condenser 30 (30b) to the liquid phase portion L of the refrigerant
15 tank 52. The condensate liquid of the refrigerant r2 condensed by the condenser 30 (30b) is automatically dropped by gravity to the liquid phase portion L of the refrigerant tank 52 via the liquid return channel 32. Thus, power for returning the recondensed refrigerant r2 to the refrigerant tank 52 is unnecessary.

[0025] In an embodiment, as shown in FIG. 3, the condenser 30 (30b) includes a housing 34
20 disposed above the refrigerant tank 52. Then, as the liquid return channel 32, the condenser 30 (30b) 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 r2 recondensed by the condenser 30
25 (30b) falls to the lower end portion 35a down the communicating tube 35. Thus, the recondensed refrigerant r2 moves to the vicinity of the liquid level of the liquid phase portion L without touching the gas phase portion G. Thus, it is possible to suppress re-evaporation in the middle of the falling. If the condenser 30 (30b) 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 in the middle of the falling.

[0026] The condenser 30 (30b) 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 30 (30a, 30b) 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 r1 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 r1 supplied to the heat exchanger 36. Thus, it is possible to control the condensation amount of the refrigerant r2 exchanging heat with the refrigerant r1. The refrigerant tank 52 is a vessel having an enclosed structure, and the inside of the refrigerant tank 52 is in a saturated condition. Therefore, controlling the recondensation amount of the refrigerant r2, it is possible to control the 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 r2 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 r1, the heat exchanger tube externally forms the gas phase portion of the refrigerant r2, 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.

[0029] In the embodiment shown in FIG. 2 or 3, the flow regulating valve 38 is disposed on

the branch passage 22 upstream of the condenser 30. However, the flow regulating valve 38 may instead be disposed on the branch passage 22 downstream of the condenser 30.

Further, in an embodiment, as shown in FIGs. 1 to 3, a pipe constituting the circulation passage 18 and the branch passage 22 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 30 (30b). 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. Controlling the opening degree of the flow regulating valve 38 based on the detected value of the pressure sensor 40, it is possible to control the pressure in the gas phase portion G of the refrigerant tank 52 to a desired pressure. Thus, it is possible to accurately control the refrigerant r2 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 cooling temperature of the superconducting current limiting element 50 by the refrigerant r2 to a temperature within a setting range close to the transition temperature. Thus, it is possible to increase responsiveness of the superconducting current limiter 16 when the short-circuit current not less than the rated current flows to a superconducting cable 12.

[0032] As shown in FIG. 4, a control method for the cooling system 10 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 r1 flowing into the condenser 30 (flow rate control step S12). Since the gas phase portion G of the refrigerant tank 52 or the communication space S can have a target pressure, it is 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 16 when the short-circuit current not less than the rated current flows to the superconducting cable 12.

[0033] Inside the refrigerant tank 52, the refrigerant r2 is maintained in the saturated condition. In an embodiment, the flow rate control step S12 includes controlling the flow rate of the refrigerant r1 flowing into the condenser 30, such that the refrigerant r2 in the refrigerant tank 52 has a target pressure Pg uniquely corresponding to a cooling target temperature Tg under the saturated condition. Targeted at the pressure of the refrigerant r2 in the refrigerant tank 52 which is easy to control as a control parameter, the flow rate of the refrigerant r1 flowing into the condenser 30 is controlled such that the pressure of the refrigerant r2 becomes the target pressure Pg. Thus, it is possible to accurately perform control to obtain the cooling target temperature Tg of the refrigerant r2 uniquely corresponding to the target pressure Pg.

[0034] 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 Pg 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 r2, which is stored to cool the superconducting current limiting element 50 included in the superconducting current limiter 16, to the cooling target temperature Tg. If the cooling target temperature Tg of the refrigerant r2 is set within the range of $T1 \leq \text{cooling target temperature } Tg \leq T2$, it is possible to set the target pressure Pg corresponding to the saturation pressure within the range of $P1 \leq \text{target pressure } Pg \leq P2$. A temperature T1 is a lower limit value of the cooling target temperature Tg, 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 Tg, and the pressure P2 is the pressure uniquely corresponding to the temperature T2 under the saturated condition.

