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(54) **CONTROL OF A REFRIGERATION CIRCUIT**

(57) There is disclosed a controller 100 for a refrigeration circuit 10, configured to monitor a set of prevailing conditions 50 relating to the refrigeration circuit including a space temperature of a temperature-controlled space associated with the refrigeration circuit. The controller 100 has a simulation module 102 configured to determine a limit setting 152 of a control variable for the refrigeration circuit by an iterative optimisation procedure based on a model 110 corresponding to the refrigeration circuit. The

objective function for the optimisation relates to an operating efficiency. The controller further comprises a dynamic control module 160 configured to: adjust an operating setting of the control variable within an operating range to target a performance threshold for a monitored performance parameter, based on monitoring of the performance parameter during operation of the refrigeration circuit; and apply the limit setting received from the simulation module as a limit to the operating range.

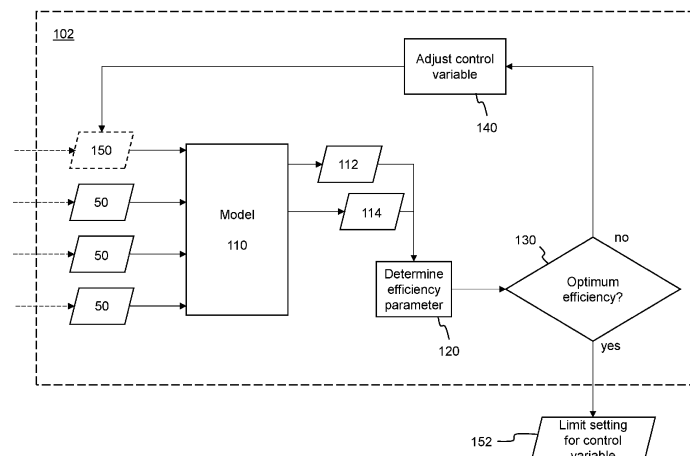


Figure 2

Description

Technical Field

[0001] The invention relates to control of a refrigeration circuit, for example as may be used in an HVAC-R system. In particular, the invention relates to controlling a control variable of the refrigeration circuit based on a minimum performance parameter and optimisation relating to efficiency.

Background

[0002] It is known to provide refrigeration circuits which can be operated through an operating map of operating conditions. It is known to adjust various operating parameters during operation of a refrigeration circuit, such as a compressor speed or an expansion valve setting. Such control is typically based on targeting thermodynamic parameters around the refrigeration circuit or in a process medium, such as a target superheat upstream of the compressor, or a target temperature of a process medium which exchanges heat with a refrigerant of the refrigeration circuit at a heat exchanger of the refrigeration circuit.

[0003] It is desirable to provide an improved method of controlling a refrigeration circuit based on performance requirements of the system.

Summary

[0004] According to a first aspect there is disclosed a controller for a refrigeration circuit ; wherein the controller is configured to monitor a set of prevailing conditions relating to the refrigeration circuit including a space temperature of a temperature-controlled space associated with the refrigeration circuit;

wherein the controller has a simulation module configured to determine a limit setting of a control variable for the refrigeration circuit by an iterative optimisation procedure based on a model corresponding to the refrigeration circuit;

wherein the iterative optimisation procedure is defined based on an objective function which relates to an operating efficiency of the refrigeration circuit and is determined based on evaluating the model for a respective simulated operating point; wherein the simulated operating point is defined by the monitored set of prevailing conditions, and by a simulated setting for the control variable which is iteratively varied in the optimisation procedure, and

wherein the controller further comprises a dynamic control module configured to: adjust an operating setting of the control variable within an operating range to target a performance threshold for a monitored performance parameter, based on monitoring of the performance parameter during operation of

the refrigeration circuit; and apply the limit setting received from the simulation module as a limit to the operating range.

[0005] The limit setting for the control variable is defined based on a simulated operating point determined to correspond to the objective function being at an optimal value (e.g. a maximum) or within a range including the optimal value (e.g. a maximum) corresponding to near-optimal performance.

[0006] It may be that the dynamic control module is configured to adjust the operating setting of the control variable during operation of the refrigeration circuit, based on concurrent monitoring of the performance parameter during operation of the refrigeration circuit.

[0007] It may be that the model does not determine the performance parameter.

[0008] It may be that the objective function is a coefficient of performance.

[0009] It may be that the coefficient of performance is determined based on a simulated heat transfer capacity (e.g. cooling capacity) and a corresponding simulated power consumption, each determined based on the model.

[0010] The heat transfer capacity may correspond to a cooling capacity when the prevailing conditions relate to operation of the refrigeration circuit in a cooling mode in which the second heat exchanger is operated as an evaporator for cooling an associated temperature-controlled environment. The heat transfer capacity may correspond to a heating capacity when the prevailing conditions relate to operation of the refrigeration circuit in a cooling mode in which the second heat exchanger is operated as a condenser for heating the associated temperature-controlled environment.

[0011] The controller may be configured to simulate operation of the refrigeration circuit at the simulated operating point using the digital twin.

[0012] It may be that the monitored performance parameter is a rate of change of a monitored condition relating to the refrigeration circuit.

[0013] It may be that the targeted performance threshold for the monitored performance parameter is selected from the group consisting of: (i) a heat transfer parameter relating to a heat transfer capacity of the refrigeration circuit, for example: a predetermined minimum heat transfer capacity of the refrigeration circuit; or a predetermined minimum magnitude of a monitored rate of change of a space temperature of the temperature-controlled space; and (ii) a predetermined minimum refrigerant superheat at a superheat monitoring location along a suction line of the refrigeration circuit.

[0014] It may be that the dynamic control module comprises a PI or PID control module configured to control the control variable of the refrigeration circuit during operation of the refrigeration circuit. It may be that the PI or PID control module is configured to vary the control variable based on an error signal relating to a difference

between the performance threshold and the monitored performance parameter. It may be that the limit setting for the control variable is applied as saturation limit of the PI or PID controller.

[0015] It may be that the targeted performance threshold for the monitored performance parameter is a predetermined minimum magnitude of a monitored rate of change of the space temperature. It may be that the PI or PID control module (i) is configured to control an operating parameter of the compressor as the control variable; and (ii) is configured to determine the error signal as the difference between the predetermined minimum magnitude of the rate of change of the space temperature and a monitored rate of change of the space temperature.

[0016] It may be that the model is configured to determine the simulated power consumption based on one or more of: (i) an operating parameter of the compressor, as the control variable or derived from the set of prevailing conditions; (ii) an operating parameter of a first fan associated with the first heat exchanger, as the control variable or derived from the set of prevailing conditions; and/or (iii) an operating parameter of a second fan associated with the second heat exchanger, as the control variable or derived from the set of prevailing conditions.

[0017] The controller may be configured to repeatedly conduct the optimisation procedure and update the limit setting. The controller may be configured to repeat the optimisation procedure at predetermined intervals; and/or repeat the optimisation procedure based on determining a threshold change or rate of change of a prevailing condition of the set of prevailing conditions.

[0018] It may be that the simulation module is configured to determine a limit setting of a plurality of control variables for the refrigeration circuit by the iterative optimisation procedure. It may be that the simulated operating point is defined by the monitored set of prevailing conditions and by respective simulation settings for the plurality of control variables. It may be that, for each control variable, the simulation control module is configured to determine a respective limit setting by the optimisation procedure. It may be that the dynamic control module is configured to adjust each respective operating setting of the control variables within respective operating ranges to target the performance threshold for the monitored performance parameter, and to apply each respective limit setting received from the simulation module as a limit to the respective operating ranges.

[0019] When there are a plurality of control variables, the references above with respect to variation, determination and setting of a control variable or respective limit are to be interpreted as corresponding to the (respective) variation, determination and setting of each respective control variable or limit.

[0020] According to a second aspect there is disclosed a refrigeration circuit comprising a compressor, a first heat exchanger, an expansion device, a second heat exchanger and a controller in accordance with the first aspect.

