

## A METHOD FOR DETECTING A REAL-TIME DEVIATION OF ENERGY EFFICIENCY IN AN HVAC PLANT

The application relates to a Heating, Ventilating, and Air  
5 Conditioning (HVAC) system for a building. In particular, the application relates to a method for detecting an anomaly in the energy efficiency of an HVAC plant of the HVAC system.

A water-cooled HVAC plant often includes chillers, water  
10 pumps, and cooling towers. After retrofitting and performance improvement works have been done, the HVAC plant requires regular monitoring and maintenance works to be carried out for keeping the HVAC plant operating efficiently.

15 A reduction of the HVAC plant efficiency often precedes a breaking down of equipment. Therefore, monitoring the HVAC plant efficiency is a proactive step to detect any deviation from the normal operating efficiency so that corrective actions can be implemented timely to avoid equipment breakdown.

20 US 2011/0023503 A1 discloses a method for detecting performance characteristics of air conditioning equipment. The method includes, for the standard operational status for the air conditioning equipment, capturing a plurality of standard operational parameters to generate performance models, and dur-  
25 ing the actual operational status, capturing a plurality of actual operational parameters for conducting analysis based on performance models to determine the performance characteristics of the air conditioning equipment and send out a warning  
30 when the performance characteristics of the air conditioning equipment are determined to be abnormal. The method improves the detection accuracy of prior techniques and enables effective control of air conditioning equipment that eventually saves electrical power and costs as a result.

It is an object of the application to provide an improved method for detecting an anomaly in the energy efficiency of an HVAC plant.

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The application provides an improved method for generating a model for determining a baseline energy efficiency of a Heating, Ventilating, and Air Conditioning (HVAC) unit. The HVAC unit is intended for adjusting the temperature of climate-controlled spaces inside a building. The building can refer to a structure, such as a house, with a roof and walls.

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The HVAC unit often comprises a chilled water loop, a cooling tower loop, and a chiller assembly comprising one or more chillers.

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The chilled water loop includes one or more electric chilled water pumps. The electric chilled water pump acts to move chilled water such that the chilled water circulates in the chilled water loop.

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Similarly, the cooling tower loop includes at least one cooling tower. The cooling tower comprises at least one electric condenser water pump. The electric condenser water pump acts to move condenser water such that the condenser water circulates in the cooling tower loop. The cooling tower loop is also called a condenser water loop.

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The chiller assembly interconnects with the chilled water loop and with the cooling tower loop for transferring heat from the chilled water in the chilled water loop to the condenser water in the cooling tower loop via refrigerant.

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The chillers and the electric pumps provide the required electrical power for adjusting the temperature of climate-controlled spaces at an operational energy efficiency. The operational efficiency can vary according to the load conditions.

5 At different load conditions, there is a desired operational energy efficiency to be achieved and maintained. This desired operational energy efficiency is also referred to as a baseline energy efficiency of the HVAC unit that is operating in a steady state.

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The method includes a step of receiving a plurality of sets of training measurement values of operational parameters of the HVAC unit. These training measurement values of the operational parameters have often been captured from a plurality of  
15 sensors of the HVAC unit in the past. The HVAC unit can operate under different environmental conditions and load conditions. The environmental conditions can include changing weather, days, and nights. The load conditions can include a high load condition when all the chillers operate together at  
20 the same time or a low load condition when some of the chillers stop operating. A set of the operational parameters is often captured within a short time interval. This set of operational parameters refers to the operating conditions of the HVAC unit at a certain time interval of an operation period.

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The set of the operational parameters includes multiple consumed electrical powers of a plurality of chillers of the chiller assembly, a temperature of chilled water being supplied from the chiller assembly (CHWS\_T), a temperature of the  
30 chilled water being returned to the chiller assembly (CHWR\_T), and a flow rate of the chilled water (CHW\_F) in a chilled water loop of the HVAC unit.

In the next step, a controller computes a value of a plant energy efficiency for each set of the operational parameters.

The computed value of the plant efficiency refers to a ratio of a total electrical power of the chiller assembly to a total cooling load (RT) of the HVAC unit.

The total electrical power of the chiller assembly provides an indication of the rate of the total energy provided by the chillers. It refers to a sum of training measurement values of the powers of the chillers of the chiller assembly.

The total cooling load provides an indication of the rate at which heat needs to be removed from spaces inside a building to maintain a desired ambient air temperature and humidity within the spaces. It refers to a product of a constant value of 1.2, a difference between a training measurement value of the temperature of the chilled water being supplied from the chiller assembly (CHWS\_T) and a training measurement value of the temperature of the chilled water being returned to the chiller assembly (CHWR\_T), and a training measurement value of the flow rate of the chilled water (CHW\_F) in the chilled water loop of the HVAC unit.

The method further includes a step of the controller performing a correlation analysis between the computed plant energy efficiency and the operational parameters to determine a correlation coefficient of each operational parameter. This correlation analysis aims to identify important or dominant operational parameters that have major influences on plant efficiency greatly.

The correlation analysis intends to measure the strength of association between the plant efficiency and each of the operational parameters. The strength of association refers to the

amount of change in the value of the plant efficiency when the value of each operational parameter changes. The analysis acts to determine the correlation coefficients of the operational parameters. The correlation coefficient of an operation parameter indicates the strength of association between this operational parameter and the plant efficiency. The higher the absolute value of the correlation coefficient, the greater is the change in the value of the plant efficiency when the value of the operational parameter changes. In other words, a large proportion of the variation in the plant energy efficiency is associated with the variation of the operational parameter having a large absolute value of the correlation coefficient.