[0035] In FIG. 4, the relationship among a detected value P of the pressure sensor 40, the target pressure Pg (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: $P1 \leq Pg \leq P2$

Condition below target pressure: $P < P1$

Condition above target pressure: $P2 < P$

10 $0 \leq V \leq 100$

[0036] 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 Pg (pressure widths P1-P2) ($P < P1$) (step 12a), the pressure of the refrigerant r2 drops and the liquid temperature of the refrigerant r2 is low.

15 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 30 (step S14a). When the pressure value P is stable within the range ($P1 \leq Pg \leq P2$) of the target pressure Pg (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 r2 is increased by the pressure rise of the refrigerant r2. Thus, the opening degree V of the flow regulating valve 38 is increased to increase the flow rate of the refrigerant r1 flowing into the condenser 30 (step S14c). 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 Pg. Further, it is possible to set the target pressure Pg near the atmospheric pressure.

25 [0037] The contents described in the above embodiments would be understood as follows, for instance.

[0038] (1) A cooling system (10) according to an aspect is a cooling system for a superconducting cable (12) and a superconducting current limiter (16) electrically connected

to the superconducting cable, the cooling system including a refrigerator (20), a circulation passage (18) for supplying a first refrigerant (r1) cooled by the refrigerator to the superconducting cable (12), and returning the first refrigerant (r1) to the refrigerator (20), a branch passage (22) disposed so as to branch from the circulation passage (18), bypass the
5 superconducting cable (12), and go through the superconducting current limiter (16), and a condenser (30) disposed on the branch passage (22), for condensing a second refrigerant (r2), which is vaporized in the superconducting current limiter (16), by cooling the second refrigerant (r2) with the first refrigerant (r1).

[0039] With the above configuration, since the evaporated second refrigerant is cooled with
10 the first refrigerant and is recondensed by the above-described condenser, a refrigerator for cooling the second refrigerant is unnecessary. Further, the gas phase portion of the second refrigerant is in the saturated condition, making it possible to control a temperature (saturation temperature) of the second refrigerant by controlling a saturation pressure in the gas phase portion of the second refrigerant. Therefore, controlling the flow rate of the first refrigerant
15 supplied to the condenser and controlling the pressure in the gas phase portion of the second refrigerant, it is possible to adjust the liquid phase portion of the second refrigerant to have a desired temperature. Thus, it is possible to cool the superconducting current limiting element cooled by the second refrigerant to the temperature close to the critical temperature. Thus, when the superconducting cable and the superconducting current limiter are used in
20 combination, with just one refrigerator for cooling the superconducting cable, it is possible to cool the superconducting cable and the superconducting current limiter to the cooling temperatures suitable therefor, respectively.

[0040] (2) The cooling system (10) according to another aspect is the cooling system according to the above configuration (1) including a reservoir (28) disposed on the circulation
25 passage (18), for recovering the first refrigerant (r1) having passed through the superconducting cable (12) and the superconducting current limiter (16).

[0041] When the short-circuit current not less than the rated current flows to the superconducting cable, the superconducting current limiting element included in the

superconducting current limiter makes transition and is heated by electrical resistance arising from the transition. Consequently, the pressure of the second refrigerant is raised, and in this case, the flow rate of the first refrigerant flowing into the condenser is increased to prevent a temperature rise of the second refrigerant. In this case as well, with the above configuration, it is possible to return the amount of the first refrigerant needed for cooling load of the superconducting cable from the condenser to the reservoir, without being influenced by the flow rate and the fluid pressure of the first refrigerant flowing into the reservoir through the superconducting cable.

[0042] (3) The cooling system (10) according to still another aspect is the cooling system according to the above configuration (1) or (2), where the condenser (30) is 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 the second refrigerant (r2) for cooling a superconducting current limiting element (50) included in the superconducting current limiter (16), and the condenser (30) includes a liquid return channel (32) for returning a condensate liquid liquefied by the condenser (30) to a liquid phase portion (L) of the refrigerant tank (52).

[0043] With the above configuration, during the operation of the superconducting current limiter, the second refrigerant, which is partially evaporated by heat received from the superconducting current limiting element and is recondensed by the condenser, is immediately returned to the refrigerant tank through the above-described liquid return channel, making it possible to efficiently recondense the second refrigerant.

