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(54) **STATIC ELECTRIC INDUCTION DEVICE, AND COOLING SYSTEM AND COOLING METHOD THEREOF**

(57) A cooling system for a static electric induction device (10) is provided. The cooling system includes a heat exchanger (14) and a plurality of fans (15A-15C) arranged to extract heat from the heat exchanger (14). The cooling system further a control system (16) comprising a control module (162) configured to determine an operation of the plurality of fans (15A-15C) based on information received from a thermal model (161) config-

ured for the static electric induction device (10) determining cooling capacity achievable from operations of one or more fans from the plurality of fans (15A-15C), such that a predetermined control objective is met by the control module (162). The predetermined control objective at least includes a value of maximum temperature inside the static electric induction device (10) being less than a corresponding temperature threshold.

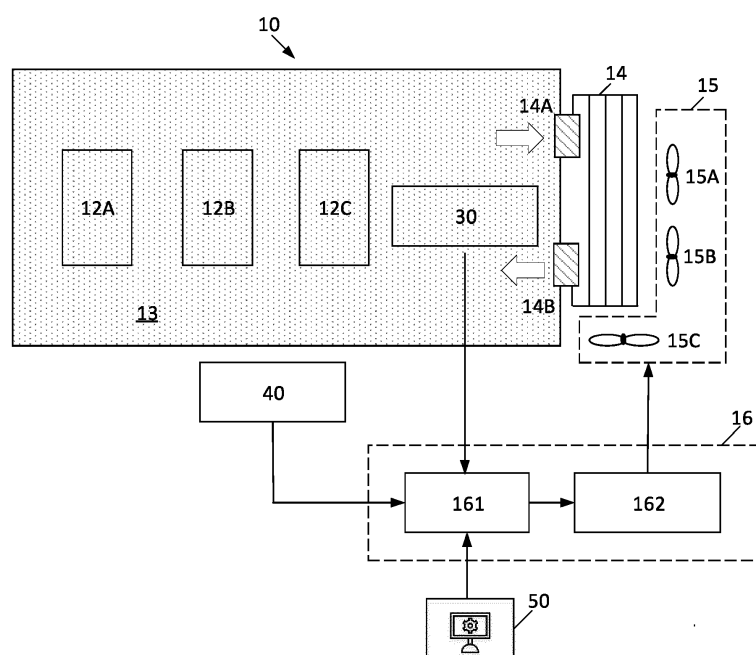


Figure 1

Description**TECHNICAL FILED**

[0001] The present disclosure generally relates to cooling of static electric induction devices. In particularly, the present disclosure relates to a cooling system and a cooling method for a static electric induction device. The present disclosure also relates to a static electric induction device including the cooling system.

BACKGROUND

[0002] Static electric induction devices (e.g., power transformers) used in high-voltage networks generate a significant amount of heat due to losses. Cooling systems including fans are typically used to dissipate the heat in order to avoid problems related to excessive temperatures. When fans are operated to dissipate excess heat, additional losses are generated due to the fans themselves. Hence, there is an interest to optimize the fan cooling.

SUMMARY

[0003] According to an embodiment of the present disclosure, a cooling system for a static electric induction device is provided. The cooling system includes a heat exchanger and a plurality of fans arranged to extract heat from the heat exchanger. The cooling system further includes a control system. The control system includes a control module configured to determine an operation of the plurality of fans based on information received from a thermal model configured for the static electric induction device determining cooling capacity achievable from operations of one or more fans from the plurality of fans, such that a predetermined control objective is met by the control module. The predetermined control objective at least includes a value of maximum temperature inside the static electric induction device being less than a corresponding temperature threshold.

[0004] According to an embodiment of the present disclosure, a static electric induction device is provided. The static electric induction device includes the cooling system as described above.

[0005] According to an embodiment of the disclosure, a method for cooling a static electric induction device by means of a cooling system is provided. The cooling system includes a heat exchanger and a plurality of fans arranged to extract heat from the heat exchanger. The method includes: determining an operation of the plurality of fans based on information received from a thermal model configured for the static electric induction device determining cooling capacity achievable from operations of one or more fans from the plurality of fans, such that a predetermined control objective is met by the control module. The predetermined control objective at least includes a value of maximum temperature inside the static electric induction device being less than a corresponding temperature threshold.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The disclosed aspects will hereinafter be described in connection with the appended drawings that are provided to illustrate but not to limit the scope of the disclosure.

Figure 1 is a block diagram of a static electric induction device including a cooling system according to an example of the present disclosure.

Figures 2A and 2B are block diagrams showing exemplary configurations of the cooling system.

Figure 3 is a flowchart of a method for cooling a static electric induction device according to an example of the present disclosure.

Figure 4 is a flowchart of a method for updating a thermal model of the static electric induction device according to an example of the present disclosure.

DETAILED DESCRIPTION

[0007] Examples of the present disclosure relate to cooling optimization for a static electric induction device by means of a cooling system. The cooling system includes a heat exchanger and a plurality of fans for extracting heat from the heat exchanger. The cooling system also includes a control system for controlling fan operations to optimize the fan cooling.

[0008] In general, different fan operations correspond to different cooling capabilities. Specifically, when fans are operated to dissipate heat, additional losses are generated due to the fans themselves. Moreover, there are temperature

dependent power losses in the static electric induction device. Moreover, when fans are operated, significant noise can be produced. Moreover, fans tend to age with time and usage, eventually requiring maintenance or replacement that will affect the availability of the static electric induction device. According to examples of the present disclosure, the control system is configurable to determine an optimal operation of the fans so that thermal constraint of the static electric induction device can be met and power losses and noises can be minimized. Also, reliability of the cooling system can be improved.