A group of operational parameters is then selected. The correlation coefficient of each selected operational parameter is larger than a predetermined selection value. These selected operational parameters have a high influence on the value of the plant energy efficiency. The selected operational parameters consist of consumed electrical powers of the chillers of the chiller assembly, the temperature of the chilled water being supplied from the chiller assembly (CHWS\_T), the temperature of the chilled water being returned to the chiller assembly (CHWR\_T), and the flow rate of the chilled water (CHW\_F) in the chilled water loop.

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The method further includes a step of providing a plurality of training data sets for the training of a predictive model. The predictive model often refers to a model that is adapted to generate predictions by finding patterns from the training data. The predictive model can comprise a machine learning algorithm. Each training data set comprises the training measurement values of the selected operational parameters and the corresponding computed value of the plant energy efficiency. Before the training, the training data sets are examined to

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remove data sets that contain abnormal data. Abnormal data can refer to the training values of the selected operational parameter of the HVAC unit that operates in transient mode. Abnormal data can also happen if a corresponding sensor is covered by an object, such as a bird sitting on the sensor. The training data sets with normal data are later used for the training of the model.

During the training of the predictive model based on the training data sets, the machine learning algorithm of the model learns from the training data such that the algorithm finds and determines relationships between the training measurement values of the selected operational parameters and the computed values of the plant efficiency. Put differently, the trained model has determined or established relationships between the training measurement values of the selected operational parameters and the corresponding computed value of the plant efficiency. The established relationships enable the trained model to provide an estimated baseline efficiency according to the training measurement values of the selected operational parameters. In other words, the trained model is also adapted to provide a baseline efficiency according to new operational measurement values of the selected operational parameters.

This improved method allows an accurate prediction model to be generated efficiently. This is because only measurement values of a few selected operational parameters are needed for the training of the model. This can be done within a short time. Furthermore, the prediction model can be used for real-time detection of an anomaly in the energy efficiency of the HVAC unit since the time needed to capture and transmit the measurement values of the few selected operational parameters for processing is short, often within less than a second.

The application also provides a method for detecting an anomaly in the energy efficiency of a Heating, Ventilating, and Air Conditioning (HVAC) unit in real-time. The anomaly in energy efficiency refers to the operational energy efficiency of the HVAC unit which deviates from the baseline energy efficiency of the HVAC unit by more than a desired margin or limit when the HVAC unit is operating at a certain load and environmental condition.

The detection method further includes a step of the sensors capturing in real time the operational measurement values of a plurality of the selected operational parameters of the HVAC unit that is operating. The selected operational parameters consist of electrical powers of a plurality of chillers of a chiller assembly of the HVAC unit, a temperature of chilled water being supplied from the chiller assembly (CHWS\_T), a temperature of the chilled water being returned to the chiller assembly (CHWR\_T), and a flow rate of the chilled water (CHW\_F) in a chilled water loop of the HVAC unit.

The controller then receives the operational measurement values of the selected operational parameters from the sensors and later computes a value of the operational efficiency of the HVAC unit. The value of the operational efficiency refers to a ratio of a sum of the operational measurement values of the electrical powers of the chillers to a total cooling load (RT) of the HVAC unit. The total cooling load refers to a product of a constant value, a difference between an operational measurement value of the temperature of the chilled water being supplied from the chiller assembly (CHWS\_T) and an operational measurement value of the temperature of the chilled water being returned to the chiller assembly (CHWR\_T), and an operational measurement value of the flow rate of the

chilled water (CHW\_F) in the chilled water loop of the HVAC unit.

The controller then generates an expected or estimated operational baseline energy efficiency of the HVAC unit according to the operational measurement values of the selected operational parameters based on a trained model that comprises a machine learning model. The trained model can be generated according to the model generating method mentioned above.

The controller later computes a difference between the estimated operational baseline efficiency and the computed value of the operational efficiency.

The controller afterward compares the absolute value of the difference to a predetermined deviation value and sends a warning signal if the absolute value of the difference is larger than the predetermined deviation value.

The improved detection method allows the energy efficiency of the HVAC unit to be monitored essentially in a continual manner to detect any anomaly in the energy efficiency quickly or almost instantly within a second. This is because measurements of only a few selected operational parameters are captured and processed. This can be done within a short time. The quick detection of the anomaly then acts to shorten the duration to restore a poor performance of the HVAC unit quickly and consequently saves electrical power and costs. Furthermore, the method improves detection accuracy regardless of the HVAC unit operating in different environmental and load conditions.

The selected operational parameters can further consist of a temperature of condenser water being supplied to the chiller assembly (CDWS\_T), a temperature of condenser water being re-

turned from the chiller assembly (DWR\_T), a flow rate of the condenser water (CDW\_F) in a cooling tower loop, a wet-bulb temperature, and a dry bulb temperature of the HVAC unit. Each of these additional selected operational parameters has a correlation coefficient that is smaller than the predetermined selection value but larger than a predetermined preferred value. These additional selected operational parameters act to further improve the prediction accuracy of the trained algorithm.

The trained model can be adapted to provide the baseline efficiency according to the configuration of the chillers. The configuration of the chillers can refer to the number of units of operating chillers and the number of units of non-operating chillers that are not required to operate due to, for example, a low cooling load. The configuration of the chillers can also refer to different combinations of the operating chillers and the non-operating chillers. The data sets used for the training of the model comprise measurement values of the powers of the chillers. A non-operating chiller has a power measurement value of zero while an operating chiller has a power measurement value of non-zero or greater than zero. A combination of one or more operating chillers and one or more non-operating chillers is represented by one or more non-zero values of the operating chillers, and one or more zero values of the non-operating chillers in the data set. The model is trained with the data sets such that the trained model has incorporated the combinations of the operating chillers and the non-operating chillers to provide the baseline efficiency accordingly. This means that the improved method can be adapted and applied easily to any HVAC plant with varying configurations of the chillers.