[0044] (4) The cooling system (10) according to yet another aspect is the cooling system according to the above configuration (3), where the condenser (30) 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).

[0045] With the above configuration, since the condenser is disposed above the refrigerant tank, the recondensed second refrigerant is automatically returned by gravity to the liquid phase portion of the refrigerant tank. Thus, power for returning the recondensed second refrigerant to the refrigerant tank is unnecessary.

[0046] (5) The cooling system (10) according to yet another aspect is the cooling system according to the above configuration (4), where the condenser (30 (30b)) includes a housing (34) disposed above the refrigerant tank (52), and a communicating tube (35) causing the housing and the refrigerant tank (52) to communicate with each other, and the condenser (30
5 (30b)) 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).

[0047] With the above configuration, the second refrigerant recondensed by the condenser can fall, down the above-described communicating tube, in the vicinity of the liquid level of the liquid phase portion of the second refrigerant stored in the refrigerant tank. Thus, going
10 down the above-described communicating tube, it is possible to avoid contact with the gas phase portion of the second refrigerant as much as possible, and to suppress re-evaporation in the middle of the falling.

[0048] (6) The cooling system (10) according to yet another aspect is the cooling system according to any one of the above configurations (3) to (5), where the condenser (30) includes
15 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).

[0049] With the above configuration, since the flow rate of the first refrigerant supplied to the above-described heat exchanger is controlled by the above-described flow regulating
20 valve, it is possible to control the recondensation amount of the second refrigerant in the condenser. Controlling the recondensation amount of the second refrigerant, it is possible to control the pressure of the refrigerant tank in the saturated condition. Thus, it is possible to control the saturation temperature of the second refrigerant, making it possible to accurately control the second refrigerant to the temperature suitable for cooling the superconducting
25 current limiting element.

[0050] (7) The cooling system (10) according to yet another aspect is the cooling system according to the above configuration (6) 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).

[0051] With the above configuration, the saturation pressure in the gas phase portion of the refrigerant tank is detected by the above-described pressure sensor and the opening degree of the flow regulating valve is controlled based on the detected value, making it possible to accurately control the second refrigerant to the temperature suitable for cooling the superconducting current limiting element.

[0052] (8) The cooling system (10) according to yet another aspect is the cooling system according to the above configuration (7), where the control part (42) is configured to control a cooling temperature of the superconducting current limiter (16) by the second refrigerant (r2) to a temperature within a setting range close to a transition temperature.

[0053] With the above configuration, controlling the cooling temperature of the superconducting current limiter to the temperature within the setting range, 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.

[0054] (9) A control method for a cooling system according to the present disclosure is a control method for a cooling system for a superconducting cable (12) and a superconducting current limiter (16) electrically connected to the superconducting cable (12), the cooling system including a refrigerator (20), a circulation passage (18) for supplying a first refrigerant (r1) cooled by the refrigerator (20) to the superconducting cable (12), and returning the first refrigerant (r1) to the refrigerator (20), a branch passage (22) disposed so as to branch from the circulation passage (18), bypass the superconducting cable (12), and go through the superconducting current limiter (16), and a condenser (30) disposed on the branch passage (22), for condensing a second refrigerant (r2), which is vaporized in the superconducting current limiter (16), by cooling the second refrigerant (r2) with the first refrigerant (r1), the condenser (30) being 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 the second

refrigerant (r2) for cooling a superconducting current limiting element (50) included in the superconducting current limiter (16), and including a liquid return channel (32) for returning a condensate liquid liquefied by the condenser (30) to a liquid phase portion (L) of the refrigerant tank (52), the control method including a pressure detection step (S10) of detecting
5 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 the first refrigerant flowing into the condenser, in accordance with the pressure value.

[0055] With the above configuration, since the gas phase portion of the refrigerant tank or
10 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 limiting element 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
15 cable.

