

A METHOD FOR DETECTING A REAL-TIME DEVIATION OF ENERGY EFFICIENCY IN A 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 energy efficiency of a HVAC plant of the HVAC system.

Water-cooled HVAC plants often consume 40% to 60% of total en-
10 ergy utilization of a commercial building. The water-cooled HVAC plant often includes chillers, water pumps, and cooling towers. After retrofitting and performance improvement works have been done, the HVAC plant still requires regular monitoring and maintenance works to be carried out for keeping the
15 HVAC plant operating efficiently.

According to studies, up to 50% of repair works of the HVAC plant can be attributed to a lack of maintenance. A reduction of the HVAC plant efficiency often precedes a breaking down of
20 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.

25 US 2011/0023503 A1 disclosures 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-
30 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 when the performance characteristics of the air conditioning

equipment are determined to be abnormal. The invention 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.

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

- 10 The application provides a method for detecting an anomaly in energy efficiency of a Heating, Ventilating, and Air Conditioning (HVAC) unit during an operation of the 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.

- The HVAC unit often comprises a chilled water loop, a cooling tower loop, and at least one chiller. 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. 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. The chiller 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.

- Before the operation of the HVAC unit, a mathematical model for estimating the baseline efficiency of the HVAC unit is provided. The provision of the model includes steps comprising

providing selected historical operational parameters of parts of the HVAC unit. The parts of the HVAC unit include the chilled water loop, the cooling tower loop, and the chiller. Examples of the operational parameters include the power of the cooling tower comprising one or more electric fans, power of the electric condenser water pump, power of the electric chilled water pump, a power of the chiller, a temperature of the chilled water being supplied from the chiller, a temperature of the chilled water being returned to the chiller, and a flow rate of the chilled water in the chilled water loop. These operational parameters can be captured by a plurality of sensors comprising temperature sensors, power meters, and flow meters.

15 The provision of the model further includes a step of deriving a plurality of predictor variables and corresponding baseline efficiencies of the HVAC unit from the historical operational parameters.

20 The predictor variables comprise a first predictor variable and a plurality of second predictor variables. The first predictor variable refers to the total power of the HVAC unit. The total power of the HVAC unit refers to a sum of the power of at least one cooling tower, the power of at least one electric condenser water pump, the power of at least one electric chilled water pump, and the power of at least one chiller of the HVAC unit. The second predictor variables comprise the temperature of the chilled water being supplied from the chiller (CHWS_T), the temperature of the chilled water being returned to the chiller (CHWR_T), and the flow rate of the chilled water in the chilled water loop (CHW_F) of the HVAC unit.

The baseline efficiency of the HVAC unit refers to a ratio of the total power of the HVAC unit to a total cooling load (RT) of the HVAC unit. The total cooling load (RT) of the HVAC unit is a product of a predetermined number (N), a difference between a temperature of chilled water being supplied from the at least one chiller (CHWS_T) and a temperature of the chilled water being returned to the at least one chiller (CHWR_T), and a flow rate of the chilled water in a chilled water loop (CHW_F) of the HVAC unit. The value of the predetermined number (N) can be 1.2.

The provision of the model also includes a step of training a machine learning algorithm with the derived predictor variables, which act as input data, and the corresponding derived baseline efficiencies of the HVAC unit, which acts as an output response. The training is an iterative process for correlating the plurality of the predictor variables to the baseline energy efficiencies to generate a trained mathematical model. This means the trained mathematical model has established mathematical relationships between the predictor variables and the corresponding baseline energy efficiencies of the HVAC unit based on the historical data. The established mathematical relationships enable the model to estimate an expected baseline energy efficiency of the HVAC unit according to new values of the predictor variables that are derived from operational parameters captured during the operation of the HVAC unit.

During the operation of the HVAC unit, the detection method includes a step of a plurality of sensors of the HVAC unit capturing the operational parameters of parts of the HVAC unit during the operation of the HVAC unit.

The sensors then transmit the captured operational parameters to a controller or a computing device of the HVAC unit.

5 The controller later receives the captured operational parameters and then generates a plurality of predictor variables or input variables for the trained mathematical model. Each predictor variable is derived from one or more of the captured operational parameters.

10 The controller afterward generates an estimated or expected baseline energy efficiency of the HVAC unit according to the plurality of predictor variables based on the trained mathematical.

15 The controller afterward determines an operational or actual energy efficiency of the HVAC unit by computing a ratio of the total power of the HVAC unit to the total cooling load (RT) of the HVAC unit.