In one implementation, the machine learning algorithm refers to a regression tree algorithm. The trained model using the regression tree algorithm has been evaluated to have good prediction accuracy as described below in this application.

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The regression tree algorithm can refer to a random-forest algorithm. This algorithm has a high prediction accuracy and short training duration compared to other algorithms that are described below in this application.

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The predetermined deviation value for detecting an anomaly in the efficiency can be 10 percent. This deviation value has been statistically derived to avoid frequent occurrences of anomaly detections that are momentary.

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The method can further comprise the controller executing a fault detection and diagnostic algorithm to identify possible causes of the warning event. This can aid the investigation process to identify the root cause of the warning event,

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thereby restoring the efficiency of the HVAC unit quickly.

The method can further comprise the controller providing a remedial action plan or measures in response to the root cause identified.

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The application also provides a controller for operating an HVAC unit. The controller comprises interfaces for a plurality of sensors that are provided for capturing operational parameters of a chilled water loop, of a cooling tower loop, and a chiller assembly comprising a plurality of chillers of the HVAC unit. The controller is also adapted to issue signals to the interfaces for receiving the operational parameters of the HVAC unit and to automatically perform steps of the method

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mentioned above to detect an anomaly in the energy efficiency of the HVAC unit.

The chilled water loop can comprise at least one electric  
5 chilled water pump, which enables chilled water to be circulating in the chilled water loop.

The cooling tower loop can comprise at least one cooling tower with at least one electric condenser water pump. The electric  
10 condenser water pump enables condenser water to be circulating in the cooling tower loop.

The chiller can comprise a thermodynamic refrigeration cycle that interconnects with the chilled water loop and with the  
15 cooling tower loop such that heat is transferred from the chilled water to the condenser water.

The application further provides an HVAC unit comprising the above-mentioned controller.

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- Fig. 1 illustrates an air cooling and circulating arrangement for a building that includes an energy control module for executing an improved method for detecting an anomaly in energy efficiency,
- 25 Fig. 2 illustrates parts of a chiller of the air cooling and circulating arrangement of Fig. 1,
- Fig. 3 illustrates a further air cooling and circulating arrangement, which is a variant of the air cooling and circulating arrangement of Fig. 1,
- 30 Fig. 4 illustrates another air cooling and circulating arrangement, which is a variant of the air cooling and circulating arrangement of Fig. 3,

- Fig. 5 illustrates a flow chart of a method for detecting an anomaly in the energy efficiency of the air cooling and circulating arrangement of Fig. 1,
- Fig. 6 illustrates a graph showing how the plant efficiency fluctuates with the cooling load of the air cooling and circulating arrangement of Fig. 1,
- Fig. 7 illustrates a plurality of operational parameters of the air cooling and circulating arrangement of Fig. 1,
- Fig. 8 illustrates a plurality of data sets used for training and testing a machine learning algorithm for estimating a chiller plant efficiency of the air cooling and circulating arrangement of Fig. 1, and
- Fig. 9 illustrates an evaluation result of the trained machine learning algorithm for estimating the chiller plant efficiency of the air cooling and circulating arrangement of Fig. 1.

In the following description, details are provided to describe embodiments of the application. It shall be apparent to one skilled in the art, however, that the embodiments may be practiced without such details.

Some embodiments have similar parts. The similar parts may have the same names or similar part reference numerals with an alphabet or prime symbol. The description of one similar part also applies by reference to another similar part, where appropriate, thereby reducing the repetition of text without limiting the disclosure.

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Fig. 1 shows an air cooling and circulating arrangement 10 for a building with an energy control module 16. The air cooling and circulating arrangement 10 is electrically connected to

the energy control module 16. The building is not shown in Fig. 1.

The air cooling and circulating arrangement 10 includes a Heating, Ventilating, and Air Conditioning (HVAC) plant 12 with an Air Handling Unit (AHU) 25 that is connected to the HVAC plant 12. The HVAC plant 12 includes a cooling tower 20 with an electric condenser water pump 22, an electric supply chilled water pump 27, an electric return chilled water pump 29, and a chiller 33. The supply chilled water pump 27 and the electric return chilled water pump 29 are respectively connected fluidically to the AHU 25. The cooling tower 20 includes one or more fans that are electrically driven. The fans are not shown in Fig. 1 for simplicity.

In detail, the cooling tower 20 is fluidically connected to the condenser water pump 22 by a condenser water pipe, which is fluidically connected to the chiller 33 by another condenser water pipe. The chiller 33 is fluidically connected to the cooling tower 20 by a further condenser water pipe. The water pump 22 circulates condensed water between the chiller 33 and the cooling tower 20.

The AHU 25 is fluidically connected to the supply chilled water pump 27 by a chilled water pipe. The supply chilled water pump 27 is fluidically connected to the chiller 33 by another chilled water pipe. The chiller 33 is fluidically connected to the return chilled water pump 29 by a further chilled water pipe. The return chilled water pump 29 is fluidically connected to the AHU 25 by another chilled water pipe. The supply chilled water pump 27 and the return chilled water pump 29 circulate chilled water between the AHU 25 and the chiller 33.

As can be seen in Fig. 2, the chiller 33 comprises a refrigerant compressor 40, an evaporator 43, a condenser 45, and an expansion valve 48.