[0009] According to an example of the present disclosure, the control system is configured to determine an optimal operation of the fans that can meet a pre-determined control objective based on the cooling capacity of fan operations output from a trained NN (e.g., PINN), thereby improving thermal management and thus energy efficiency of the static electric induction device. Moreover, retraining of the NN can be performed to adapt to real-time changes during device lifetime.

[0010] Examples of the static electric induction device will be described with reference to Figure 1. The static electric induction device for example is a power transformer or a shunt reactor. For clarity, a power transformer is illustrated in Figure 1, as an example of the static electric induction device.

[0011] Figure 1 illustrates a power transformer 10 including a casing 11, an electric component 12, a liquid 13, a heat exchanger 14, a cooling device 15 and a control system 16. The heat exchanger 14, the cooling device 15 and the control system 16 constitute a cooling system for cooling the power transformer 10.

[0012] Figure 1 further illustrates ambient air 20 outside the casing 11. The air 20 can be the atmosphere. The air 20 is one example of an ambient fluid.

[0013] Figure 1 further illustrates an internal sensing unit 30. The internal sensing unit 30 is arranged inside the casing 11. The internal sensing unit 30 can include one or more of thermocouples, resistance thermometers and fiber optic sensors. In an example, those sensors are located at different vertical positions between the inlet 14A and the outlet 14B, and provide temperature measurements at those places. It is advantageous to consider vertical temperature variation and disregard horizontal temperature variation, since the buoyancy of the liquid will counteract horizontal temperature variations by forcing hot liquid upwards and cold liquid downwards until the temperature is uniform in each horizontal plane.

[0014] Figure 1 further illustrates an external sensing unit 40. The external sensing unit 40 is arranged outside the casing 11. The external sensing unit 40 can include a plurality of thermal cameras arranged to provide temperature measurements from different viewpoints or angles.

[0015] Figure 1 further illustrates an asset management system 50. The asset management system 50 manages assets of the power transformer 10 and thus can provide reference data of the power transformer 10, such as historical data and design data of the power transformer 10. The historical data for example include information on diagnosis and maintenance of the power transformer 10. The design data for example include information on design parameters such as the dimension of the power transformer 10, the dimension of each coil and oil heat coefficients. The asset management system 50 can also provide reference data associated with another power transformer with the same heat exchanger, the same load, the same number of fans and the same arrangement of the fans as the power transformer 10. The reference data associated with another power transformer for example include historical data and design data of said another power transformer.

[0016] In an example, the power transformer 10 can include one or more of the internal sensing unit 30, the external sensing unit 40 and the asset managing system 50. In another example, the internal sensing unit 30, the external sensing unit 40 and the asset managing system 50 are provide as accessories of the power transformer 10.

[0017] Referring to Figure 1, the casing 11 can be referred to as a tank. The electric component 12 is arranged inside the casing 11. The electric component 12 is submerged in the liquid 13. As shown in Figure 1, the electric component 12 for example includes windings (e.g., coils 12A~12C) of the power transformer 10. The electric component 12 generates heat during operation of the power transformer 10. The liquid 13 for example is dielectric oil.

[0018] The heat exchanger 14 includes an inlet 14A and an outlet 14B. Each of the inlet 14A and the outlet 14B is in fluid communication with the liquid 13. For example, each of the inlet 14A and the outlet 14B is arranged fluidly between the casing 11 and the heat exchanger 14. In an example, the inlet 14A is arranged geodetically higher than the outlet 14B.

[0019] Referring again to Figure 1, the liquid 13 flows in a circuit in a clockwise direction during operation of the power transformer 10, as indicated with arrows. That is, the liquid 13 is heated by the electric component 12. The hot liquid 13 then enters the heat exchanger 14 through the inlet 14A. The hot liquid 13 in the heat exchanger 14 is then cooled by heat exchange with the air 20. Cold liquid 13 then exits the heat exchanger 14 through the outlet 14B. The electric component 12 is then cooled by the cold liquid 13.

[0020] The cooling device 15 includes a plurality of fans 15A~15C. The plurality of fans can include one or more groups of fans. The number of the fans in each group can be equal or different. The plurality of fans can be arranged to blow air through the heat exchanger 14 from one or more directions. In an example, as shown in Figure 1, the plurality of fans include front fans 15A and 15B configured to blow the air 20 horizontally into the heat exchanger 14 and a bottom fan 15C configured to blow the air 20 vertically into the heat exchanger 14.

[0021] The control system 16 can individually control the operation of each of the plurality of fans. For example, the control system 16 can control a fan to turn on or off by controlling a switch (not shown) coupled with that fan. The control

system 16 can also control a fan to adjust speed by controlling a motor (not shown) coupled with that fan. The control system 16 can also control a fan to turn on and off according to a predetermined switching sequence.

[0022] The control system 16 can be implemented as including a thermal model 161 and a control module 162 in communication with the thermal model 161.

[0023] The thermal model 161 can be obtained by training a neural network (NN) using measurements received from the internal sensing unit 30 and/or the external sensing unit 40 and references received from the asset management system 50. The NN is trained to be able to estimate cooling capacity of fan operations. In an example, the NN is implemented as a physics-informed neural network (PINN).