20 The controller then computes a difference between the estimated baseline energy efficiency and the operational energy efficiency.

The controller later compares the difference with a predetermined value and sends a warning signal if the difference is
25 larger than the predetermined value.

This detection method allows a predetermined deviation in the energy efficiency of the HVAC unit to be detected automatically and accurately. Corrective actions can be taken quickly to
30 restore the efficiency of the HVAC unit to its desired level, thereby reducing energy cost.

The application also provides a further method for detecting an anomaly in the energy efficiency of an HVAC unit an operation of the HVAC unit.

5 The further method comprises a step of a plurality of sensors of the HVAC unit capturing the operational parameters of parts of the HVAC unit during the operation of the HVAC unit. These parts of the HVAC unit include a chilled water loop, a cooling tower loop, and at least one chiller.

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These sensors then transmit the captured operational parameters to a controller of the HVAC unit.

This controller later receives the captured operational parameters and then generates a plurality of predictor variables for a mathematical model. Each predictor variable is derived from one or more of the captured operational parameters.

20 These predictor variables comprise a first predictor variable and a plurality of second predictor variables. This first predictor variable refers to the chiller power of the HVAC unit. The chiller power refers to a sum of the power of one or more chillers of the HVAC unit. The second predictor variables comprise a temperature of the chilled water being supplied from the chiller (CHWS_T), a temperature of the chilled water being returned to the chiller (CHWR_T), and a flow rate of the chilled water in the chilled water loop (CHW_F) of the HVAC unit.

30 This controller afterward generates an estimated baseline energy efficiency according to the values of the plurality of predictor variables based on a trained mathematical model.

This controller afterward determines an operational energy efficiency of the HVAC unit by computing a ratio of the chiller power to a total cooling load (RT) of the HVAC unit. The total cooling load (RT) of the HVAC unit is a product of a predetermined number (N), a difference between a temperature of chilled water being supplied from the at least one chiller (CHWS_T) and a temperature of the chilled water being returned to the at least one chiller (CHWR_T), and a flow rate of the chilled water in a chilled water loop (CHW_F) of the HVAC unit

This controller then computes a difference between the estimated baseline energy efficiency and the operational energy efficiency.

This controller later compares the difference with a predetermined value and sends a warning signal if the difference is larger than the predetermined value.

In one implementation, the value of the predetermined number (N) is 1.2.

In another embodiment, the predictor variables further comprise a plurality of third predictor variables. The third predictor variables comprise a temperature of condenser water being supplied to the chiller (CDWS_T), a temperature of the condenser water being returned from the chiller (CDWR_T), and a flow rate of the condenser water in a tower loop (CDW_F).

The mathematical model can be generated using a machine learning algorithm such as a random forest algorithm. The random forest algorithm uses multivariate regression analysis techniques to establish mathematical relationships between the baseline energy efficiency and the predictor variables.

The method can further comprise a step of 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, thereby restoring the efficiency of the HVAC unit quickly.

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

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 of at least one chiller 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 perform automatically steps of the method mentioned above such that the aforementioned steps provide detection of an anomaly in the energy efficiency of the HVAC unit.

The chilled water loop can comprise at least one electric 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 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 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.

- 5 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,
- Fig. 2 illustrates parts of a chiller of the air cooling
10 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, and
- Fig. 4 illustrates a flow chart of a method for detecting
15 an anomaly in energy 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
20 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
25 alphabet or prime symbol. The description of one similar part also applies by reference to another similar part, where appropriate, thereby reducing repetition of text without limiting the disclosure.

30 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.

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.

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.

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.

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.

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.

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.

5 Only one VSD 52 is shown in Fig. 1. The MC 73 is electrically connected to the VSDs 52 and to the parameter measurement module 74.

The MC 73 is electrically connected to the VSDs 52, which are
10 respectively connected to an electric motor of the water 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.

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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.

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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 operational parameters of the parts. The operational parameter
25 measurements provide indications of operating states of 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
30 ing 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.

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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
10 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.
15 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
20 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
25 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
30 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 Fig. 3.

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.

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

In use, the air cooling and circulating arrangement 10 is used
25 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
30 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.

Regarding the chilled water loop 51, the chilled water absorbs
5 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 transfer heat energy from the chilled water to the condenser
10 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
15 tower 20 acts to expel the heat energy in the condenser water, which flows through the cooling tower 20, to an outside space.

Fig. 4 shows a flow chart 80 of a method for detecting an anomaly in energy efficiency of the HVAC plant 12 of the
20 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 at least one chiller 33.