- 5 The compressor 40, the evaporator 43, the condenser 45, and the expansion valve 48 are fluidically connected by a set of refrigerant pipes to form a refrigerant loop 49 that allows a refrigerant to circulate in a thermodynamic cycle.
- 10 The compressor 40 is fluidically connected to the condenser 45, which is fluidically connected to the expansion valve 48. The expansion valve 48 is fluidically connected to the evaporator 43. The evaporator 43 is fluidically connected to the compressor 40. The compressor 40, the condenser 45, the expansion valve 48, and the evaporator 43 contain a refrigerant, which can be in the form of a gas and/or liquid.
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As can be seen in Figs. 1 and 2, the chiller condenser 45 is fluidically connected to the condenser water pipes such that the cooling tower 20, the condenser water pump 22, and the chiller condenser 45 form a condenser water loop 50 that allows condenser water to circulate.

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The chiller evaporator 43 is fluidically connected to the chilled water pipes such that the AHU 25, the supply chilled water pump 27 with the return chilled water pump 29, and the chiller evaporator 43 form a chilled water loop 51 that allows chilled water to circulate.

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30 The supply chilled water pump 27 and the return chilled water pump 29 are adapted for circulating chilled water between the AHU 25 and the chiller evaporator 43.

The AHU 25 is intended for supplying and distributing the conditioned air to parts of the building and for returning the air to the AHU 25.

- 5 Referring to the energy control module 16, it includes a plurality of Variable Speed Drives (VSDs), a parameter measurement module 74 for measuring parameters of the air cooling and circulating arrangement 10, and a master controller (MC) 73. Only one VSD 52 is shown in Fig. 1. The MC 73 is electrically  
10 connected to the VSDs 52 and to the parameter measurement module 74.

The MC 73 is electrically connected to the VSDs 52, which are respectively connected to an electric motor of the water  
15 pumps, of the cooling towers, of the AHUs, and of the compressors of the air cooling and circulating arrangement 10. The VSD 52 is configured to change the speed of the electric motor.

- 20 The MC 73 is also electrically connected to sensors of the air cooling and circulating arrangement 10. The connection lines between the MC 73 and the sensors are not shown in Fig. 1 for simplicity.

- 25 The sensors include temperature sensors, power meters, and flow meters. These sensors are connected to the parts of the air cooling and circulating arrangement 10 for measuring the operational parameters of the parts. The operational parameter measurements provide indications of operating conditions of  
30 the parts of the air cooling and circulating arrangement 10, which include the cooling tower 30, the condenser water pump 22, the AHU 25, the supply chilled water pump 27, the return chilled water pump 29, and the chiller 33. The parts of the

air cooling and circulating arrangement 10 also include the condenser water loop 50 and the chilled water loop 51.

Referring to the temperature sensors, a temperature sensor 60 is provided to measure the temperature of the condenser water being supplied to the chiller 33. Another temperature sensor 60a is provided to measure the temperature of the condenser water being returned from the chiller 33. The condenser water is flowing out of the chiller 33.

Similarly, a temperature sensor 61 is provided to measure the temperature of the chilled water being supplied from the chiller 33. Another temperature sensor 61a is provided to measure the temperature of the chilled water being returned to the chiller 33.

Referring to the power meters, power meters 53 are installed on each cooling tower, each chiller, and each AHU for measuring the electrical power consumption of each of these parts. For simplicity, the power meters 53 are not shown in the figures.

Referring to the flow meters, a flow meter 70 is provided to measure the flow rate of the condenser water pump 22. In effect, this flow meter 70 is adapted for measuring the rate of flow of fluid in the condenser water loop 50. Another flow meter 71 is provided to measure the flow rate of the supply chilled water pump 27 or the flow rate of the return chilled water pump 29. In effect, this flow meter 71 is adapted for measuring the rate of flow of fluid in the chilled water loop 51.

In a general sense, the air cooling and circulating arrangement 10 can also include more than one supply chilled water

pump 27, or more than one return chilled water pump 29, or more than one condenser water pump 22, or more than one chiller 33, or more than one cooling tower 20, as shown in Figs. 3 and 4.

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If more than one supply chilled water pump 27 is provided, the supply chilled water pumps 27 can be fluidically connected in parallel, wherein each supply chilled water pump 27 is activated and be deactivated by the MC 73.

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Similarly, if more than one return chilled water pump 29 is provided, the return chilled water pumps 29 can be connected in parallel, wherein each return chilled water pump 29 can be activated and be deactivated by the MC 73.

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If more than one condenser water pump 22 is provided, the condenser water pumps 22 can be connected in parallel, wherein each condenser water pump 22 can be activated and be deactivated by the MC 73.

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If more than one cooling tower 20 is provided, the cooling towers 20 can be connected in parallel, wherein each cooling tower 20 can be activated and be deactivated by the MC 73.

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If more than one chiller 33 is provided, the chillers 33 can be connected in parallel to form a chiller assembly 32, wherein each chiller 33 can be activated and be deactivated by the MC 73.

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In use, the air cooling and circulating arrangement 10 is used for adjusting the temperature of climate-controlled spaces of a building.

The energy control module 16 commands the respective VSD 52 to change the speed of the respective electric motors of the respective parts of the air cooling and circulating arrangement 10 for changing the energy consumption of the air cooling and circulating arrangement 10 while maintaining the user desired comfortable temperature of the controlled spaces. The electric motor is often used in water pumps, cooling towers, AHUs, and compressors of chillers.

10 Regarding the chilled water loop 51, the chilled water absorbs heat energy from the AHU 25 and transfers this heat energy to the chiller 33.

Regarding the refrigerant loop 49, the chiller 33 acts to  
15 transfer heat energy from the chilled water to the condenser water of the condenser water loop 50, wherein said chilled water and said condenser water flow through the chiller 33.

Regarding the condenser water loop 50, it transfers heat energy from the chiller 33 to the cooling tower 20. The cooling  
20 tower 20 acts to expel the heat energy in the condenser water, which flows through the cooling tower 20, to an outside space.