[0021] According to a third aspect there is disclosed a method of controlling a refrigeration circuit (e.g. in accordance with the second aspect) using a controller according to the first aspect, wherein a control variable of the refrigeration circuit is variable during operation of the refrigeration circuit, the method comprising: monitoring a set of prevailing conditions relating to the refrigeration circuit, including a space temperature of a temperature-controlled space associated with the refrigeration circuit;

the simulation module conducting the iterative optimisation procedure to determine a limit setting of a control variable for the refrigeration circuit; applying the limit setting as a limit to an operating range for the control variable; monitoring a performance parameter for the refrigeration circuit during operation of the refrigeration circuit; the dynamic control module adjusting an operating setting of the control variable within the operating range to target a performance threshold for the monitored performance parameter;

whereby the dynamic control module biases operation of the refrigeration circuit to the limit setting of the control variable determined by the optimisation procedure when the limit setting corresponds to compliance with the performance threshold during operation of the refrigeration circuit; and

whereby the dynamic control module biases operation of the refrigeration circuit to depart from the limit setting of the control variable to achieve the target performance threshold, when the limit setting corresponds to non-compliance with the performance threshold during operation of the refrigeration circuit.

[0022] According to a fourth aspect there is provided a non-transitory machine-readable medium comprising instructions that, when executed by a processor, cause performance of a method in accordance with the third aspect.

[0023] The controller(s) described herein may comprise a processor. The controller and/or the processor may comprise any suitable circuitry to cause performance of the methods described herein and as illustrated in the Figures. The controller or processor may comprise: at least one application specific integrated circuit (ASIC); and/or at least one field programmable gate array (FPGA); and/or single or multi-processor architectures; and/or sequential (Von Neumann)/parallel architectures; and/or at least one programmable logic controllers (PLCs); and/or at least one microprocessor; and/or at least one microcontroller; and/or a central processing unit (CPU), to perform the methods and or stated functions for which the controller or processor is configured.

[0024] The controller may comprise or the processor may comprise or be in communication with one or more memories that store that data described herein, and/or

that store machine readable instructions (e.g. software) for performing the processes and functions described herein (e.g. determinations of parameters and execution of control routines).

[0025] The memory may be any suitable non-transitory computer readable storage medium, data storage device or devices, and may comprise a hard disk and/or solid state memory (such as flash memory). In some examples, the computer readable instructions may be transferred to the memory via a wireless signal or via a wired signal. The memory may be permanent non-removable memory, or may be removable memory (such as a universal serial bus (USB) flash drive). The memory may store a computer program comprising computer readable instructions that, when read by a processor or controller, causes performance of the methods described herein, and/or as illustrated in the Figures. The computer program may be software or firmware, or be a combination of software and firmware.

[0026] The skilled person will appreciate that except where mutually exclusive, a feature described in relation to any one of the above aspects may be applied mutatis mutandis to any other aspect. Furthermore, except where mutually exclusive any feature described herein may be applied to any aspect and/or combined with any other features described herein.

List of Drawings

[0027] The invention will be described with reference to the drawings, in which:

Figure 1 schematically shows a refrigeration circuit;

Figure 2 schematically shows a flow diagram of control actions conducted by a simulation module of a controller for the refrigeration circuit;

Figure 3 schematically shows the simulation module and dynamic module of the controller;

Figure 4 schematically shows a flow diagram of control actions conducted by a dynamic module of a controller for the refrigeration circuit;

Figures 5 and 6 show plots of performance and efficiency parameters of a refrigeration circuit through an operating range of a control variable for a refrigeration circuit;

Figure 7 schematically illustrates example operating ranges of a control variable for a refrigeration circuit;

Figure 8 is a flow diagram of a method of controlling a refrigeration circuit; and

Figure 9 schematically shows a machine-readable medium and processor.

Detailed Description

[0028] Figure 1 schematically shows an example refrigeration circuit 10 (e.g. heat pump or vapor compression cycle) for transferring heat from one heat exchange medium to another, for example between a controlled environment 2 (e.g. temperature-controlled space) and an ambient environment. Examples applications of such refrigeration circuits include a chiller system (e.g. for centrally heating and cooling a process fluid such as water that circulates within a building or other installation to heat transfer terminals, e.g. for room heating), or a refrigeration system such as an HVAC system or a transport refrigeration system.

[0029] The refrigeration circuit 10 of Figures 1 comprises a compressor 12, a first heat exchanger 14, an expansion device 16, and a second heat exchanger 18. The first and second heat exchangers 14, 18 are provided with respective fans 15, 19.

[0030] The refrigeration circuit 10 may be configured to define two flow paths through the heat pump for operation in different modes, namely a cooling mode and a heating mode (conventionally known as a reversible heat pump).

[0031] The expressions "heating" and "cooling" refer to the direction of heat transfer with respect to a heat exchange medium which is being actively heated or cooled, for example to maintain a set-point temperature in a temperature-controlled space (e.g. air in a cargo space, or process fluid/water in a chiller system). In the present disclosure, this is referred to as the regulated heat exchange medium.

[0032] Figure 1 shows the refrigeration circuit in a cooling mode, whereby there is a flow path (indicated by arrows) extending through, in flow order, the compressor 12, the first heat exchanger 14 which functions as a condenser for discharging heat to an ambient heat exchange medium (e.g. ambient air), the expansion device 16, the second heat exchanger 18 which functions as an evaporator for receiving heat from a regulated heat exchange medium in the temperature-controlled space 2, returning to the compressor 12. The flow path of Figure 1 is for cooling the regulated heat exchange medium, and it is the second heat exchanger 18 which is in thermal communication with the regulated heat exchange medium. Correspondingly, the fan 15 associated with the first heat exchanger 14 may be referred to as a condenser fan 15, and the fan 19 associated with the second heat exchanger 18 may be referred to as an evaporator fan 19.

[0033] A suitable valve arrangement may be provided to reverse a flow direction for a heating mode as is known in the art, such that the second heat exchanger 18 functions as a condenser for rejecting heat to the regulated heat exchange medium, and the first heat exchanger 14 functions as an evaporator for receiving heat from an ambient heat exchange medium.

[0034] The further description is by reference to the refrigeration circuit in the cooling mode shown in Figure

1. A portion of the flow path between the compressor 12 and the condenser 14 is referred to as the discharge line, a portion of the flow path between the condenser 14 and the expansion device 16 is referred to as the liquid line, a portion of the flow path between the expansion device 16 and the evaporator 18 is referred to as the distribution line, and a portion of the flow path between the evaporator 18 and the compressor 12 is referred to as the suction line.

[0035] A suction line heat exchanger 20 is provided for heat exchange between refrigerant in the liquid line and the suction line. The suction line heat exchanger 20 has a liquid line portion 22 along the liquid line, and a suction line portion 24 along the suction line. In other examples, there may be no such suction line heat exchanger.

[0036] In use in the cooling mode of Figure 1, gaseous refrigerant is compressed at the compressor 12 to a high pressure and is condensed in the condenser 14 to reject heat to the ambient heat exchange medium, thereby providing high pressure and high temperature condensed refrigerant in the liquid line. The condensed refrigerant is expanded at the expansion device 16, to provide a multi-phase refrigerant flow to the evaporator 18. This flow is evaporated in the evaporator 18, before being provided to the compressor 12. Evaporation at the evaporator 18 cools the regulated heat exchange medium associated with the evaporator.

[0037] When present, the suction line heat exchanger 20 transfers heat from the high temperature liquid refrigerant in the liquid line to the relatively lower temperature refrigerant in the suction line. This may be considered to temporarily remove thermal energy from the refrigerant for a portion of the circuit comprising the expansion device and the evaporator. This may permit the refrigerant to be expanded to a relatively lower pressure and saturation temperature for absorbing heat from the ambient heat exchange medium at the evaporator. The thermal energy returns to the refrigerant at the suction line portion 24 of the suction line heat exchanger, which may correspond to further evaporation and/or superheating of the refrigerant upstream of the compressor 12.

[0038] Figure 1 shows further monitoring and control equipment of or associated with the refrigeration circuit 10. A controller 100 is provided and is operatively connected to control operating variables of the compressor 12 and/or the expansion device 16. The controller 100 may control only one of the compressor 12 and the expansion device 16, or may control both. For example, the expansion valve 16 may be provided with its own controller (e.g. as an electronic expansion valve, EXV), or may be configured as a thermostatic control valve.

[0039] The controller 100 is further coupled to one or more sensors around the refrigeration circuit for monitoring one or more prevailing conditions of the refrigeration circuit, which may include one or more thermodynamic parameters of the refrigerant and/or one or more parameters associated with the ambient heat exchange medium and/or the regulated heat exchange medium.

