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(54) GAS PROCESSING UNIT AND METHOD OF OPERATING THE SAME

(57) A plant (1) and a gas processing unit (GPU) (17) of the plant can be configured to operate in accordance with a method that is configured to permit the GPU (17) to operate such that the optimum operating point for the GPU (17) at steady state to produce liquid carbon dioxide product from a separation unit (117) of the GPU (17) for sending to a storage device (19) is achieved with a desired purity level while simultaneously maintaining a required minimum carbon capture rate with the minimum consumption of power and/or minimum economic cost associated with operations of the GPU (17). A controller (23) can be configured to communicate with elements of the GPU (17) to receive parameter values to calculate manipulated variables configured to bias set points for parameters used to control operations of different elements of the GPU (17).

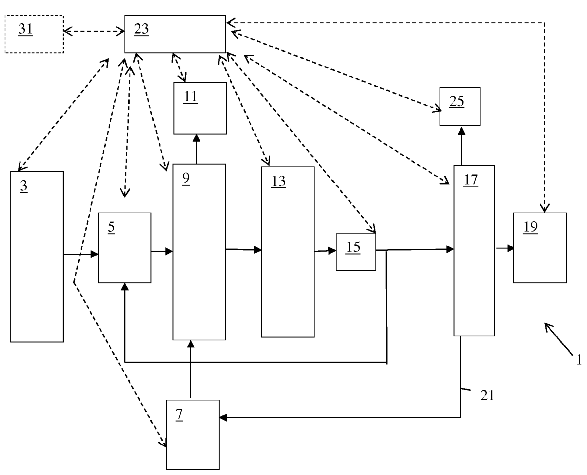

FIG. 1

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Description

FIELD

[0001] The present disclosure relates to a combustion system such as a power generation system that utilizes at least one gas processing unit as well as a control system for such a combustion system, and methods of operating the same.

BACKGROUND

[0002] Energy production systems that burn coal to produce power may include a boiler and a turbine. Energy production systems that are utilized in electricity production and other components of such systems are described, for example, in U.S. Patent Application Publication Nos. 2014/0106284, 2014/0065560, 2014/0065046, 2014/0026613, 2014/0004028, 2013/0315810, 2013/0298599, 2013/0291719, 2013/0255272, 2013/0205827, 2013/0167583, 2012/0052450, 2012/0145052, 2010/0236500, and 2009/0133611 and U.S. Patent Nos. 7,954,458 and 6,505,567, European Patent Application Publication No. EP 2 497 560, and International Publication Nos. WO 2013/144853, WO 2013/057661, WO 2013/027115, WO 2013/024339, and WO 2013/024337.

[0003] For example, in U.S. Patent Application Publication No. 2012/0145052, it is disclosed that some oxy-combustion systems may include an air separation unit, a boiler, an air pollution control system, and a gas processing unit for separating carbon dioxide from flue gas. The heat from the flue gas of the boiler may be captured by steam, which is then used to drive a steam turbine generator to produce electricity. The flue gas may then be processed to remove certain pollutants (e.g. NO_x, SO_x, etc.) and a portion of the treated flue gas may then be recycled to the boiler to effect combustion.

SUMMARY

[0004] According to aspects illustrated herein, there is provided a method of operating a plant having a gas processing unit that includes the can include the steps of determining parameter values associated with operations of the gas processing unit, utilizing the parameter values associated with the operations of the gas processing unit to determine biasing values for biasing set points used to control operations of elements of the gas processing unit, and sending the biasing values for adjusting the set points.

[0005] According to other aspects illustrated herein, an apparatus can include a gas processing unit, a controller having a processor connected to non-transitory memory, and a model predictive control program stored in the memory. The gas processing unit can be configured to connect to a combustion unit such that flue gas emitted from the combustion unit will be fed to the gas processing unit. The gas processing unit can be configured to separate carbon dioxide from the flue gas to capture the carbon dioxide from the flue gas. The controller can be communicatively connected to the gas processing unit to control operations of the gas processing unit with the model predictive control program.

[0006] The above described and other features are exemplified by the following figures and detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Exemplary embodiments of an apparatus, a plant, and associated exemplary methods are shown in the accompanying drawings. It should be understood that like reference numbers used in the drawings may identify like components, wherein:

Fig. 1 is a block diagram of a first exemplary embodiment of a plant.

Fig. 2 is a block diagram a first exemplary embodiment of the gas processing unit of the first exemplary embodiment of the plant.