Fig. 5 shows a flow chart 80 of a method for detecting an  
25 anomaly in the energy efficiency of the HVAC plant 12 of the air cooling and circulating arrangement 10, wherein the HVAC plant 12 comprises at least one cooling tower 20, at least one condenser water pump 22, at least one supply chilled water pump 27, at least one return chilled water pump 29, and a  
30 chiller assembly 32 comprising a plurality of chillers 33 that are arranged in parallel as shown in Fig. 4.

The method includes a training phase and an operational phase.

The training phase aims to identify and select operational parameters of the HVAC plant 12 that are highly correlated to the energy efficiency of the HVAC plant 12. The training phase also aims to generate a model for determining the baseline energy efficiency of the HVAC plant 12 according to the measurement values of the selected operational parameters.

In the training phase, the method includes a step 83 of providing a plurality of measurement values of operational parameters of the HVAC plant 12, wherein the measurement values of the operational parameters have been captured by multiple sensors of the HVAC plant 12 over a period. This period often refers to a duration in which the HVAC plant 12 operates in a normal or stable condition. In this period, the HVAC plant 12 can operate under different environmental conditions, for example, in hot and cold weather, or on days and nights. The HVAC plant 12 can also operate under different load conditions. In some parts of the period, all the chillers 33 operate at the same time when the total cooling load of the HVAC plant 12 is high. In another part of the period, some of the chillers 33 stop operating when the total cooling load is low when some chillers 33 are shut down.

The measurement values of the operational parameters captured within a short interval are arranged as a set. The values of the operational parameters indicate the operating conditions of the parts of the HVAC plant 12 within this short interval. A sample of the data sets is shown in Fig. 8. The set of the operational parameters can include consumed electrical powers (KW) of the multiple chillers 33, a temperature of the chilled water being supplied from the chiller assembly 32 (CHWS\_T), a temperature of the chilled water being returned to the chiller assembly 32 (CHWR\_T), a flow rate of the chilled water (CHW\_F) in the chilled water loop 51. The operational parameters can

further include a temperature of the condenser water being supplied to the chiller assembly 32 (CDWS\_T), a temperature of the condenser water being returned from the chiller assembly 32 (DWR\_T), a flow rate of the condenser water (CDW\_F) in the condenser water loop 50, a wet-bulb temperature, and a dry bulb temperature of the HVAC plant 12.

In a next step 85, a value of a plant energy efficiency is computed for each set of the operational parameters. The value of the plant efficiency refers to a ratio of a value of the total consumed electrical power of the chiller assembly 32 to a value of the total cooling load (RT) of the HVAC plant 12.

The total electrical power of the chiller assembly 32 indicates the rate of the total energy that the chillers 33 provide to the HVAC plant 12. It refers to a sum of values of the electrical powers of the chillers 33.

The cooling load (RT) indicates the rate at which heat needs to be removed from building spaces to maintain an essentially constant ambient air temperature and humidity within the spaces. It refers to a product of a constant value of 1.2, a difference between a measurement value of the temperature of the chilled water being supplied from the chiller assembly 32 (CHWS\_T) and a measurement value of the temperature of the chilled water being returned to the chiller assembly 32 (CHWR\_T), and a flow rate of the chilled water (CHW\_F) in the chilled water loop 51 of the HVAC plant 12. The cooling load can be represented according to the below equation:

$$RT = 1.2 \times (CHWR\_T - CHWS\_T) \times CHW\_F.$$

Fig. 6 shows a graph illustrating how the plant energy efficiency fluctuates with the cooling load for a HVAC plant.

Both the plant efficiency and the cooling load are influenced by the operating conditions of the HVAC plant. The operating conditions are indicated by the measurement values of the operational parameters. Examples of close to a hundred operational parameters are shown in Fig. 7.

The method further includes an analysis of the relationships between the plant efficiency and the operational parameters to identify important or dominant operational parameters that influence the plant efficiency greatly compared with the other operational parameters.

In detail, in a subsequent step 86, a correlation analysis between the plant efficiency and the operational parameters is performed. The correlation analysis aims to measure the strength of association between the plant efficiency and each of the operational parameters. The strength of association refers to the amount of change in the value of the plant efficiency when the value of each operational parameter changes. This analysis is done using a statistical method such as Pearson's Correlation Coefficient algorithm to determine the correlation coefficients of the operational parameters. The correlation coefficient of an operation parameter indicates the strength of association between this operational parameter and the plant efficiency. The higher the absolute value of the correlation coefficient, the greater the change in the value of the plant efficiency when the value of the operational parameter changes. In other words, a large proportion of the variation in the plant energy efficiency is associated with the variation of the operational parameter having a large absolute value of the correlation coefficient.

The correlation analysis is performed using the Pearson's Correlation Coefficient algorithm to find the values of the cor-

relation coefficients. The operational parameters are then grouped into a high correlation group, a medium correlation group, and a low correlation group according to the absolute values of their correlation coefficients.

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The high correlation group includes operational parameters that have correlation coefficients with absolute values larger than a predetermined high limit. This group includes the electrical powers of the different chillers 33, the temperature of the chilled water being supplied from the chiller assembly 32 (CHWS\_T), the temperature of the chilled water being returned to the chiller assembly 32 (CHWR\_T), and the flow rate of the chilled water (CHW\_F). This group is also called the first predictor group, which has a high influence on the value of the plant energy efficiency.

The medium correlation group includes operational parameters that have correlation coefficients with absolute values smaller than the predetermined high limit but larger than a predetermined low limit. This group includes a temperature of the condenser water being supplied to the chiller assembly 32 (CDWS\_T), a temperature of the condenser water being returned from the chiller assembly 32 (DWR\_T), a flow rate of the condenser water (CDW\_F) in the condenser water loop 50, a wet-bulb temperature, and a dry bulb temperature of the HVAC plant 12. This group is also called the second predictor group, which has a lesser influence on the plant energy efficiency value than the first predictor group.