[0040] Figure 1 shows monitoring locations for such sensors, including a discharge line monitoring location 32 along the discharge line, a first liquid line monitoring location 34 along the liquid line upstream of the suction line heat exchanger 20, a second liquid line monitoring location 35 along the liquid line downstream of the suction line heat exchanger 20, a distribution line monitoring location 36 along the distribution line, a first suction line monitoring location 38 along the suction line upstream of the suction line heat exchanger 20 and a second suction line monitoring location 39 along the suction line downstream of the suction line heat exchanger 20. A further monitoring location 40 is associated with the regulated heat exchange medium, for example a temperature sensor may be provided to monitor a flow of supply air or return air provided to/from the temperature-controlled space 2, or a temperature sensor disposed in the temperature-controlled space 2. Similarly, a further monitoring location 42 is associated with the ambient heat exchange medium 4, for example a temperature sensor may be provided to monitor a temperature of ambient flow conveyed to the condenser 14 (for example by the condenser fan 15). The temperature sensor may be co-located with the condenser 14 or condenser fan 15 for such monitoring, or otherwise provided in the ambient heat exchange medium. Any one or more of the monitoring locations may be used in a refrigeration circuit according to the present disclosure. Further, for any monitoring location provided with at least one sensor may be provided with a temperature sensor and/or a pressure sensor.

[0041] Although not schematically shown by links between the monitoring locations and the controller 100, signals from the pressure and/or temperature sensors may be provided to the controller 100 for use in controlling the refrigeration circuit as will be discussed below.

[0042] Figure 2 schematically shows a flow diagram of a control actions implemented by a simulation module 102 of the controller 100. The simulation module 102 comprises or is configured to reference (e.g. remotely access) a model 110.

[0043] The model is configured to relate one or more parameters that relate to an operating point of the refrigeration circuit to one or more performance parameters of the refrigeration circuit. The expression "operating point" refers to a state of the refrigeration circuit, such that example parameters relating to the operating point describe thermodynamic or operational parameters associated with respective parts of the refrigeration circuit. For example, such parameters may include one or more of: a temperature of the temperature-controlled space 2 (e.g. as monitored by a temperature sensor at monitoring location 40), a temperature of the ambient heat exchange medium (e.g. as monitored by a temperature sensor at monitoring location 42), an operating parameter of the condenser fan 15 (e.g. a fan speed or a power parameter relating to power provided to the fan (e.g. a power, frequency, voltage or current), an operating parameter of

the evaporator fan 19 (which may be similar to the operating parameter of the condenser fan), an operating parameter of the expansion device 16 (for example a valve setting relating to a state of the valve, such as a parameter relating to how open the valve is and/or whether it is in a closed state), an operating parameter of the compressor 12 (for example a compressor speed parameter (e.g. an rotary speed (e.g. revolutions per minute), angular speed, or frequency of rotation), or a power parameter relating to power provided to the compressor (e.g. a power, frequency, voltage or current). Further, such parameters may include one or more temperatures or pressures of the refrigerant around the refrigeration circuit. As is known in the art, refrigerant pressure may be used to determine a saturation temperature of the refrigerant, and thereby permit an amount of subcooling or superheating of refrigerant at an associated location to be determined.

[0044] In the example of Figure 2, the model 110 is configured to relate four parameters 50, 150 that relate to the operating point of the refrigeration circuit (operating point parameters) to two performance parameters 112, 114. In this example, the operating point parameters are the temperature of the ambient heat exchange medium, the temperature of the temperature-controlled space, the condenser fan speed and a compressor speed parameter. The model 110 is configured to relate these parameters to a cooling capacity of the refrigeration circuit, and a power consumption of the refrigeration circuit. The expression cooling capacity has a well understood meaning in the art, and relates to the amount of heat than can be removed by the system. The SI unit is watt (W), and the cooling capacity is typically derived as the product of a mass flow rate (e.g. of either the ambient heat exchange medium or the regulated heat exchange medium), the respective specific heat capacity (Cp), and the observed temperature change.

[0045] Although a particular example of a relation between operating point parameters and performance parameters has been described, it should be appreciated that in other examples the model 110 may be configured to implement a wide variety of similar relations that relate a different or overlapping set of operating point parameters to a different or overlapping set of performance parameters. Such a relation may be based on any suitable number of operating point parameters (rather than four parameters as in the example above).

[0046] As shown in Figure 2, three of the example operating point parameters 50 are received as inputs from outside of the simulation module 102 (e.g. from sensors at respective monitoring locations), whereas at least one of the operating point parameters 150 is iteratively derived by the simulation module 102, and corresponds to a control variable of the refrigeration circuit. In this example, the respective control variable 150 is the compressor speed parameter 150. As shown in Figure 2, this may be derived from outside of the simulation module (102) (e.g. as an output of a motor or motor controller for

the compressor) or iteratively derived within the simulation module 102. It may be that an initial value for the control variable 150 is obtained by observation, and subsequent values for the control variable 150 are determined by the simulation module 102 without corresponding variation of the control variable 150 as applied to the refrigeration circuit, as will be described in further detail below.

[0047] In this example, a further performance parameter 120 is derived based on the performance parameters 112, 114. In particular, a coefficient of performance (COP) is determined based on the cooling capacity of the refrigeration circuit 112 and the power consumption of the refrigeration circuit 114. In other examples, the model 110 may relate the operating point parameters 50, 150 directly to a single performance parameter, such as the COP.

[0048] At block 130, the simulation module 102 is configured to iteratively evaluate the performance parameter (e.g. COP) to determine a value for the control variable which corresponds to an optimum (e.g. maximum) value of the performance parameter (e.g. COP). It is to be appreciated that this evaluation occurs iteratively rather than being based on a single value of the control variable and a single variable of the respective performance parameter. Block 130 of the simulation module 102 may therefore be considered to implement an iterative adjustment of the control variable to conduct a search for the optimum value of the performance parameter. It is considered that many suitable methods for conducting such an iterative optimisation or search may be implemented, as are known in the art. Block 130 and the simulation module 102 may therefore be considered to conduct an optimization procedure in which the objective function is defined based on the performance parameter (e.g. to maximise a COP), and the independent variable is the control variable 150.

[0049] Figure 2 shows how the control variable is iteratively adjusted (140) and the adjusted value is provided to the model 110 for further iterations. The iterative adjustment of the control variable within the simulation module 102 occurs solely within the simulation module 102, without corresponding direct adjustment of the value of the control variable applied to the refrigeration circuit during the iterative adjustment. Accordingly, the model 110 may be considered to operate based on a combination of prevailing operating conditions 50 derived from monitoring of the refrigeration circuit, and a simulated setting 150 for the control variable.

[0050] When block 130 determines that the optimum performance parameter is reached, the corresponding value 152 for the control variable is output as a limit setting 152 for the control variable. The limit setting is provided to a dynamic control module as will now be described.

[0051] As schematically shown in Figure 3, the controller 100 comprises the simulation module 102 and a dynamic control module 160. The simulation module 102

is configured to derive the limit setting for the control variable based on prevailing conditions relating to an operating point of the refrigeration circuit (i.e. without direct adjustment of the control variable as applied in the refrigeration circuit - e.g. without directly adjusting the compressor speed). In contrast, the dynamic control module 160 is configured to adjust operation of the refrigeration circuit by adjusting the control variable as applied in the refrigeration circuit (e.g. directly adjusting the compressor speed). However, the dynamic control module 160 does not simply take the value 152 for the control variable determined by the simulation module 102, but instead determines whether to adopt the value 152 based on one or more other performance-related objectives.

[0052] Figure 4 is a flow diagram showing control actions of the dynamic control module 160. As indicated by the dashed arrows in Figure 4, various parameters are provided from outside of the dynamic control module 160, whereas others may be determined or stored locally to the dynamic control module. Firstly, the dynamic control module 160 receives the limit setting 152 from the simulation module 102. Secondly, the dynamic control module 160 receives a performance parameter relating to performance of the refrigeration circuit. The performance parameter may be an observed performance parameter, for example derived from monitoring signals from one or more sensors. In the present example, the performance parameter is a rate of change of temperature in the temperature-cooled space 2, as derived from a series of temperature observations derived by the controller 100 from a temperature sensor at the respective monitoring location 42.