[0024] The control model 162 performs control for cooling optimization by determines an optimal operation of the plurality of fans that can meet a predetermined control objective based on the cooling capacity output from the trained NN.

[0025] The cooling optimization can include a multiple-objective optimization, such as a thermal limit based on a temperature threshold, minimization of energy expenditure, reduction of noise, and improvement of system reliability.

[0026] It is noted that the control objective is configurable and extendable. For example, an additional control objective can be about a switching frequency of a fan. Specifically, it is desirable not to turn on/off fans too frequently, therefore if a fan is turned on in a given period, additional constraints can be added to the optimization at the following period to prevent from turning off that fan. This additional control objective can be implemented as a switching frequency of activation or deactivation operations of a fan being below a predetermined switching frequency.

[0027] According to examples of the present disclosure, the control system 16 further includes an interface 163. The interface 163 can include a hardware interface for wired communications and/or an air interface for wireless communications. Exemplary configurations of the control system 16 including the interface 163 will be described below.

[0028] In an example, referring to Figure 2A, the NN is disposed in an edge server or a cloud server. Both the thermal model 161 and the control module 162 are disposed in a local controller (not shown) of the power transformer 10. Data for training the NN are transferred to the edge server or the cloud server the interface 163 and the estimated cooling capacity output from the trained NN is transferred to the thermal model 161 via the interface 163.

[0029] In another example, referring to Figure 2B, the interface 163 includes multiple interfaces 163A and 163B. The NN is disposed in a cloud server, the thermal model 161 is disposed in an edge server and the control module 162 is disposed in a local controller of the power transformer 10. Data for training the NN are transferred to the cloud server via the interface 163A and the estimated cooling capacity is transferred to the control module 162 from the thermal model 161 via the interface 163B.

[0030] An advantage of the above configurations is that the training of NN does not use local computing resources of the local controller of the transformer. In this way, the local controller of the transformer can be cost effective.

[0031] Further to example devices and systems described above, example methods are now described. Such methods can be performed by the cooling system described above. It should be understood that the operations involved in the following methods need not be performed in the precise order described. Rather, various operations may be performed in a different order or simultaneously, and operations may be added or omitted.

[0032] Figure 3 illustrates a method 300 for cooling the power transformer 10 according to an example of the present disclosure. The method 300 can be implemented by means of the above-mentioned cooling system.

[0033] Referring to Figure 3, at block 302, the thermal model 161 configured for describing the impact of fan operations on the transformer internal temperature is obtained. The thermal model 161 can be a trainable parametric model coupled with one or more partial differential equations associated with the power transformer 10. An example of such a (nonlinear) parametric model is an NN, such as a PINN.

[0034] In an example, the thermal model 161 can be obtained by training an NN. The trained NN can estimate cooling capacity of fan operations and output the estimated cooling capacity. The thermal model 161 can be a geometry-specific dynamic surrogate model of the power transformer 10.

[0035] In an example, the fan operations include on and off operations of an array of fans (e.g., N fans) and the thermal model is implemented as a function presented below where the power transformer 10 uses an air-forced cooling method (e.g., ONAF, OFAF or ODAF) with the array of N fans. It is noted that the N fans can be all or some of the plurality of fans. This function is to compute the effect of on/off operations of fans, operating conditions (e.g., a load factor of the transformer and an ambient temperature) and initial conditions (e.g. an internal transformer temperature at the beginning of a time period) on the internal transformer temperature during a time period.

$$T(x, y, z, t) = f(I_1, \dots, I_N, K(t), T_a(t), T_0(x, y, z), x, y, z, t), \quad t \in [0, P] \quad (1)$$

where:

P represents a time interval of duration P during which each fan is either active or inactive;

$I_1, \dots, I_N$ represents binary variables that describe whether the i -th fan is active ($I_i = 1$) or inactive ($I_i = 0$) during the period P ;

$K(t)$ represents the load factor of the power transformer at a specific time $t \in [0, P]$;

$T_a(t)$ represents the ambient temperature at the specific time $t \in [0, P]$;

$T(x, y, z, t)$ represents the internal temperature at a specific location inside the transformer tank (determined by the x, y, z coordinates) at the specific time $t \in [0, P]$; and

$T_0(x, y, z) = T(x, y, z, 0)$ represents the initial temperature values at the beginning of the time interval P (initial conditions).

[0036] In another example, the fan operations include adjusting speeds of one or more fans, and the thermal model can be implemented as a function similar to the function described above and the difference is that the binary variables $I_1, \dots, I_N$ is replaced by discrete variables $S_1, \dots, S_N$, where $S_1, \dots, S_N$ represents speeds of the N fans.

[0037] In yet another example, the fan operations can include a combination of on/off operations and speed adjustment operations. For example, the fan operations include turning on one of the plurality of fans and increasing the speed of another one of the plurality of fans.

[0038] In an example where the thermal model is obtained by training a physics-informed neural network (PINN), the PINN has the following features:

Inputs: spatial (x, y, z) and temporal (t) coordinates, time series of load factor, ambient temperature, and fan activation variables;

Output: internal transformer temperature $T(x, y, z, t)$;

Initial conditions: internal transformer temperature at the beginning of the period $T_0(x, y, z)$;

Geometry: the boundaries within which the spatial coordinates x, y, z vary are depending on the transformer geometry; and

Regularizing term: a set of partial-differential equations (PDEs) describing the heat transfer within the transformer with air-forced cooling.