The low correlation group includes operational parameters that have correlation coefficients with absolute values smaller than a predetermined low limit. The other operational parameters are in this group, which has little influence on the value of the plant energy efficiency.

The correlation analysis for different HVAC plants shows that the operational parameters of the first predictor group are the same for each HVAC plant. Similarly, the operational parameters of the second predictor group are also the same for each HVAC plant.

In next step 86, the operational parameters of the first predictor group are selected for the training of a model that includes a multi-variate machine learning algorithm.

The training of the model is performed in step 89. The training is done with a plurality of training data sets. A sample of the training data sets is shown in Fig. 8. Each training data set includes measurement values of the selected operational parameters and a corresponding value of the plant energy efficiency.

In particular, the measurement values of the powers of the chillers 33 indicate the configuration of the chiller assembly 32. The configuration of the chiller assembly 32 can refer to the number of units of operating chillers 33 and the number of units of non-operating chillers 33. The chillers 33 that are not required to operate can be due to, for example, a low loading condition. The configuration of the chillers can also refer to different combinations of the operating chillers and different combinations of the non-operating chillers. In each data set, each non-operating chiller 33 has a power measurement value of zero while each operating chiller 33 has a power measurement value of non-zero or greater than zero. In other words, a combination of one or more operating chillers 33 and one or more non-operating chillers 33 is represented by one or more non-zero values of the operating chillers 33, and one or

more zero values of the non-operating chillers 33 in the data set.

Before the training of the model, each training data set is  
5 examined for abnormality. Data sets with abnormal values are discarded. Abnormal data can be caused by the HVAC plant operating in transient periods, a sensor covered by an object, such as a bird sitting on the sensor, a chiller operating at an inefficient part-load, and a degraded part of the HVAC plant.  
10 Only data sets with normal data are used for the training of the model. Normal data indicates that the HVAC plant is well maintained and operates in a stable condition.

During the training of the model, the algorithm learns from  
15 the training data to find and determine relationships between the measurement values of the selected operational parameters and the values of the plant efficiency. The determined relationships enable the trained model to provide a value of baseline plant efficiency of the HVAC plant 12 corresponding to  
20 measurement values of the selected operational parameters.

The trained model is later evaluated with a plurality of testing data sets. The testing data sets are similar to the training data sets, wherein measurement values of the operational  
25 parameters of both data sets are captured and collected from the same period. A sample of the testing data sets is shown in Fig. 8. The evaluation aims to assess the accuracy of the baseline efficiency predicted by the trained model. This is done by comparing the estimated values of the energy efficiency  
30 provided by the trained model to the computed values of the energy efficiency according to the values of the operational parameters of the testing data sets.

Fig. 9 shows a summary of the evaluation results of trained models comprising a random-forest algorithm, a neural network algorithm, a boosted-tree regressor algorithm, and a linear regression algorithm.

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The evaluation criteria include a mean absolute error, a root mean squared error, a relative squared error, a relative absolute error, and a coefficient of determination. The mean absolute error, the root mean squared error, the relative squared error, and the relative absolute error indicates the magnitude of difference between the predicted value of the plant baseline energy efficiency and the computed or measured value of the plant energy efficiency. The smaller the values of these evaluation criteria, the closer the predicted values are to the measured values. The coefficient of determination indicates the proportion of the variation in the plant energy efficiency that can be predicted from the selected operational parameters. The larger the values of the coefficient of determination, the closer the predicted values are to the measured values.

20

Both the models using the random forest algorithm and the boosted-tree regressor algorithm have the most accurate prediction accuracy. They also have a coefficient of determination of more than 90%, indicating that more than 90% of the variation in the plant energy efficiency can be predicted from the selected operational parameters. Both these algorithms use regression tree methods.

25

Compared to the random-forest algorithm, the boosted-tree regressor algorithm has a longer training duration, which is about one-third longer. Consequently, the random-forest algorithm is selected for implementation. The trained model is also called a prediction model.

30

The prediction model can then be used to provide the estimated baseline energy efficiency of the HVAC plant 12 according to new measurement values of the selected operational parameters  
5 in the operational phase.

In the operational phase, the method further includes a step 93 of the sensors capturing or measuring the selected operational parameters of the parts of the HVAC plant 12 that is  
10 operating. The sensors later transmit the measurement values of the selected operational parameters to the MC 73. The selected operational parameters consist of the electrical power of the multiple chillers 33, the temperature of the chilled water being supplied from the chiller assembly 32 (CHWS\_T),  
15 the temperature of the chilled water being returned to the chiller assembly 32 (CHWR\_T), and the flow rate of the chilled water (CHW\_F) in the chilled water loop 51.

The MC 73 then receives the values of the selected operational  
20 parameters and generates an expected or estimated baseline energy efficiency of the HVAC plant 12 according to the values of the selected operational parameters based on the prediction model, in step 96.

25 In subsequent step 99, the MC 73 computes a value of the operational energy efficiency of the HVAC plant 12 according to the values of the selected operational parameters.

The MC 73 afterward computes a difference between the operational energy efficiency and the estimated baseline energy efficiency,  
30 in step 103.

The MC 73 then compares the absolute value of the difference to a predetermined deviation value or threshold. The predeter-

mined deviation value can be 10 percent. If the difference is larger than the predetermined deviation value, the MC 73 sends an anomaly warning, for example, to an operator of the HVAC plant 12, in step 106.