[0053] The dynamic control module 160 stores or references a performance threshold 130 for the respective performance parameter. For example, the performance threshold may correspond to a minimum magnitude of the rate of change of the temperature in the temperature-controlled space 2 during a cooling operation, for example a minimum magnitude of 0.21 °C/minute.

[0054] The dynamic control module 160 is configured to determine a value 154 for the control variable based on comparing the performance parameter with the performance threshold; and/or based on the limit setting 152 received from the simulation module 102, so as to (i) target compliance with the performance threshold, and (ii) apply the limit setting 152 from the simulation module 102 if this corresponds to compliance with the performance threshold.

[0055] The dynamic control module 160 may determine the value 154 for the control variable in any suitable way to achieve this effect. For example, the dynamic control module 160 may be configured to effect gradual changes in the control variable based on the performance parameter comparison and/or the limit setting.

[0056] Although a particular example of a performance threshold and associated performance parameter has been described, it should be appreciated that other performance parameters and thresholds may be applied,

and it may be that two or more such performance parameters and thresholds are monitored and targeted. For example, in addition or as an alternative to a minimum heat transfer capacity of the refrigeration circuit and/or a minimum magnitude of a rate of change of a space temperature of the temperature-controlled space, the dynamic control module may monitor a performance parameter related to a thermodynamic property associated with the refrigeration circuit, for example a superheat at a superheat monitoring location along a suction line of the refrigeration circuit (e.g. upstream of the compressor, optionally upstream or downstream of any suction line heat exchanger when provided). It may be desirable to monitor such parameters when associated with operating requirements or advantages of the refrigeration circuit. For example, it may be desirable for there to be a minimum superheat in refrigerant provided to the compressor, to prevent slugging and associated adverse effects.

[0057] A preferred implementation of the dynamic control module 160 is as a PID (proportional-integral-derivative) or PI (proportional-integral) controller. Such a controller is configured to adjust a variable based on a target, for example to reduce an error between two signals while minimising overshoot and related behaviours. A PI (or PID) controller may be used for the dynamic control module 160 to adjust the control variable (e.g. the compressor speed parameter) to minimise an error signal determined as a difference between the performance parameter (e.g. an observed rate of change of temperature in the temperature-controlled space) and the performance threshold for the performance parameter (e.g. a minimum rate of change of that temperature).

[0058] When the dynamic control module is implemented as a PI or PID controller, the limit setting for the control variable is applied as a saturation limit of the PI or PID controller, in particular a lower saturation limit (a minimum). A saturation limit of a PI or PID controller is a term of the relevant technical field, relating to a limit value (e.g. maximum or minimum) that the PI or PID can output.

[0059] By applying the limit setting as the lower saturation limit, the PI or PID controller is configured to ensure that the control variable is set to a value which is equal to or greater than the value for optimal operation as determined by the simulation module 102, but is free to be adjusted to a higher setting that may be required to achieve the minimum performance threshold (e.g. the minimum rate of change of temperature). This provides a particularly efficient implementation of the desired control functionality which minimises control complexity and equipment cost.

[0060] Figures 5 and 6 show plots of performance parameters for a refrigeration circuit. In each plot, the X-axis corresponds to variation of the control variable, which in this example is the compressor speed parameter. The plotted quantities are in different units, with the solid lines 502, 506 corresponding to coefficients of performance (COP), and the dash-dot lines 504 and 530 corresponding to cooling capacity. Solid line 502 corre-

sponds to compressor COP, whereas solid line 506 corresponds to total COP. Dash-dot line 504 corresponds to the cooling capacity of the system, whereas dash-dot line 530 corresponds to the performance threshold for a corresponding performance parameter (e.g. a minimum cooling capacity).

[0061] Point 508 on the total COP line 506 corresponds to a maximum efficiency for the refrigeration circuit.

[0062] Figure 5 shows two points on the cooling capacity line 504: a first point 510 corresponding to intersection with the performance threshold line 503; and a second point 512 corresponding to the maximum efficiency point 508.

[0063] The controller 100 as described above is configured to determine the limit setting 152 for the control variable using the simulation module 102, such that the limit setting 152 of the control variable corresponds to the maximum efficiency point 508 and the second point 512 on the cooling capacity line 504.

[0064] The dynamic control module is configured such that, in the absence of the limit setting, it adjusts the value of the control variable to target the performance threshold (e.g. a minimum cooling capacity as represented by line 530). This is represented on Figure 5 as the first point 510 on the cooling capacity line 504, and is annotated where it intersects the X-axis for the control variable as the "performance threshold".

[0065] In the example shown in Figure 5, the value of the control variable corresponding to the performance threshold is lower than the value of the limit setting for the control variable (corresponding to optimum operation). When the control variable is a compressor speed parameter, this effectively means that it is more efficient to operate at a compressor speed higher than is required to merely meet the performance threshold (e.g. a minimum rate of change of temperature). The dynamic control module 160 is configured to apply the limit setting as a limit to the operating range of the control variable (in particular a lower limit), and as such the dynamic control module 160 causes the limit setting for the control variable to be applied. The dynamic control module maintains the control variable at the limit setting despite being biased to target the performance threshold, since this bias would only drive the control variable to a lower value and is therefore prevented by the limit setting (e.g. as applied by a lower saturation limit in a PI or PID controller).

[0066] In a contrasting example shown in Figure 6, the same COP and cooling capacity lines are shown, but the performance threshold is higher such that the first point 610 where the cooling capacity line 504 intersects the performance threshold 630 corresponds to a value for the control variable which is higher than the limit setting (corresponding to optimum performance). The dynamic control module still applies the limit setting as a limit to the operating range of the control variable (in particular a lower limit), but is free to adjust to higher values of the control variable in order to target the performance thresh-

old. For example, the dynamic control module may be adjusted in a range above the limit setting until a value is found which causes performance at the performance threshold (e.g. at a minimum threshold cooling capacity).

[0067] These contrasting examples are schematically illustrated in **Figure 7**, which schematically shows a range of values for the control variable as a horizontal line, with various settings for the control variable indicated along the range. In example (A), the performance setting corresponding to the performance threshold (e.g. a minimum cooling rate) is lower than the limit setting corresponding to optimum performance. The dynamic control module applies the limit setting as a lower limit to the operational range, effectively constraining the refrigeration circuit to be operated with the limit setting for the control variable. In example (B) the performance setting corresponding to the performance threshold is higher than the limit setting corresponding to optimum performance, and is therefore within the operating range bounded by the limit setting. The dynamic control module therefore adjusts the value of the control variable towards the performance setting.

[0068] **Figure 8** schematically shows a flow diagram of a method 800 of controlling a refrigeration circuit, to vary a control variable of the refrigeration circuit during operation of the refrigeration circuit. It will be described, by way of example only, with reference to the controller 100 and refrigeration circuit 10 described above with respect to Figures 1-4.

[0069] In block 802, the controller monitors prevailing conditions of the refrigeration circuit, for example a space temperature of a temperature-controlled space associated with the refrigeration circuit, and optionally one or more further operating conditions as described above.

[0070] In block 804, a simulation module of the controller determines a limit setting for a control variable of the refrigeration circuit. The simulation module conducts an iterative optimisation procedure to determine the limit setting. The iterative optimisation procedure is defined based on an objective function which relates to an operating efficiency of the refrigeration circuit. The objective function is determined based on evaluating a model and is determined by evaluating a model for the refrigeration circuit at a respective simulated operating point (i.e. an operating point which varies according to iterative variation of the control variable). The simulated operating point is defined by a monitored set of prevailing conditions, and by a simulated setting for the control variable.

[0071] As shown in **Figure 8**, the determined limit setting 805 resulting from the optimisation procedure is stored, for example in a memory of the controller.

[0072] In block 806, the dynamic control module of the controller monitors a performance parameter, for example relating to a rate of change of the temperature-controlled space, or a monitored cooling capacity of the system. In block 808, the dynamic control module adjusts an operating setting of the control variable (i.e. a setting that is applied to the refrigeration circuit, rather than

merely simulated) within an operating range, to target a performance threshold 807 (e.g. a predetermined performance threshold stored in a memory of the controller) for the monitored performance parameter. The limit setting received from the simulation module is applied as a limit to the operating range, for example as described above.