[0039] The PINN can be trained by means of information received from at least one of the internal sensing unit 30, the external sensing unit 40 and the asset management system 50. For example, data for training the PINN include on one or more of: measurement data of the power transformer 10; simulation data of the power transformer 10; history data of the power transformer 10 and reference data associated with another power transformer having the same heat exchanger, the same load, the same number of fans and the same arrangement of the fans as the power transformer 10. The PINN can be trained during a testing phase, an operating phase and/or a design phase of the power transformer 10.

[0040] In an example, the PINN is trained by finding neuron weights which minimize a PINN loss function. The PINN loss function includes both a data-based loss term and a physics-based loss term. The data-based loss term evaluates the difference between the neural network approximation at a given input and the corresponding output in the training set. The physics-based loss term considers a number of collocation points and evaluates a function f in these points. The values of the function f depend on the neural network outputs and hence change with the neuron weights. The PINN is trained via iterative minimization of the sum of the loss terms, which stops when the sum is lower than a predetermined convergence criterion. After training, the PINN was able to reproduce the heat transfer prediction for different boundary conditions at much lower computational cost.

[0041] The thermal model which is obtained based on the trained PINN, can be used multiple times in the subsequent optimization step, which is run periodically during transformer operation and as such do not need to rely on complex multi-physics models with high computational complexity. In this sense, using a trained PINN is beneficial, since inference on a trained PINN can be very fast (in the order of few seconds or less, depending on the size of the neural network).

[0042] At block 304, the control module 162 determines an operation of the plurality of fans based on the obtained cooling capacity achievable from operations of one or more fans from the plurality of fans, such that a predetermined control objective can be met by the control module 162. The predetermined control objective at least includes a value of maximum temperature within the transformer being less than a corresponding temperature threshold.

[0043] The control objective is predetermined for cooling optimization. The control objective can include one or more constraints such as a thermal limit that cannot be violated. The control objective can also include one or more selectable

optimizations such as optimizations for energy expenditure, noises, and ageing and maintenance. The control objective can be predetermined to include multiple control objectives. Examples of the multiple control objectives are described below.

5 Temperature control

[0044] The temperature inside the transformer must be kept within a desired range. For example, for a hotspot located at coordinates x_H, y_H, z_H , a control objective can be formulated as

$$10 \quad T(x_H, y_H, z_H, t) < T_{thr}, \quad t \in [0, P] \quad (2)$$

where:

15 $T(x_H, y_H, z_H, t)$ represents the temperature at the hotspot position x_H, y_H, z_H at the specific time $t \in [0, P]$; and

T_{thr} represents the temperature threshold.

[0045] The hotspot temperature can be computed as $T(x_H, y_H, z_H, t) = f(I_1, \dots, I_N, K(t), T_a(t), x_H, y_H, z_H, t)$, whose value depend on the operation values of fan operations, for example, variables $I_1, \dots, I_N$.

20 **[0046]** Hotspots can be understood as regions of high energy density or temperature. Positions of the hotspots can be related to the structure of the transformer such as placement of windings/heat sources with respect to tank volume, and placement of the heat exchanger and positions of the fans.

25 **[0047]** In an example, positions of the hotspots are determined before the temperature control. In this way, the temperature control is only performed for the hotspots without checking all the spatial coordinates in the considered geometry of the transformer, and thus the high computational complexity during the temperature control can be reduced. For example, regions where hotspots are most likely to occur are determined first and then calculation for the temperature control is performed only for those regions.

30 **[0048]** The temperature threshold is determined based on the properties of the solid insulation material of the transformer (e.g., with Kraft paper the rated hotspot is 95°C according to IEEE or 97°C according to IEC) and relevant loading guides (e.g. IEC 60076-7, IEC 60076-14, IEEE Std C57.91.).

[0049] According to examples of the present disclosure, the temperature threshold is a configurable parameter, which could be dynamically adjusted during the transformer lifetime.

35 **[0050]** In general, the maximum temperature within the considered geometry of the power transformer should be below the temperature threshold. According to examples of the present disclosure, there can be different temperature thresholds for different types of hotspots, such as a winding hotspot, a core hotspot, and a bushing hotspot. For example, the winding may have certain sections insulated by aramid insulation which has a higher temperature limit. Top liquid temperature is not generally referred to as hotspot but represents another temperature limit that must be respected. Thus, the temperature threshold for the winding hotspot can be higher than that for the top liquid hotspot.

40 Power losses control

[0051] One of the multiple control objective can be an optimization based on minimum energy expenditure. The energy expenditure includes: 1) power to operate fans (i.e., power losses connected to fans); and 2) temperature dependent power losses in the power transformer.

45 **[0052]** In an example, a control objective is that power losses connected to the fans are minimized and this control objective can be formulated as:

$$50 \quad \min_{I_1, \dots, I_N} \sum_{i=1}^N \alpha_i I_i \quad (3)$$

where $\alpha_i \in (0, 1)$ are non-negative weights indicating the relative impact of the operation of the i-th fan in the total cooling losses. In general, fans of the same rating and model will have very similar power losses. Thus, in a case where all fans have equal impact on total cooling losses, α_i can be pre-fixed to be 1.

55 **[0053]** It is noted that power losses of the power transformer depend on the temperature of the power transformer, and different fan operations have different impact on the cooling capacity, which means that the transformer will have different losses depending on which fan is in operation.

[0054] Moreover, there might be a case where a fan starts operating in preparation for a future load peak or fans may be

selected based on need for maintenance. In this case, the optimization about energy expenditure can be implemented based on forecast information on future energy expenditure. In an example, the forecast information can include one or more of: energy expenditure forecast based on a load forecast of the power transformer; a weather forecast; and an aging forecast of the fans.