Fig. 3 is a block diagram illustrating an exemplary embodiment of a controller of the first exemplary embodiment of the plant.

Fig. 4 is a schematic diagram illustrating an exemplary model structure for the exemplary embodiment of the controller of the first exemplary embodiment of the plant.

[0008] Other details, objects, and advantages of embodiments of the innovations disclosed herein will become apparent from the following description of exemplary embodiments and associated exemplary methods.

DETAILED DESCRIPTION

[0009] Referring to Figures 1-4, a plant 1 can be configured as an industrial plant, power plant, or electricity generation plant. The plant 1 can be configured to include a combustion unit. The combustion unit can include a combustor such as a furnace or boiler that is configured to combust a fossil fuel (e.g. coal, natural gas, etc.) or other type of fuel to form combustion products (e.g. steam, carbon dioxide, carbon monoxide, etc.) at a temperature within a desired pre-specified temperature range. Steam emitted by the combustion unit can be utilized to generate electricity or otherwise provide thermal energy for conversion into a desired system output. Flue gas emitted from the combustion process can be routed through a series of other devices configured to treat the flue gas prior to the flue gas being emitted from the plant. The treatment of the flue gas can be configured to help ensure that the emitted flue gas complies with applicable emission regulations or otherwise meets a desired set of design criteria.

[0010] In some embodiments, the plant 1 can be configured as an oxygen fired plant that is configured to generate electricity from the burning of a fossil fuel. For example, some embodiments of the plant can be configured as an oxygen fired pulverized coal plant. As another example, other embodiments of the plant 1 can be configured as an oxygen fired natural gas plant.

[0011] An embodiment of the plant 1 can be configured to include an air separation unit (ASU) 3 that is configured to separate oxygen from other air components (e.g. nitrogen, carbon dioxide, etc.) and feed the oxygen gas flow separated from the air to a mixer 5 via an oxygen feed conduit connected between the ASU 3 and the mixer 5. The mixer 5 can be configured to mix the oxygen with at least one other recycled plant fluid flow to form an oxidant flow for feeding the oxidant flow of fluid to a combustion unit 9 via at least one oxidant flow feed conduit connected between the mixer 5 and the combustion unit 9. In some embodiments, a portion of flue gas emitted by the combustion unit 9 can be recycled back to the mixer 5 for mixing with the oxygen from the ASU 3 to form the oxidant flow.

[0012] A fuel source 7 can be connected to a combustion unit 9 for feeding fuel to the combustion unit. The fuel source 7 can be, for example, a coal mill that pulverizes coal for providing the coal to the combustion unit 9 or can be another type of fuel source. The combustion unit 9 can be configured as a boiler such as an oxygen fired boiler, or can be configured as a furnace or other type of combustor.

[0013] The combustion unit 9 can be configured to combust the fuel from the fuel source 7 in the presence of the oxidant flow received from the mixer 5 to produce steam and flue gas. The steam can be fed to a turbine of a generator or other power generation unit 11 via a steam transport conduit connected between the combustion unit 9 and the power generation unit 11. Flue gas formed in the combustion unit 9 can be separated from the steam and subsequently sent toward a number of flue gas treatment devices for treating the flue gas prior to recycling the flue gas within the plant and/or emitting a portion of the flue gas to the atmosphere external to the plant 1.

[0014] For instance, the flue gas from the combustion unit 9 can be transported to a particulate collector unit 13 via a particulate collector unit flue gas feed conduit connected between the particulate collector unit 13 and the combustion unit 9. The particulate collector unit 13 can be configured as a dust eliminator, a particulate filter, or other type of particulate removal device. The particulate collector unit 13 can be configured to separate fly ash and other particulates from the flue gas received from the combustion unit 9.

[0015] After the flue gas is treated by the particulate collector unit 13, the treated flue gas can be sent to a desulfurization unit 15 that is configured to remove sulfur oxides from the flue gas. The desulfurization unit 15 can be configured as a dry flue gas desulfurization system or a wet flue gas desulfurization system, for example. The desulfurization unit 15 can receive the flue gas from the particulate collector unit 13 via a desulfurization unit feed conduit connected between the desulfurization unit 15 and the particulate collector unit 13.