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The method includes a step 83 of the sensors capturing or measuring the operational parameters of the parts of the HVAC plant 12 and later transmitting the captured operational parameters to the MC 73. The captured operational parameters include the power of the cooling tower 20, power of the condenser water pump 22, power of the supply chilled water pump 27, power of the return chilled water pump 29, and power of the chiller 33. The captured operational parameters also include the temperature of the chilled water being supplied from the
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chiller 33, the temperature of the chilled water being re-
turned to the chiller 33, the flow rate of the chilled water
in the chilled water loop 51, the temperature of the condenser
water being supplied to the chiller 33, the temperature of the
5 condenser water being returned from the chiller 33, and the
flow rate of the condenser water in the condenser water loop
50.

In a next step 85, the MC 73 then receives the captured opera-
10 tional parameters and later generates a plurality of predictor
variables according to the captured operational parameters.
The predictor variables are independent variables for a mathe-
matical or prediction model. Each predictor variable is de-
rived from at least one of the captured operational parame-
15 ters.

The predictor variables include a set of first predictor vari-
ables. Each first predictor variable refers to the total power
input of the HVAC plant 12. The total power input is the sum
20 of the power of the cooling tower 20, power of the condenser
water pump 22, power of the supply chilled water pump 27, pow-
er of the return chilled water pump 29, and power of the
chiller 33.

25 The predictor variables further include a set of second pre-
dictor variables. The second predictor variables include the
temperature (CHWS_T) of the chilled water being supplied from
the chiller 33, the temperature (CHWR_T) of the chilled water
being returned to the chiller 33, and the flow rate (CHW_F) of
30 the chilled water in the chilled water loop 51.

The predictor variables can also include a set of third pre-
dictor variables. The third predictor variables include the
temperature of the condenser water being supplied to the

chiller 33 (CDWS_T), the temperature of the condenser water being returned from the chiller 33 (CDWR_T), and the rate of flow of the condenser water in the condenser water loop 50 (CDW_F).

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The other predictor variables can also include a wet-bulb temperature of the cooling towers 20, a configuration of chillers, and/or a configuration of the pumps.

10 The MC 73 later generates an expected or estimated baseline energy efficiency of the HVAC plant 12 according to the plurality of predictor variables based on the prediction model, in a step 86.

15 The prediction model has been trained or generated before it is used for estimation. It is trained using one or more supervised machine learning algorithms that are selected from the group consisting of a random-forest algorithm, a neural network algorithm, and a boosted-tree algorithm.

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In one implementation, the prediction model is generated or trained using the random-forest algorithm.

The training of the prediction model uses a plurality of
25 training data sets. Each data set includes the predictor variables and measured baseline efficiencies corresponding to the predictor variables. The predictor variables and the corresponding measured baseline efficiencies are derived from the captured operational parameter measurements.

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The measured baseline efficiency is often derived by calculating a ratio of a total power input of the HVAC plant 12 to a cooling load (RT) of the HVAC plant 12. In another embodiment, the baseline energy efficiency is computed as a ratio of the

cooling load (RT) of the HVAC plant 12 to the total power input of the HVAC plant 12.

The total power input refers to a sum of the power of the cooling tower 20, power of the pumps 22, 27, 29, and power of the chiller 33 of the HVAC plant 12.

The cooling load (RT) refers to a product of a constant of a predetermined number (N), a difference between a temperature of the chilled water being supplied from the chiller 33 and a temperature of the chilled water being returned to the chiller 33, and a flow rate of the chilled water in the chilled water loop 51 of the HVAC plant 12. The RT can be represented according to the below equation:

$$RT = N \times (CHWR_T - CHWS_T) \times CHW_F.$$

In one implementation, the value of the predetermined number N is 1.2.

The captured parameter measurements are often collected from periods during which the HVAC plant 12 operates with measured efficiencies that are within a normal or allowable range. The collected parameter measurements resemble the acceptable HVAC plant operating condition within the allowable efficiency.

Each collected data is then examined and classified as normal or acceptable data or abnormal or unacceptable data according to the operating conditions of the HVAC plant 12. The unacceptable data points are discarded, and only acceptable data points are used for regression training of the model. Training of the machine-learning model with only acceptable data leads to a highly accuracy prediction of the baseline efficiency of the HVAC plant 12.

The training with the random forest algorithm comprise multiple multivariate regression analysis processes for estimating mathematical relationships between the baseline efficiency of the HVAC plant 12 and multiple predictor variables. The mathematical relationships allow the prediction model with the random forest algorithm to estimate a baseline efficiency for new values of the predictor variables.