Noise control

[0055] One of the multiple control objective can be an optimization based on minimizing noises caused by the fans. In an example, a control objective is that noises connected to the fans are minimized and this control objective can be formulated as

$$\min_{I_1, \dots, I_N} \sum_{i=1}^N \beta_i I_i \quad (4)$$

where $\beta_i \in (0, 1)$ are non-negative weights indicating the relative impact of the operation of the i -th fan in the total noise. Unbalanced impact on the noise could be assessed during factory testing by turning fans on one-by-one while measuring noise levels at different locations, and thus β_i can be determined. In a case where all fans have equal impact on the total noise losses, β_i can be pre-fixed to be 1.

Ageing and maintenance control

[0056] Whenever a fan is operated for a given amount of time, its aging increases. It is desirable that the aging is as evenly distributed as possible among the different fans to avoid that some fans age faster than others and trigger unnecessary maintenance actions. Thus, one of the multiple control objectives is to align ageing with maintenance intervals of the fans so as to ensure the maximum reliability of the cooling system. In an example, this control objective is to minimize the maximum accumulated aging at the end of the control period P and can be formulated as:

$$A_{i,P} = A_{i,0} + I_i \cdot a_P. \quad (5)$$

$$\min_{I_1, \dots, I_N} \max_i A_{i,P} \quad (6)$$

where:

$A_{i,0}$ represents the accumulated aging for the i -th fan at the beginning of the control period P ;
 a_P represents a coefficient describing the aging of an active fan during the control period P ; and
 $A_{i,P} = A_{i,0} + I_i \cdot a_P$ represents the accumulated aging for the i -th fan at the end of the control period P .

[0057] It is noted that the coefficient a_P can be a fixed term which is pre-determined based on information provided by the manufacturer of the fan and further based on accelerated aging tests on the fans.

[0058] In an example, various control objectives can be combined into a joint function for a multi-objective optimization and this joint function can be formulated as:

$$\min_{I_1, \dots, I_N} k1 \left(\sum_{i=1}^N \alpha_i I_i \right) + k2 \left(\sum_{i=1}^N \beta_i I_i \right) + k3 \left(\max_i A_{i,P} \right)$$

subject to:

$$T(x_H, y_H, z_H, t) < T_{thr}, \quad t \in [0, P] \quad (7)$$

where $k1$, $k2$ and $k3$ are weights that can be adjusted to prioritize different control objectives. The weights can be adjusted based on requirements or preferences of a user. Here, the user can be, for example, an operator or purchaser of the cooling system, a designer or purchaser of the power transformer, a central monitoring platform (for example, a central monitoring platform that monitors multiple power transformers).

[0059] In general, the multi objectives can be achieved based on control for different aspects of fan operations. For example, taking the above Formula (7) as an example, in the case that the temperature constrain is met, the optimization of minimizing power loss is achieved by controlling on/off operations of the fans, the optimization of minimizing noise can be achieved by controlling speeds of the fans, and the optimization of aligning ageing with maintenance intervals can be achieved by controlling fan switch timings.

[0060] At block 306, the control module 162 controls one or more fans from the plurality of fans to operate according to the determined operation.

[0061] In addition, the thermal model is used continuously during the device lifetime. There is a situation where different factors may change the relation between the operation of the fans and the internal transformer temperature over time (i. e., the cooling capacity is changed over time), such as degradation in the transformer and/or in the fans. The present disclosure can solve this problem by updating the thermal model during the device life time.

[0062] Examples of the present disclosure provides a method for updating the thermal model to adapt to real-time changes during device lifetime. Figure 4 illustrates a method 400 for updating the thermal model according to an example of the disclosure. The method 400 for example can be implemented by means of the cooling system.

[0063] Referring to Figure 4, at block 402, the NN is retrained using measurements which are obtain from the internal sensing unit 30 and/or the external sensing unit 40 during operation of the transformer 10. It is noted that the retraining can be performed in a similar way as the above described training and thus the above described features and advantages of the training of the NN are also applicable here.

[0064] At block 404, the thermal model 161 is updated with the retrained NN such that the updated thermal can provide new cooling capacity achievable from operations of the fans. In an example, new neuron weights which minimize the PINN loss function are obtained by retraining the NN and the thermal model 161 is updated with the new neuron weights.

[0065] At block 406, an indicator for determining whether maintenance of any of the plurality of fans is needed is generated based on changes in the cooling capacity. For example, the changes in the neuron weights can be used as a quantitative indicator to indicate if one or more of the plurality of fans are needed to be maintained or replaced.

[0066] In an example, the thermal model can be updated periodically. In another example, the thermal model can be updated when it is detected that the confidence level of the thermal model is below a confidence threshold.

[0067] In addition, examples of the present disclosure can provide an optimization for the arrangement of the fans. For example, the thermal model could be modified so that fan locations become explicit parameters (e.g., as parameters of the PDEs used as regularizing terms in the PINN). Then, it could run an optimization to derive the optimal placements of the fans that can provide best cooling effectiveness from the aspect of fan placements. This optimization can be performed off-line, for example, during a design phase of the transformer. This optimization can also be performed on-line, for example, during operation of the transformer. In this case, the fans can be automatically moved during the transformer operation according to the optimal placements.