[0073] Figure 9 schematically shows a machine-readable medium 900 comprising instructions 902. The instructions are defined so that, when executed by a compressor 904, they cause performance of a method as described herein, for example as described with reference to Figure 8, and/or with reference to any of Figures 1-7.

Claims

1. A controller (100) for a refrigeration circuit (10);

wherein the controller (100) is configured to monitor a set of prevailing conditions (50) relating to the refrigeration circuit including a space temperature of a temperature-controlled space associated with the refrigeration circuit; wherein the controller has a simulation module (102) configured to determine a limit setting (152) of a control variable for the refrigeration circuit by an iterative optimisation procedure based on a model (110) corresponding to the refrigeration circuit;

wherein the iterative optimisation procedure is defined based on an objective function which relates to an operating efficiency (120) of the refrigeration circuit and is determined based on evaluating the model for a respective simulated operating point; wherein the simulated operating point is defined by the monitored set of prevailing conditions (50), and by a simulated setting (150) for the control variable which is iteratively varied in the optimisation procedure, and

wherein the controller further comprises a dynamic control module (160) configured to:

adjust an operating setting of the control variable within an operating range to target a performance threshold for a monitored performance parameter, based on monitoring of the performance parameter during operation of the refrigeration circuit; apply the limit setting received from the simulation module as a limit to the operating range.

2. A controller according to claim 1, wherein the dy-

namic control module is configured to adjust the operating setting of the control variable during operation of the refrigeration circuit, based on concurrent monitoring of the performance parameter during operation of the refrigeration circuit.

3. A controller according to claim 1 or 2, wherein the model does not determine the performance parameter.

4. A controller according to any preceding claim, wherein the objective function is a coefficient of performance.

5. A controller according to claim 4, wherein the coefficient of performance is determined based on a simulated heat transfer capacity and a corresponding simulated power consumption, each determined based on the model.

6. A controller according to any preceding claim, wherein the monitored performance parameter is a rate of change of a monitored condition relating to the refrigeration circuit.

7. A controller according to any preceding claim, wherein the targeted performance threshold for the monitored performance parameter is selected from the group consisting of:

a heat transfer parameter relating to a heat transfer capacity of the refrigeration circuit, for example:

a predetermined minimum heat transfer capacity of the refrigeration circuit; or
a predetermined minimum magnitude of a monitored rate of change of a space temperature of the temperature-controlled space;

a predetermined minimum refrigerant superheat at a superheat monitoring location along a suction line of the refrigeration circuit.

8. A controller according to any preceding claim, wherein the dynamic control module comprises a PI or PID control module configured to control the control variable of the refrigeration circuit during operation of the refrigeration circuit;

wherein the PI or PID control module is configured to vary the control variable based on an error signal relating to a difference between the performance threshold and the monitored performance parameter; and

wherein the limit setting for the control variable is applied as saturation limit of the PI or PID con-

troller.

9. A controller according to claim 8, wherein the target-
ed performance threshold for the monitored perform-
ance parameter is a predetermined minimum mag-
nitude of a monitored rate of change of the space
temperature; and
wherein the PI or PID control module:

is configured to control an operating parameter of
the compressor as the control variable;
is configured to determine the error signal as the
difference between the predetermined minimum
magnitude of the rate of change of the space
temperature and a monitored rate of change of
the space temperature.
10. A controller according to claim 6 and optionally any
of claims 7-9, wherein the model is configured to
determine the simulated power consumption based
on one or more of:

an operating parameter of the compressor, as
the control variable or derived from the set of
prevailing conditions;
an operating parameter of a first fan associated
with the first heat exchanger, as the control var-
iable or derived from the set of prevailing con-
ditions; and/or
an operating parameter of a second fan associ-
ated with the second heat exchanger, as the
control variable or derived from the set of pre-
vailing conditions.
11. A controller according to any preceding claim, con-
figured to repeatedly conduct the optimisation pro-
cedure and update the limit setting; optionally where-
in the controller is configured to:

repeat the optimisation procedure at predeter-
mined intervals; and/or
repeat the optimisation procedure based on de-
termining a threshold change or rate of change
of a prevailing condition of the set of prevailing
conditions.
12. A controller according to any preceding claim,
wherein the simulation module is configured to de-
termine a limit setting of a plurality of control variables
for the refrigeration circuit by the iterative optimisa-
tion procedure;

wherein the simulated operating point is defined
by the monitored set of prevailing conditions and
by respective simulation settings for the plurality
of control variables;
wherein for each control variable, the simulation
control module is configured to determine a re-

spective limit setting by the optimisation proce-
dure;

wherein the dynamic control module is config-
ured to adjust each respective operating setting
of the control variables within respective oper-
ating ranges to target the performance threshold
for the monitored performance parameter, and
to apply each respective limit setting received
from the simulation module as a limit to the re-
spective operating ranges.

13. A refrigeration circuit (10) comprising a compressor
(12), a first heat exchanger (14), an expansion de-
vice (16), a second heat exchanger (18) and a con-
troller (100);
wherein the controller (100) is in accordance with
any preceding claim.
14. A method of controlling a refrigeration circuit using
a controller according to any preceding claim, where-
in a control variable of the refrigeration circuit is var-
iable during operation of the refrigeration circuit, the
method comprising:

monitoring a set of prevailing conditions relating
to the refrigeration circuit, including a space tem-
perature of a temperature-controlled space as-
sociated with the refrigeration circuit;
the simulation module conducting the iterative
optimisation procedure to determine a limit set-
ting of a control variable for the refrigeration cir-
cuit;
applying the limit setting as a limit to an operating
range for the control variable;
monitoring a performance parameter for the re-
frigeration circuit during operation of the refrig-
eration circuit;
the dynamic control module adjusting an oper-
ating setting of the control variable within the
operating range to target a performance thresh-
old for the monitored performance parameter;
whereby the dynamic control module biases op-
eration of the refrigeration circuit to the limit set-
ting of the control variable determined by the
optimisation procedure when the limit setting
corresponds to compliance with the perform-
ance threshold during operation of the refriger-
ation circuit; and
whereby the dynamic control module biases op-
eration of the refrigeration circuit to depart from
the limit setting of the control variable to achieve
the target performance threshold, when the limit
setting corresponds to non-compliance with the
performance threshold during operation of the
refrigeration circuit.
15. A non-transitory machine-readable medium com-
prising instructions that, when executed by a proc-

error, cause performance of a method in accordance with claim 14.