The random forest algorithm establishes a plurality of decision trees that are combined into a forest to produce a prediction of the baseline energy efficiency of the HVAC plant 12 according to the predictor variables. Different numbers of decision trees, for examples, 100 trees, 200 trees, 400 trees, 600 trees, and 800 have been evaluated. Other parameters such as `max_depth`, `min_samples_split`, `min_samples_leaf` and `max_leaf_nodes` are obtained using grid search during hyperparameter tuning to achieve best accuracy and generalization of the model to prevent over-fitting.

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The trained prediction model is established with mathematical relationships between the predictor variables and the baseline energy efficiency of the HVAC plant 12.

During the training, the supervised machine learning algorithm can also rank the predictor variables according to their relative significances in relation to the prediction of the baseline energy efficiency. In other words, less significant predictor variables can be removed to retrain the prediction model such that the accuracy of the retrained prediction module is substantially the same as the prediction model that is trained earlier.

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In one embodiment, the trained prediction model provides an estimated baseline energy efficiency based on the first predictor variables and the second predictor variables.

- 5 In another embodiment, the trained prediction model provides an estimated baseline energy efficiency based on the first predictor variables, the second predictor variables, and the third predictor variables.
- 10 In a subsequent step 89, the MC 73 computes a measured energy efficiency of the HVAC plant 12 according to the predictor variables that are derived from the received parameter measurements.
- 15 The MC 73 afterward computes a difference between the measured energy efficiency and the estimated baseline energy efficiency, in a step 93.

The MC 73 then compares the difference to a predetermined value or threshold. If the difference is larger than the predetermined value, the MC 73 sends a warning to an operator of the HVAC plant 12, in a step 96. 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 and provide a recommended remedial action plan or measures to the operator.

The MC 73 is also configured to compute an estimated cost of the loss in energy efficiency during the warning event. The estimated cost is computed by aggregating the differences between the measured 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 MC 73 can transmit the computed estimated cost for dis-

playing to the operator who can then decide the next action based on the information provided.

5 Different implementations of the prediction module are possible.

In one implementation, the prediction module is trained with data sets, wherein each data set includes a first further predictor variable, the second predictor variables, and corresponding baseline efficiencies of the HVAC plant 12. The first further predictor variable refers to chiller power which is a sum of power of one or more chillers 33. Each baseline efficiency refers to a ratio of the chiller power to the total cooling load (RT) of the HVAC plant 12.

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In another implementation, the prediction module is trained with data sets, wherein each data set includes the first further predictor variable, the second predictor variables, the third predictor variables, and corresponding baseline efficiencies of the HVAC plant 12. Each baseline efficiency refers to a ratio of the chiller power to the total cooling load (RT) of the HVAC plant 12.

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In these implementations, the trained prediction model is adapted to provide an estimated baseline energy efficiency according to new values of the predictor variables. The estimated baseline energy efficiency is used to compare with the actual or operational energy efficiency. The operational energy efficiency is a ratio of the chiller power to the total cooling load (RT) of the HVAC plant 12.

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The improved method for detecting an anomaly in the energy efficiency of the HVAC plant allows any deviation in the energy efficiency of the HVAC plant from the estimated baseline effi-

ciency to be detected automatically, accurately, and instantly, thereby enabling corrective actions to be taken quickly to rectify poor performance of any HVAC equipment and/or to stop any equipment operating unintentionally. This can reduce the duration during which the HVAC plant operates below the expected or baseline efficiency, and it saves costs. Furthermore, the improved method can be adapted and applied to any HVAC plant with a varying configuration by determining an expected efficiency that is only relevant and applicable to said HVAC plant for plant performance monitoring. This means the improved method does not need 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 embodiments 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 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	33	chiller
	40	compressor
	43	evaporator
	45	condenser
	48	expansion valve
15	49	refrigerant loop
	50	condenser water loop
	51	chilled water loop
	52	Variable Speed Drive (VSD)
	53	power meter
20	60	temperature sensor
	70	flow meter
	71	flow meter
	73	master controller (MC)
	80	flow chart
25	83	step
	85	step
	86	step
	89	step
	93	step
30	96	step