[0068] It is noted that the control module 162 can be implemented by means of hardware or software or a combination of hardware and software, including code stored in a non-transitory computer-readable medium such as a memory and implemented as instructions executed by a processor. Regarding the part implemented by means of hardware, it may be implemented in an application-specific integrated circuit (ASIC), a digital signal processor (DSP), a data signal processing device (DSPD), a programmable logic device (PLD), a field programmable gate array (FPGA), a processor, a controller, a microcontroller, a microprocessor, an electronic unit, or a combination thereof. The part implemented by software may include a microcode, a program code or code segments. The software may be stored in a machine-readable storage medium, such as a memory.

[0069] It is noted that software should be considered broadly to represent instructions, instruction sets, code, code segments, program code, programs, subroutines, software modules, applications, software applications, software packages, routines, subroutines, objects, running threads, processes, functions, and the like. Software can reside on computer readable medium. Computer readable medium may include, for example, a memory, which may be, for example, a magnetic storage device (e.g., a hard disk, a floppy disk, a magnetic strip), an optical disk, a smart card, a flash memory device, a random access memory (RAM), a read only memory (ROM), a programmable ROM (PROM), an erasable PROM (EPROM), an electrically erasable PROM (EEPROM), a register, or a removable disk. Although a memory is shown as being separate from the processor in various aspects presented in this disclosure, a memory may also be internal to the processor (e.g., a cache or a register).

[0070] The previous description is provided to enable any person skilled in the art to practice the various aspects described herein. Various modifications to these aspects will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other aspects. Thus, the claims are not intended to be limited to the aspects shown herein. All structural and functional equivalent transformations to the elements of the various aspects of the present disclosure, which are known or to be apparent to those skilled in the art, are intended to be covered by the claims.

Claims

1. A cooling system for a static electric induction device, comprising:

a heat exchanger;
a plurality of fans arranged to extract heat from the heat exchanger; and
a control system comprising a control module configured to determine an operation of the plurality of fans based on information received from a thermal model configured for the static electric induction device determining cooling capacity achievable from operations of one or more fans from the plurality of fans, such that a predetermined control objective is met by the control module, the predetermined control objective at least comprising a value of maximum temperature inside the static electric induction device being less than a corresponding temperature threshold.

2. The cooling system of claim 1, wherein the static electric induction device is a transformer or a shunt reactor.

3. The cooling system of any of claims 1-2, wherein the thermal model comprises:

a correlation between the value of temperature at each hotspot and an operation of the plurality of fans in accordance with an activation or deactivation of one or more fans from the plurality of fans; and/or
a correlation between the value of temperature at each hotspot and an operation of the plurality of fans in accordance with a value of speed at which one or more fans from the plurality of fans are operated.

4. The cooling system of any of claims 1-3, wherein the cooling system is configured to operate one or more fans from the plurality of fans to switch on or off according to the determined operation; and/or
the cooling system is configured to operate one or more fans from the plurality of fans to adjust speed according to the determined operation.

5. The cooling system of any of claims 1-4, wherein the predetermined control objective further comprise one or more of:

minimizing power loss comprising power to operate the plurality of fans and temperature dependent power losses in the static electric induction device;
minimizing noise caused by the fan cooling; and
maximizing reliability of the cooling system based on aligning ageing with maintenance intervals of the plurality of fans.

6. The cooling system of any of claims 1-5, wherein the control module is configurable to determine an operation of the plurality of fans based on one or more of:

energy expenditure based on a load forecast of the static electric induction device;
a weather forecast; and
an aging forecast of one or more fans from the plurality of fans.

7. The cooling system of any of claims 1-6, wherein the control system further comprising the thermal dynamic model, and the thermal dynamic model is obtained by training a neural network (NN) which is coupled to one or more partial differential equations associated with heat transfer of the static electric induction device, and wherein, the NN is a physics-informed neural network, and the thermal model is a surrogate model.

8. The cooling system of claim 7, wherein data for training the NN comprise one of more of:

measurement data of the static electric induction device;
simulation data of the static electric induction device;
history data of the static electric induction device and
reference data associated with another static electric induction device with the same heat exchanger, the same load, the same number of fans and the same arrangement of the fans as the static electric induction device.

9. The cooling system of any of claims 7-8, wherein the NN is updated when the cooling capacity is changed over time for at least one of:

degradation of at least one fan of the plurality of fans;
 performance of at least one fan of the plurality of fans being improved after maintenance;
 at least one fan of the plurality of fans being moved; and
 robustness is of the thermal model being below a predetermined robustness threshold.

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10. The cooling system of any of claims 7-9, wherein the NN is retrained with field data during operation of the static electric induction device; and
 wherein a change in the cooling capacity is obtained by means of the retraining of the PINN, and the change in the cooling capacity is used as an indicator for determining whether maintenance of the plurality of fans is needed.
- 10
11. The cooling system of any of claims 7-10, further comprising an interface, wherein the information on the cooling capacity is transferred to the control system from the trained NN in a wireless way via the interface.
- 15
12. The cooling system of any of claims 1-11, wherein the control module is comprised in a local controller of the static electric induction device, and wherein the thermal model is comprised in the local controller, a cloud server or an edge sever.
13. A static electric induction device comprising a cooling system of any of claims 1-12.
- 20
14. A method for cooling a static electric induction device by means of a cooling system, the cooling system comprising a heat exchanger and a plurality of fans arranged to extract heat from the heat exchanger, the method comprising:
 determining an operation of the plurality of fans based on information received from a thermal model configured for the static electric induction device determining cooling capacity achievable from operations of one or more fans from the plurality of fans, such that a predetermined control objective is met by the control module, the predetermined control
 25 objective at least comprising a value of maximum temperature inside the static electric induction device being less than a corresponding temperature threshold.
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15. The method of claim 14, further comprising:
 operating one or more fans from the plurality of fans to switch on or off according to the determined operation;
 and/or
 operating one or more fans from the plurality of fans to adjust speed according to the determined operation.