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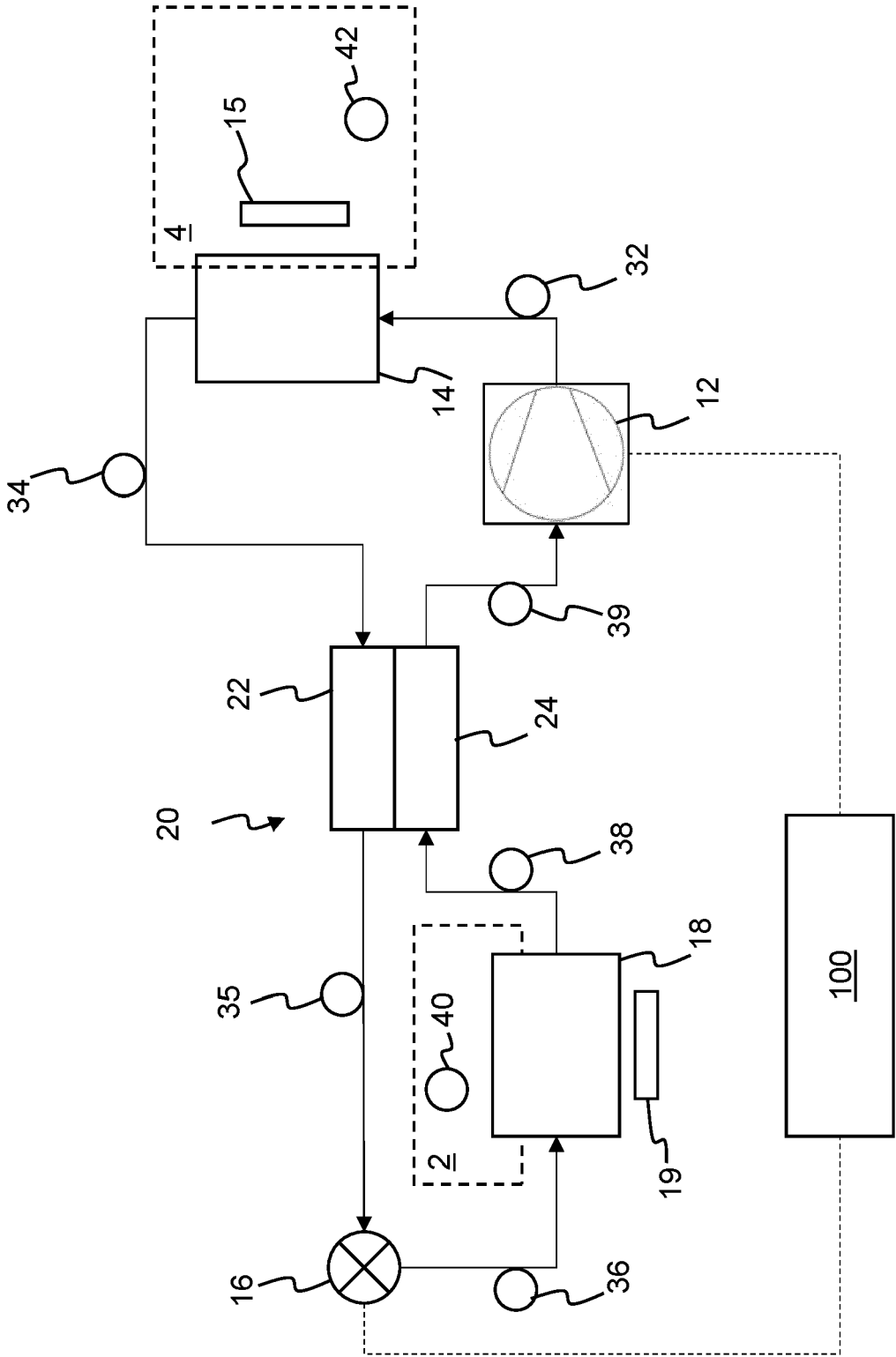