5

At the same time, the MC 73 executes a fault detection and diagnostic algorithm to identify possible causes and/or the root cause of the warning event. The possible causes can include a chiller operating at an inefficient setpoint, a chiller operating at an inefficient part-load, equipment that is operating unnecessarily resulting in higher power consumption than necessary, interruption and inconsistency in sensor measurements, and degradation in machine efficiency and performance.

10

15 The fault detection and diagnostic algorithm can also provide a recommended remedial action plan or measures to the operator. The action plan can include no action required if the anomaly flag is momentary, which may be due to, for example, a transient operation or an interruption in sensor measurement.

20 The action plan can also include performing maintenance of faulty parts of the HVAC plant.

The MC 73 can also compute an estimated loss in energy efficiency during the warning event. The estimated energy loss is computed by aggregating the differences between the operational energy efficiencies and the estimated baseline energy efficiencies. The aggregation is then multiplied by the cooling load during the duration of the warning event. The estimated energy loss can be represented mathematically as follows:

25

30

$$\text{Estimated Energy loss} = (\text{operational efficiency} - \text{estimated efficiency}) / \text{cooling load}$$

The MC 73 can display the computed estimated energy loss to the operator who can then decide the next action.

Different implementations of the prediction model are possible.

In another embodiment, the selected operational parameters consist of the electrical powers of the chillers 33, the temperature of the chilled water being supplied from the chiller assembly 32 (CHWS\_T), the temperature of the chilled water being returned to the chiller assembly 32 (CHWR\_T), and the flow rate of the chilled water (CHW\_F) of the first predictor group. The selected operational parameters further consist of the temperature of the condenser water being supplied to the chiller assembly 32 (CDWS\_T), the temperature of the condenser water being returned from the chiller assembly 32 (DWR\_T), the flow rate of the condenser water (CDW\_F) in the condenser water loop 50, the wet-bulb temperature, and the dry bulb temperature of the second predictor group.

The random forest algorithm is trained with data sets comprising these selected operational parameters. This trained random forest algorithm has a prediction accuracy that is better than the prediction accuracy of the random forest algorithm that is trained with the operational parameters of the first predictor group because of the additional selected operational parameters.

Instead of computing the plant energy efficiency as a ratio of the total electrical power of the chiller assembly 32 to the cooling load of the HVAC plant 12, the plant energy efficiency can also be computed as a ratio of the cooling load of the HVAC plant 12 to the total electrical power of the chiller assembly 32.

In a further embodiment, the plant energy efficiency is computed as a ratio of the total electrical power of the HVAC plant 12 to the cooling load of the HVAC plant 12. The total  
5 electrical power of the HVAC plant 12 refers to the total electrical power of the chiller assembly 32, electrical power of the cooling tower 20, electrical power of the electric condenser water pump 22, electrical power of the electric chilled water pump 27, and electrical power of the return chilled wa-  
10 ter pump 29.

In this further embodiment, the selected operational parameters can consist of the operational parameters of the first predictor group. The selected operational parameters can also  
15 further consist of the operational parameters of the second predictor group.

The improved detection method for an anomaly in the energy efficiency of the HVAC plant provides several benefits.

20

The improved detection method includes capturing only a few selected operational parameters of the HVAC plant. This allows the values of the selected operational parameters to be captured and transmitted to the controller for processing almost  
25 instantly. Any deviation in the energy efficiency of the HVAC plant can thus be detected quickly to allow correction actions to be executed to restore the poor performance of the HVAC plant within a short duration. It saves electrical energy and costs.

30

Moreover, the method improves detection accuracy regardless of the HVAC plant operating in different environmental and load conditions.

Furthermore, the improved method can be adapted and applied to any HVAC plant with varying configurations. This is because the algorithm is trained according to any unique configuration of any HVAC plant. The improved method hence does not need  
5 tuning parameters that are required by other detection methods to fit a particular HVAC plant.

Although the above description contains much specificity, this should not be construed as limiting the scope of the embodi-  
10 ments but merely providing illustration of the foreseeable embodiments. The above stated advantages of the embodiments should not be construed especially as limiting the scope of the embodiments but merely to explain possible achievements if the described embodiments are put into practice. Thus, the  
15 scope of the embodiments should be determined by the claims and their equivalents, rather than by the examples given.

## REFERENCE NUMBERS

|    |    |                                         |
|----|----|-----------------------------------------|
|    | 10 | air cooling and circulating arrangement |
|    | 12 | HVAC plant                              |
|    | 16 | energy control module                   |
| 5  | 20 | cooling tower                           |
|    | 22 | condenser water pump                    |
|    | 25 | Air Handling Unit (AHU)                 |
|    | 27 | supply chilled water pump               |
|    | 29 | return chilled water pump               |
| 10 | 32 | chiller assembly                        |
|    | 33 | chiller                                 |
|    | 40 | compressor                              |
|    | 43 | evaporator                              |
|    | 45 | condenser                               |
| 15 | 48 | expansion valve                         |
|    | 49 | refrigerant loop                        |
|    | 50 | condenser water loop                    |
|    | 51 | chilled water loop                      |
|    | 52 | Variable Speed Drive (VSD)              |
| 20 | 53 | power meter                             |
|    | 60 | temperature sensor                      |
|    | 70 | flow meter                              |
|    | 71 | flow meter                              |
|    | 73 | master controller (MC)                  |
| 25 | 80 | flow chart                              |
|    | 83 | step                                    |
|    | 85 | step                                    |
|    | 86 | step                                    |
|    | 89 | step                                    |
| 30 | 93 | step                                    |
|    | 96 | step                                    |