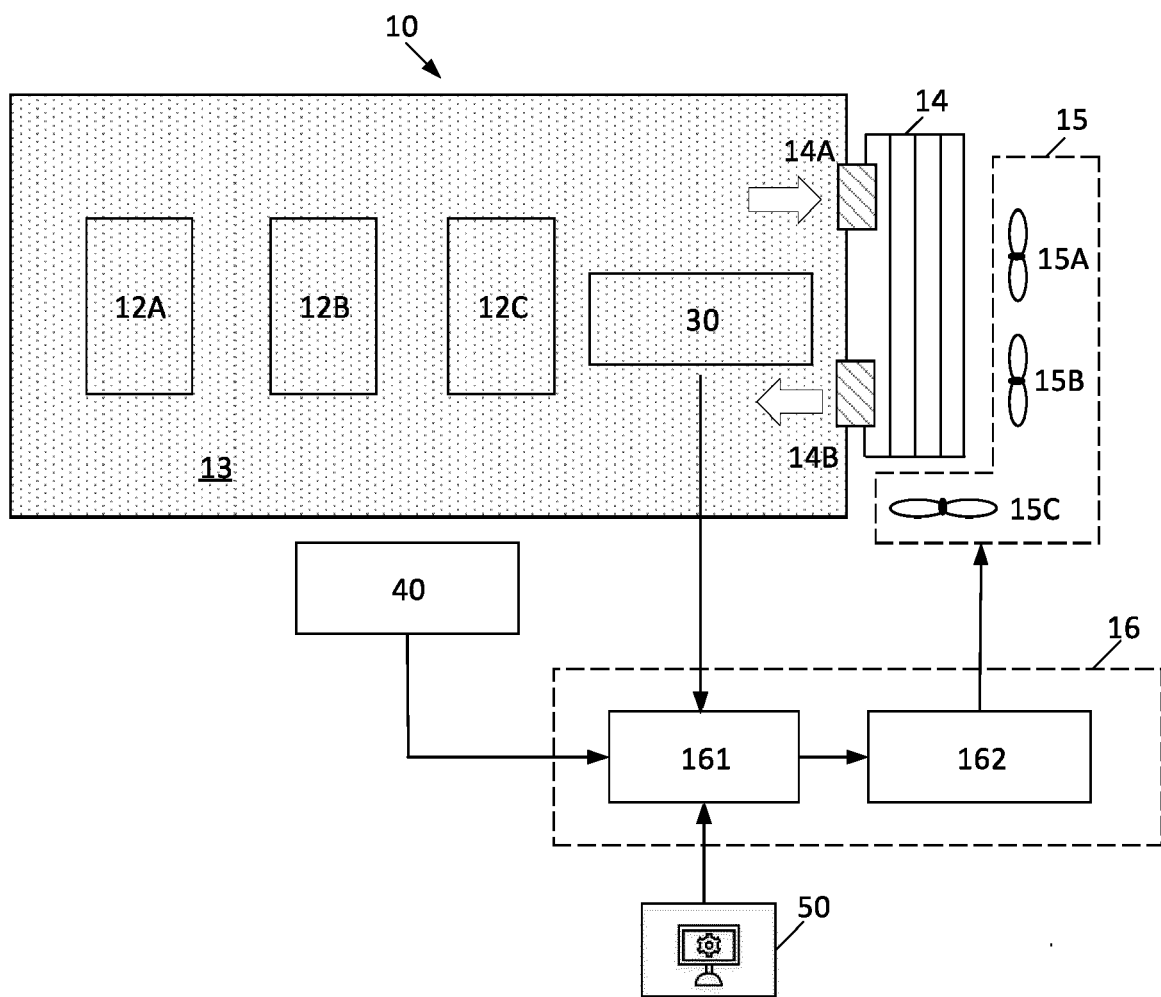


Figure 1

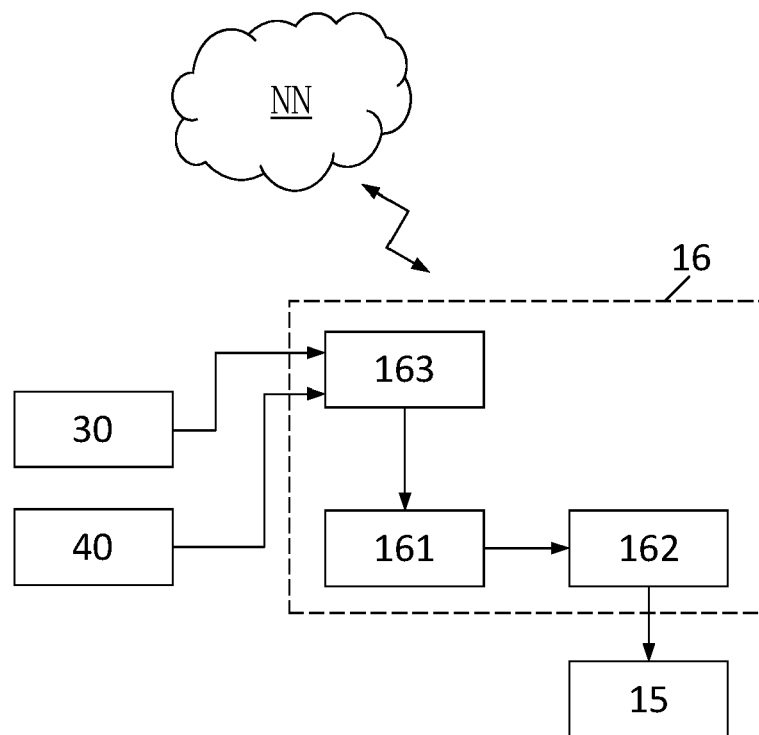


Figure 2A

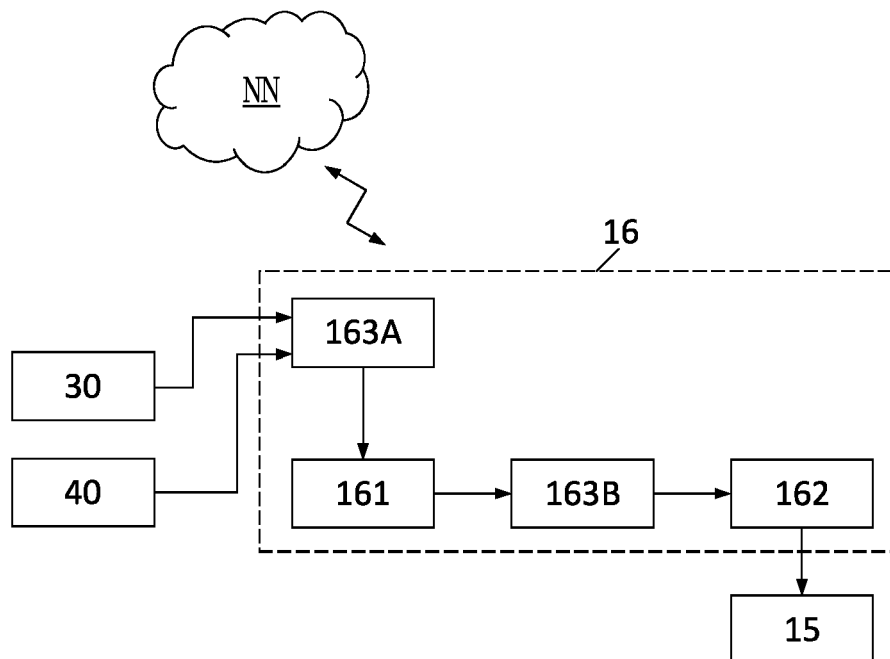


Figure 2B

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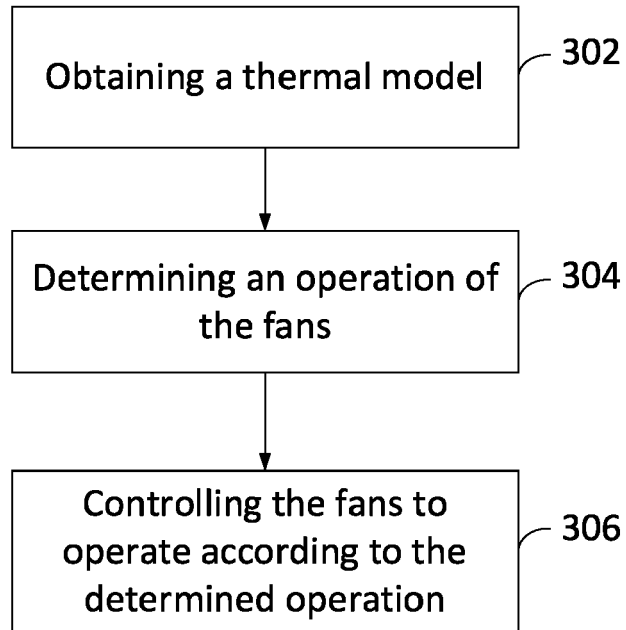


Figure 3

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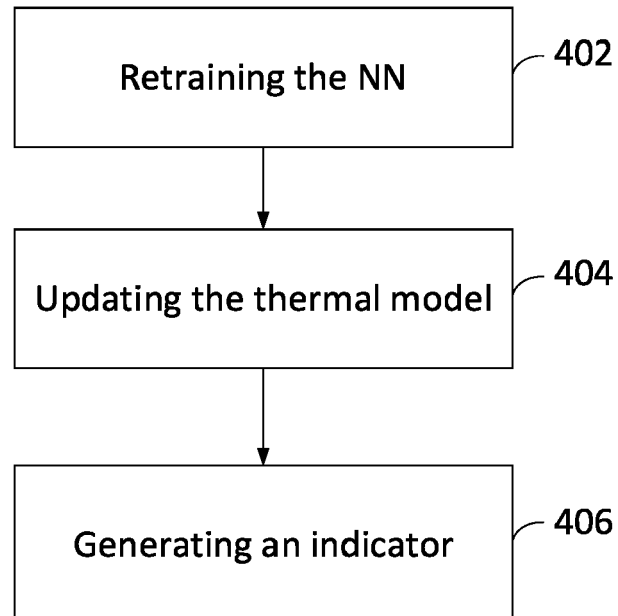


Figure 4



EUROPEAN SEARCH REPORT

Application Number

EP 23 20 9976

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Munich		10 April 2024	Warneck, Nicolas
CATEGORY OF CITED DOCUMENTS			
X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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