Figure 1

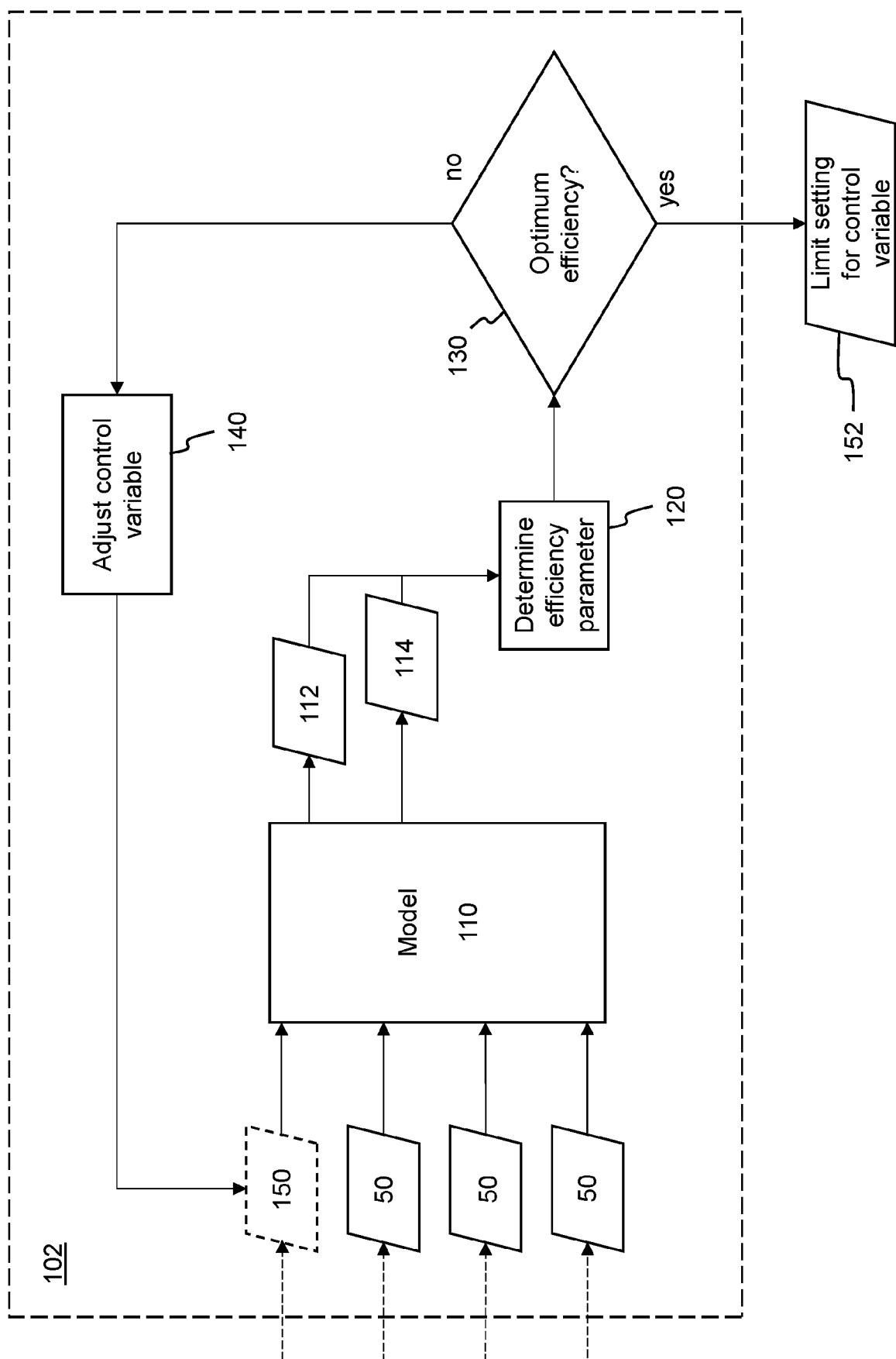


Figure 2

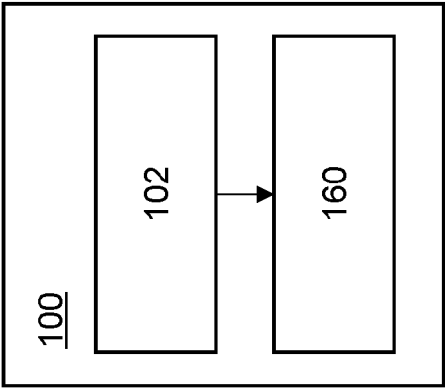


Figure 3

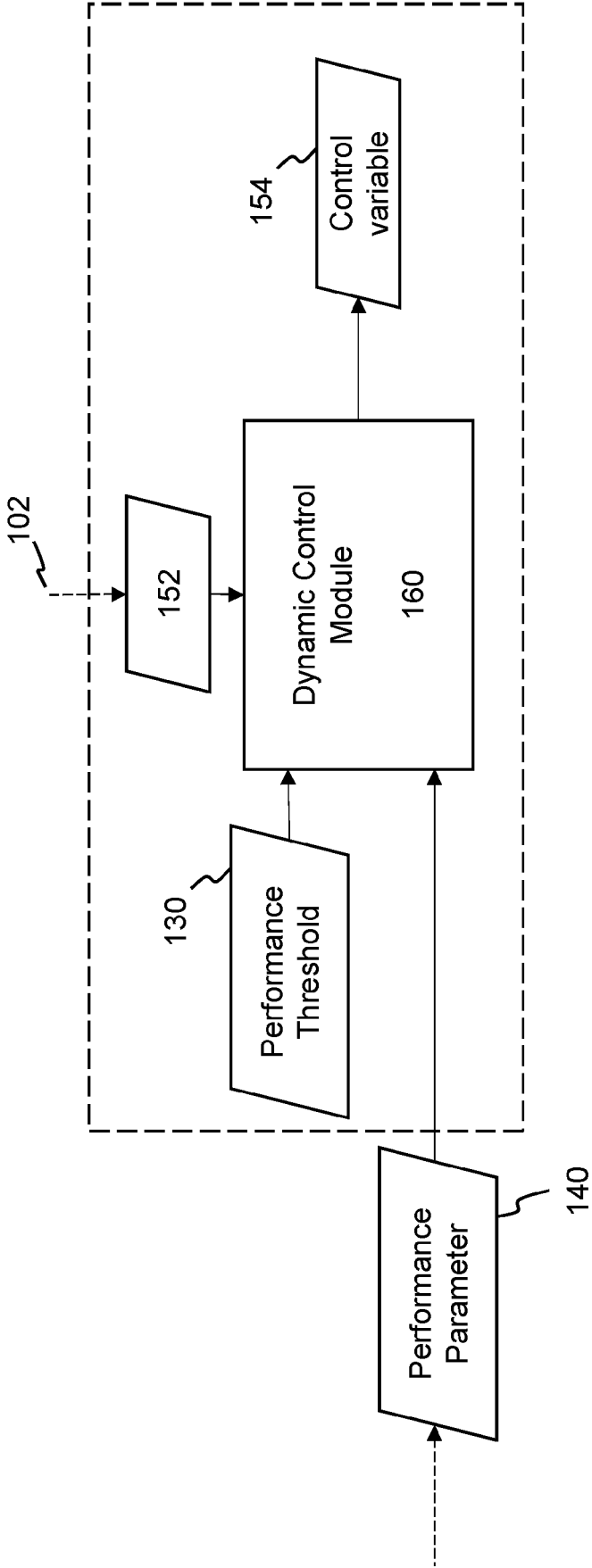


Figure 4

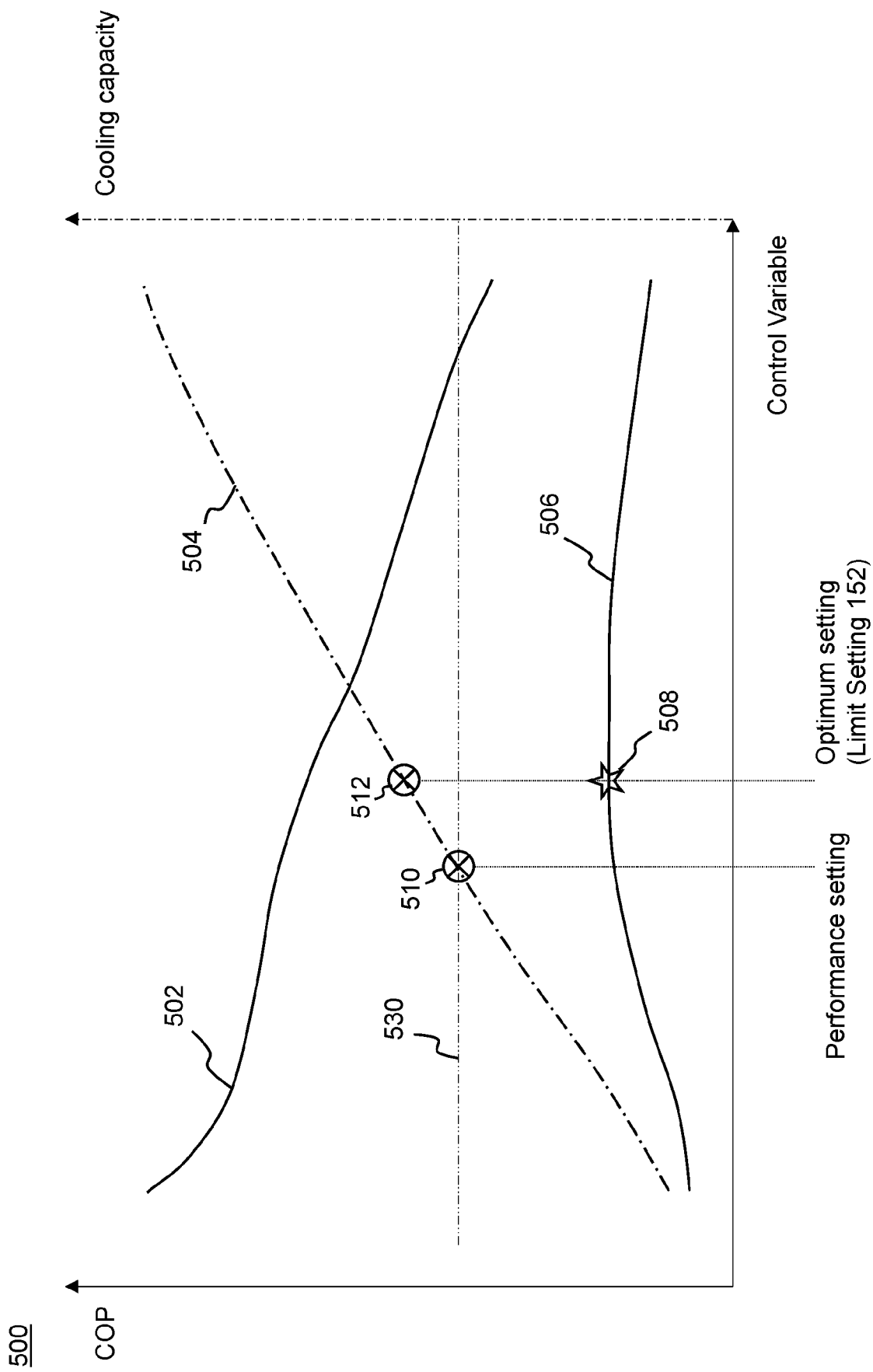


Figure 5

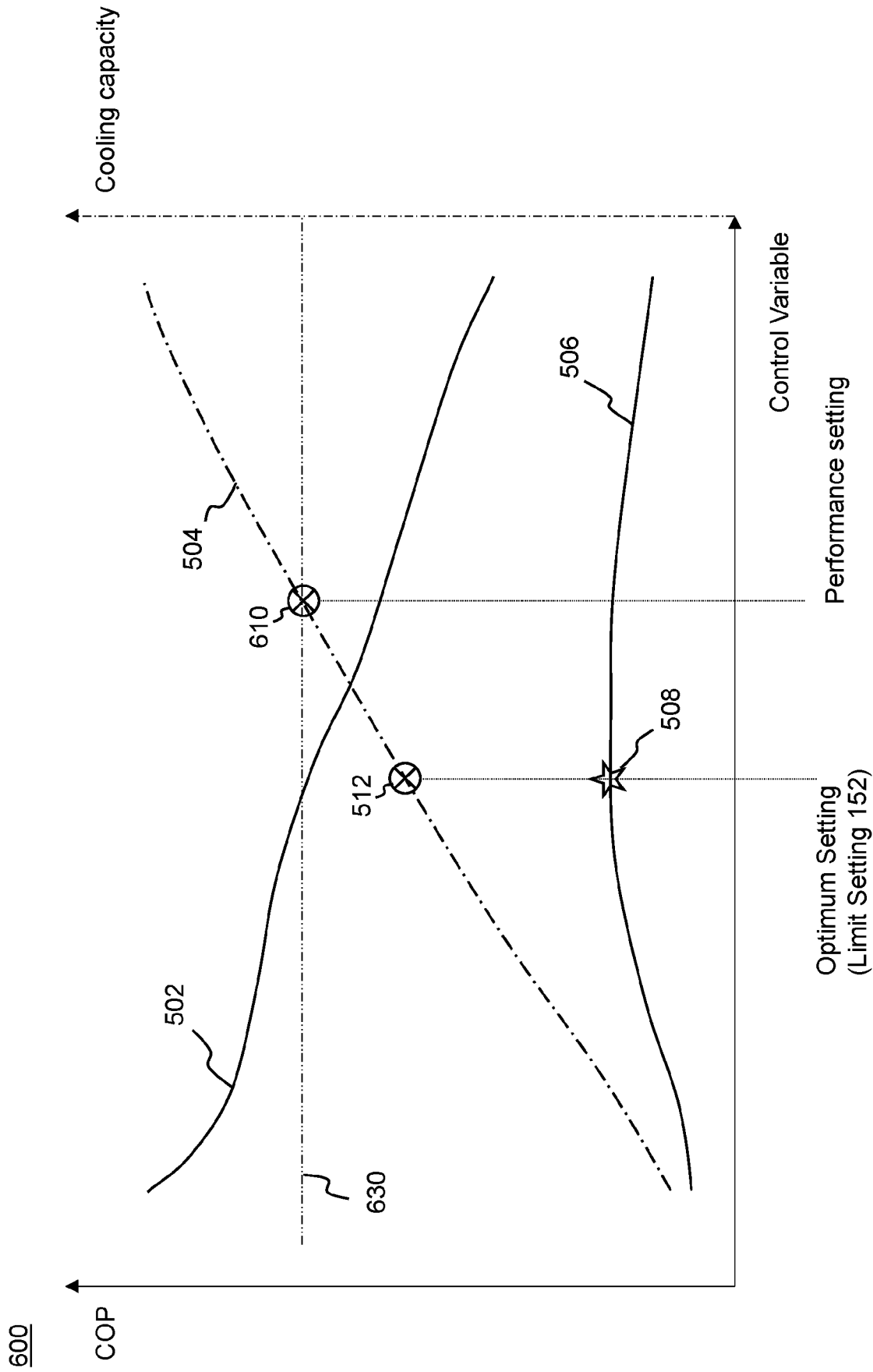


Figure 6