[0056] (10) The control method for the cooling system according to an aspect is the control method for the cooling system according to the above configuration (9), where, the refrigerant tank (52) is configured to internally maintain the second refrigerant (r2) in a saturated condition, and the flow rate control step (S12) includes controlling the flow rate of the first
20 refrigerant (r1) flowing into the condenser (30), such that the second refrigerant (r2) 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 second refrigerant in the refrigerant tank which is easy to control as a control parameter, the flow rate of the first
25 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 second refrigerant uniquely corresponding to the target pressure P_g .

Reference Signs List

[0058]

	10	Cooling system
	12	Superconducting cable
5	14	Terminal
	16	Superconducting current limiter
	18	Circulation passage
	20	Refrigerator
	22	Branch passage
10	24	Power transmission equipment
	26	Refrigerant pump
	28	Reservoir
	30 (30a, 30b)	Condenser
	32	Liquid return channel
15	34	Housing
	35	Communicating tube
	35a	Lower end portion
	36	Heat exchanger
	38	Flow regulating valve
20	40	Pressure sensor
	42	Control part
	44	Heat insulating layer
	50	Superconducting current limiting element
	52	Refrigerant tank
25	54	Ceiling surface
	56	Liquid level meter
	r1	Refrigerant (first refrigerant)
	r2	Refrigerant (second refrigerant)

- G Gas phase portion
- L Liquid phase portion
- S Communication space

CLAIMS

1. A cooling system for a superconducting cable and a superconducting current limiter electrically connected to the superconducting cable, the cooling system comprising:
 - 5 a refrigerator;
 - a circulation passage for supplying a first refrigerant cooled by the refrigerator to the superconducting cable, and returning the first refrigerant to the refrigerator;
 - a branch passage disposed so as to branch from the circulation passage, bypass the superconducting cable, and go through the superconducting current limiter; and
 - 10 a condenser disposed on the branch passage, for condensing a second refrigerant, which is vaporized in the superconducting current limiter, by cooling the second refrigerant with the first refrigerant.
2. The cooling system according to claim 1, comprising a reservoir disposed on the
15 circulation passage, for recovering the first refrigerant having passed through the superconducting cable and the superconducting current limiter.
3. The cooling system according to claim 1 or 2,
 - wherein the condenser is disposed in a gas phase portion of a refrigerant tank or a
20 space communicating with the gas phase portion, the refrigerant tank storing the second refrigerant for cooling a superconducting current limiting element included in the superconducting current limiter, and
 - wherein the condenser includes a liquid return channel for returning a condensate liquid liquefied by the condenser to a liquid phase portion of the refrigerant tank.
- 25 4. The cooling system according to claim 3,
 - 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.

5. The cooling system according to claim 4,

wherein the condenser includes:

5 a housing disposed above the refrigerant tank; and

a communicating tube causing the housing and the refrigerant tank to communicate with each other, and

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.

10

6. The cooling system according to any one of claims 3 to 5,

wherein the condenser includes:

a heat exchanger for exchanging heat between the first refrigerant and the second refrigerant; and

15 a flow regulating valve for controlling a flow rate of the first refrigerant supplied to the heat exchanger.

7. The cooling system according to claim 6, comprising:

20 a pressure sensor for detecting a pressure in the gas phase portion of the refrigerant tank 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.

8. The cooling system according to claim 7,

25 wherein the control part is configured to control a cooling temperature of the second refrigerant by the first refrigerant to a temperature within a setting range close to a transition temperature.

9. A control method for a cooling system for a superconducting cable and a superconducting current limiter electrically connected to the superconducting cable, the cooling system including:

a refrigerator;

5 a circulation passage for supplying a first refrigerant cooled by the refrigerator to the superconducting cable, and returning the first refrigerant to the refrigerator;

a branch passage disposed so as to branch from the circulation passage, bypass the superconducting cable, and go through the superconducting current limiter; and

a condenser disposed on the branch passage, for condensing a second refrigerant,
10 which is vaporized in the superconducting current limiter, by cooling the second refrigerant with the first refrigerant,

the condenser being disposed in a gas phase portion of a refrigerant tank or a space communicating with the gas phase portion, the refrigerant tank storing the second refrigerant for cooling a superconducting current limiting element included in the superconducting
15 current limiter, and including 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

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

10. The control method for the cooling system according to claim 9,

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

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