CLAIMS

1. A method for detecting an anomaly in energy efficiency of a Heating, Ventilating, and Air Conditioning (HVAC) unit, the method comprising
- capturing operational parameters of the HVAC unit by a plurality of sensors,
 - generating a plurality of predictor variables by the controller, each predictor variable being derived from at least one of the captured operational parameters, wherein the predictor variables comprise
 - a first predictor variable that refers to total power of the HVAC unit, wherein the total power of the HVAC unit refers to a sum of power of at least one cooling tower, power of at least one electric condenser water pump, power of at least one electric chilled water pump, and power of at least one chiller of the HVAC unit, and
 - a plurality of second predictor variables comprising a temperature of the chilled water being supplied from the chiller (CHWS_T), a temperature of the chilled water being returned to the chiller (CHWR_T), and a flow rate of the chilled water in the chilled water loop (CHW_F) of the HVAC unit,
 - generating an estimated baseline efficiency of the HVAC unit according to the plurality of predictor variables by the controller based on a model,
 - determining an operational efficiency of the HVAC unit by the controller by computing a ratio of the total power of the HVAC unit to a total cooling load (RT) of the HVAC unit, wherein the total cooling load (RT) of the HVAC unit refers to a product of a predetermined number (N),

- a difference between the temperature of chilled water being supplied from the at least one chiller (CHWS_T) and the temperature of the chilled water being returned to the at least one chiller (CHWR_T), and the flow rate of the chilled water in a chilled water loop (CHW_F) of the HVAC unit,
- computing a difference between the estimated baseline efficiency and the determined operational efficiency by the controller, and
 - sending a warning signal by the controller if the difference is larger than a predetermined value.
2. A method for detecting an anomaly in energy efficiency of a Heating, Ventilating, and Air Conditioning (HVAC) unit, the method comprising
- capturing operational parameters of the HVAC unit by a plurality of sensors,
 - generating a plurality of predictor variables by the controller, each predictor variable being derived from at least one of the captured operational parameters, wherein the predictor variables comprise
 - a first predictor variable that refers to chiller power, wherein the chiller power refers to a sum of power of at least one chiller of the HVAC unit, and
 - a plurality of second predictor variables comprising a temperature of the chilled water being supplied from the chiller (CHWS_T), a temperature of the chilled water being returned to the chiller (CHWR_T), and a flow rate of the chilled water in the chilled water loop (CHW_F) of the HVAC unit,

- generating an estimated baseline efficiency of the HVAC unit according to the plurality of predictor variables by the controller based on a model,

5 - determining an operational efficiency of the HVAC unit by the controller by computing a ratio of the chiller power to a total cooling load (RT) of the HVAC unit, wherein the total cooling load (RT) of the HVAC unit refers a product of a predetermined number (N), a difference between the temperature of chilled water being
10 supplied from the at least one chiller (CHWS_T) and the temperature of the chilled water being returned to the at least one chiller (CHWR_T), and the flow rate of the chilled water in a chilled water loop (CHW_F) of the HVAC unit,

15 - computing a difference between the estimated baseline efficiency and the determined operational efficiency by the controller, and

 - sending a warning signal by the controller if the difference is larger than a predetermined value.

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3. The method according to claim 1 or 2, wherein the value of the predetermined number (N) is 1.2.

4. The method according to one of claims 1 to 3, wherein the
25 predictor variables further comprise a plurality of third predictor variables comprising a temperature of condenser water being supplied to the chiller (CDWS_T), a temperature of the condenser water being returned from the chiller (DWR_T), and a flow rate of the condenser water
30 in a tower loop (CDW_F).

5. The method according to one of the above-mentioned claims, wherein the model is generated using a machine learning algorithm.

6. The method according to claim 5, wherein the machine learning algorithm refers to a random-forest algorithm.
- 5 7. The method according to one of the above-mentioned claims further comprising executing a fault detection and diagnostic algorithm by the controller to identify causes of the warning event.
- 10 8. The method according to claim 7 further comprising providing a remedial action plan by the controller.
9. 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 at least one chiller of the HVAC unit,
15 wherein the controller is adapted to issue signals to the interfaces for receiving the operational parameters, and wherein the controller is adapted to perform automatically steps of a method according to one of claims 1 to 8 such that the aforementioned steps provide detection of an anomaly in the energy efficiency of the HVAC unit.
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- 25 10. The controller according to claim 9, wherein the chilled water loop comprises at least one electric chilled water pump, wherein chilled water is circulating in the chilled loop.
- 30 11. The controller according to claim 9 or 10, 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.

12. The controller according to one of claim 9 to 11, wherein
5 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.
- 10 13. A HVAC unit comprising a controller according to one of claims 9 to 12.