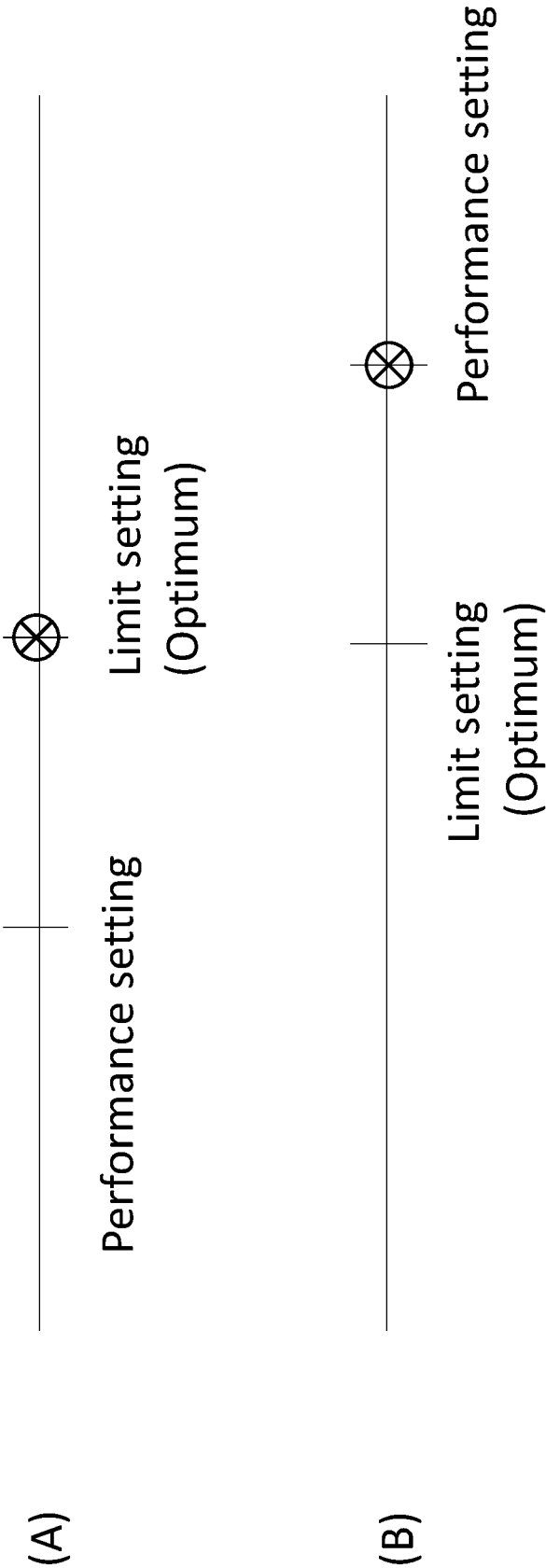


Figure 7

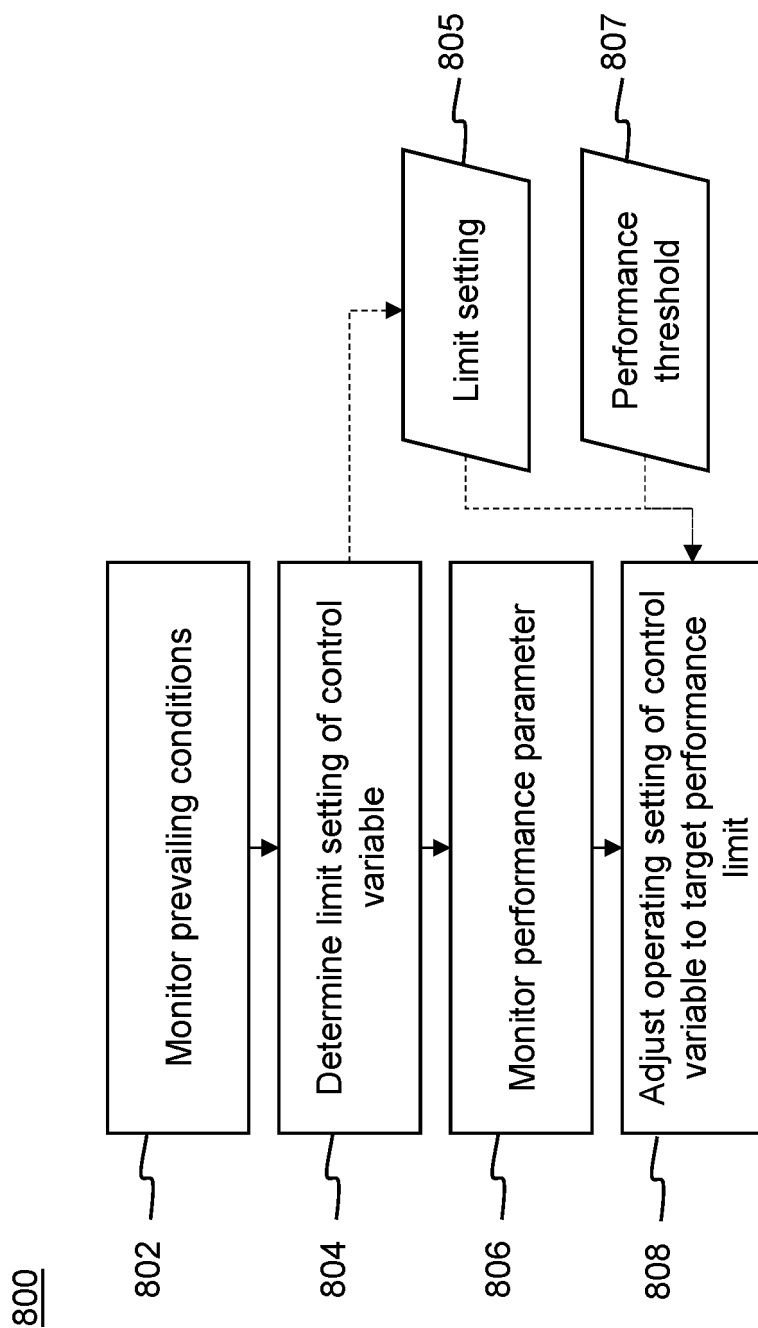


Figure 8

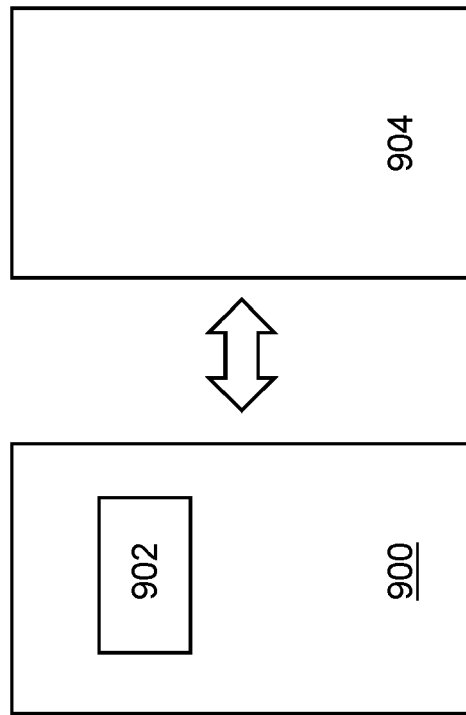


Figure 9



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Munich		10 August 2023	Gaspar, Ralf
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