## CLAIMS

1. A method for generating a model for determining a base-line energy efficiency of a Heating, Ventilating, and Air Conditioning (HVAC) unit, the method comprising
- receiving a plurality of sets of training measurement values of operational parameters of the HVAC unit, wherein the operational parameters comprise
    - electrical powers of a plurality of chillers of a chiller assembly of the HVAC unit,
    - a temperature of chilled water being supplied from the chiller assembly (CHWS\_T),
    - a temperature of the chilled water being returned to the chiller assembly (CHWR\_T), and
    - a flow rate of the chilled water (CHW\_F) in a chilled water loop of the HVAC unit,
  - computing a value of efficiency of the HVAC unit for each set of the operational parameters, the value refers to a ratio of a sum of the training measurement values of the electrical powers of the chillers to a total cooling load (RT) of the HVAC unit, wherein the total cooling load (RT) refers to a product of
    - a constant value,
    - a difference between a training measurement value of the temperature of the chilled water being supplied from the chiller assembly (CHWS\_T) and a training measurement value of the temperature of the chilled water being returned to the chiller assembly (CHWR\_T), and
    - a training measurement value of the flow rate of the chilled water (CHW\_F) in the chilled water loop of the HVAC unit,

- performing an analysis between the computed efficiency and the operational parameters to determine a correlation coefficient of each operational parameter,

- selecting operational parameters, wherein the correlation coefficient of each selected operational parameter is larger than a predetermined selection value, wherein the selected operational parameters consist of the electrical powers of the chillers, the temperature of the chilled water being supplied from the chiller assembly (CHWS\_T), the temperature of the chilled water being returned to the chiller assembly (CHWR\_T), and the flow rate of the chilled water (CHW\_F) in the chilled water loop,

- providing a plurality of training sets, each training set comprising training measurement values of the selected operational parameters and a corresponding computed value of the efficiency,

- training a model based on the training sets to generate a trained model, the model comprising a machine learning algorithm, wherein the trained model is adapted to provide a baseline efficiency according to the training measurement values of the selected operational parameters.

2. A method for detecting an anomaly in energy efficiency of a Heating, Ventilating, and Air Conditioning (HVAC) unit in real time, the method comprising

- capturing operational measurement values of selected operational parameters of the HVAC unit,

wherein the selected operational parameters consist of

- electrical powers of a plurality of chillers of a chiller assembly of the HVAC unit,

- a temperature of chilled water being supplied from the chiller assembly (CHWS\_T),  
- a temperature of the chilled water being returned to the chiller assembly (CHWR\_T), and  
5       - a flow rate of the chilled water (CHW\_F) in a chilled water loop of the HVAC unit,  
- computing (a value of) an operational efficiency of the HVAC unit, the (value of the) operational efficiency refers to a ratio of a sum of the operational  
10 measurement values of the electrical powers of the chillers to a total cooling load (RT) of the HVAC unit, wherein the total cooling load (RT) refers to a product of  
- a constant value,  
- a difference between an operational measurement value of the temperature of the chilled water  
15 being supplied from the chiller assembly (CHWS\_T) and an operational measurement value of the temperature of the chilled water being returned to the chiller assembly (CHWR\_T), and  
- an operational measurement value of the flow rate of the chilled water (CHW\_F) in the chilled water loop of the HVAC unit,  
20 - generating an operational baseline efficiency of the HVAC unit according to the operational measurement values of the selected operational parameters based on a trained model,  
25 - computing a difference between the operational baseline efficiency and the computed operational efficiency, and  
30 - sending a warning signal if the difference is larger than a predetermined deviation value.

3. The method according to one of claim 1 or 2, wherein the selected operational parameters further consist of a tem-

perature of condenser water being supplied to the chiller assembly (CDWS\_T), a temperature of condenser water being returned from the chiller assembly (DWR\_T), a flow rate of the condenser water (CDW\_F) in a cooling tower loop, a  
5 wet-bulb temperature, and a dry bulb temperature of the HVAC unit.

4. The method according to one of claims 1 to 3, wherein the  
10 trained model is adapted to provide the baseline efficiency according to a configuration of the chillers comprising at least one operating chiller and at least one non-operating chiller.

5. The method according to one of claims 1 to 4, wherein the  
15 machine learning algorithm refers to a regression tree algorithm.

6. The method according to claim 5, wherein the regression  
20 tree algorithm refers to a random-forest algorithm.

7. The method according to one of claims 2 to 6, wherein the  
predetermined deviation value is 10 percent.

8. The method according to one of claims 2 to 6 further com-  
25 prising executing a fault detection and diagnostic algorithm to identify causes of the warning signal.

9. The method according to claim 8 further comprising  
30 providing a remedial action plan.

10. A controller for operating a Heating, Ventilating, and  
Air Conditioning (HVAC) unit, wherein the controller comprises interfaces for a plurality of sensors that are provided for capturing operational parameters of a

chilled water loop, of a cooling tower loop, and of a chiller assembly comprising a plurality of chillers of the HVAC unit,

wherein the controller is adapted to issue signals to the interfaces for receiving the operational parameters, and wherein the controller is adapted to perform steps of a method according to one of claims 2 to 9 to detect an anomaly in the energy efficiency of the HVAC unit.

11. The controller according to claim 10, wherein the chilled water loop comprises at least one electric chilled water pump, wherein chilled water is circulating in the chilled water loop.

12. The controller according to claim 10 or 11, wherein the cooling tower loop comprises at least one cooling tower with at least one electric condenser water pump, wherein condenser water is circulating in the cooling tower loop.

13. The controller according to one of claims 10 to 12, wherein the chiller comprises a thermodynamic refrigeration cycle that interconnects with the chilled water loop and with the cooling tower loop such that heat is transferred from the chilled water to the condenser water.

14. A HVAC unit comprising a controller according to one of claims 10 to 13.