[0016] After the flue gas is treated by the desulfurization unit 15, it can be fed to a gas processing unit (GPU) 17 via a GPU feed conduit connected between the desulfurization unit 15 and the GPU 17. Prior to being fed to the GPU 17, the flue gas can be split into a first portion and a second portion. The first portion of the flue gas can be recycled to the mixer 5 for mixing with oxygen from the ASU 3 to form the oxidant flow for feeding to the combustion unit 9. The second portion of the flue gas can be transported to the GPU 17 via the GPU feed conduit.

[0017] The GPU 17 can be configured to remove a substantial portion of carbon dioxide from the flue gas to capture that carbon dioxide and output a fluid that is substantially composed of carbon dioxide for storage, further purification, or other distribution. The GPU 17 can be configured to feed a first portion of the flue gas treated by the GPU 17 to have a substantially lower portion of carbon dioxide to another device 25 for further processing or for emitting to the atmosphere after the GPU 17 has processed that flue gas. For instance, the device 25 can be a stack or heat recovery steam generator (HRSG) that is connected to the GPU 17 for receiving the first portion of treated flue gas via an outlet conduit connected between device 25 and GPU 17. A second portion of the flue gas treated by the GPU 17 can be distributed to the fuel source 7 for being used in operations for treating the fuel prior to feeding the fuel to the combustion unit 9. A fuel source conduit 21 can be connected between the GPU 17 and fuel source 7 for recycling that second portion of the flue gas after that gas was treated by the GPU 17.

[0018] The fluid substantially composed of carbon dioxide generated by the treatment of the flue gas performed by the GPU 17 can be output to a storage device 19 or other type of processing device via a carbon dioxide fluid output conduit connected between the GPU 17 and storage device 19. The substantially pure carbon dioxide fluid may be stored in a storage device 19 or other type of vessel. The substantially pure carbon dioxide containing fluid can be composed of 80-100 molar percent carbon dioxide or greater than 70 molar percent carbon dioxide for some embodiments of the plant. For instance, some embodiments of the plant can be configured so that the substantially pure carbon dioxide containing fluid output by the GPU 17 can be between 92-98 molar percent carbon dioxide.

[0019] In some embodiments, the substantially pure carbon dioxide containing fluid stored in the storage device 19 can also be subsequently processed further for forming a product to be distributed to a vendor that desires such a compound. In other embodiments, that fluid may be stored for a relatively long period of time for sequestration of the carbon dioxide.

[0020] At least one controller 23 can be communicatively connected to the ASU 3, the mixer 5, the fuel source 7, the combustion unit 9, the power generation unit 11, the particulate collector unit 13, the desulfurization unit 15, the GPU 17 and device 25 as indicated by the broken line arrows in Figure 1. The controller 23 can also be communicatively connected to conduit elements connected between such devices, valves, proportional-integral-derivative controllers, and measurement sensors such as flow sensors, temperature sensors, and pressure sensors connected to portions of conduits or portions of the GPU 17, device 25, combustion unit 9, ASU 3, fuel source 7, mixer 5, power generation unit 11, particulate collector unit 13, and desulfurization unit 15 as indicated by broken line arrows in Figures 1 and 2 such that the controller 23 can receive information relating to one or more parameters of operation of the plant 1 and/or operation of GPU 17.

[0021] The controller 23 can be an electronic device such as a computer, workstation, computer device, or other type controller. The controller 23 can include at least one non-transitory memory 201, at least one transceiver unit 203 that can include at least one receiver and at least one transmitter configured for communicating with other devices to which the controller 23 is communicatively connected, and at least one processor 205 connected to the memory 201 and transceiver unit 203. The transceiver unit 203 can also be configured to permit the controller 23 to communicate with remote devices via a network connection such as the internet or an intranet. The processor 205 can be a central processing unit, a microprocessor, or other type of hardware processor element configured to run one or more applications stored on the memory 201 such that the controller 23 is able to perform a method defined by code or other instructions of those one or more applications stored in the memory 201. For instance, the controller 23 can have a model predictive control program stored in the memory 201 of the controller 23 that can be run by the processor 205 to control operations of the GPU 17 and/or plant 1.

[0022] As can be appreciated from Figure 2. The GPU 17 can include a cooling device 101 such as direct contract cooler (DCC) or other type of cooling device that is configured to cool flue gas received from the desulfurization device 15. Cooling water can be fed from a source of water 103 to the cooling device 101 via a cooling water feed conduit so that the water can be used to cool the flue gas to a temperature that is within a pre-specified temperature range that is cooler than the temperature the flue gas was at when it was initially fed to the cooling device 101. The cooling water from the source of water 103 can be mixed with glycol or other refrigerant or otherwise exposed to such a refrigerant to help the water be within a desired pre-specified temperature range for providing a desired amount of heat transfer of heat from the flue gas to the water as the water passes through the cooling device 101.

[0023] The water output from the cooling device 101 can be warmer than the water fed to the cooling device 101. The output water can be fed to a first water collecting device 105a via a water output conduit connected between the cooling device and the first water collecting device 10a for subsequently being routed to another device for use of the heat of the warmer water or for sending to a tank for the water to be temporarily stored until being reused for another plant process or GPU process.

[0024] The cooled flue gas can be output from the cooling device and fed to a flue gas compressor system 107 via a flue gas compressor system feed conduit connected between the compressor system 107 and the cooling device 101. The flue gas compressor system 107 can be a one stage compressor system, two-stage compressor system, three-stage compressor system, or other type compression system utilizing one or more compressors to compress the flue gas to a desired pressure. After each compressor stage, the compressed flue gas can be passed through a cooling device for cooling the flue gas to a desired temperature prior to being fed to another compressor for further compression or prior to being fed to a purifier unit 109 for purifying the compressed flue gas. Water from at least one source of water can be fed to heat exchangers for use as a cooling fluid for the heat exchangers positioned between compressor stages or positioned between the last compressor stage and the purification unit 109 for cooling the compressed flue gas to a temperature within a pre-specified temperature range. Water that is heated from its use in such heat exchangers of the flue gas compressor system 107 can be transported from the heat exchangers to a second water collecting device 105b. In some embodiments, the first and second water collecting devices can be separate vessels or can be conduits that feed water to the same storage vessel for that water to be temporarily stored for further use or processing of the plant 1 or GPU 17.

[0025] After being compressed to a desired pressure that is within a pre-specified pressure range by the flue gas compressor system 107 the flue gas can be transported to a purification unit 109 via a purification unit feed conduit connected between the flue gas compressor system 107 and the purification unit 109. The purification unit 109 can be configured to remove undesirable components within the flue gas. For instance, the purification unit 109 can be a mercury adsorber that is configured to utilize activated carbon to remove mercury and other undesired heavy metals or other compounds from the flue gas passing through the purification unit 109. The purification unit 109 can also be configured to utilize at least one absorption mechanism, other types of adsorption mechanisms or combinations of adsorption and absorption mechanisms for removing pre-specified components from the flue gas.

[0026] After being passed through the purification unit 109, the purified flue gas can be transported to a dryer unit 111 to dry the flue gas via a dryer unit feed conduit connected between the purification unit 109 and the dryer unit 111. The flue gas can be dried in the dryer unit so that the flue gas has a humidity level that is at a pre-selected value that is below the dew point of the lowest temperature in a condenser unit 115 that is downstream of the dryer unit 111 to prevent condensation or freezing of water in the condenser unit 115.

[0027] A regeneration unit 113 can receive a flow of heated, drying fluid that was passed through the dryer unit 111 to dry the flue gas. The heated drying fluid can be transported from the dryer unit 111 to the regeneration unit 113 via a regeneration unit feed conduit connected between the dryer unit 111 and the regeneration unit 113. In some embodiments, the dryer unit 111 can be configured so that the drying fluid is routed vertically upwards through a depressurized exhausted dryer bed prior to being sent to a device 25 (e.g. stack and/or HRSG) for subsequent emission to the atmosphere. After being regenerated, at least a portion of the regenerated fluid emitted from the regeneration device can be transported to the device 25 for emission to the atmosphere.

[0028] As indicated by the broken line arrow shown in Figure 2, the drying fluid can include off gas from a separation unit 117 that is passed through a condenser unit 115 and is subsequently passed through the dryer unit 111 as a drying fluid. The off gas from the separation unit 117 can be transported through the condenser 115 and dryer unit 111 via an off gas recycle conduit connected between the separation unit 117 and the dryer unit 111. After being regenerated in the regeneration unit 113, the drying fluid can be fed to device 25 via an off gas feed conduit connected between device 25 and regeneration unit 113. After passing through device 25, the drying fluid can be emitted to the atmosphere that is external to the plant 1.

[0029] The dried flue gas can be transported from the dryer unit 111 to the condenser unit 115 that is configured to cool the flue gas to condense the dried, purified flue gas. The condenser unit 115 can be configured as a carbon dioxide condenser for condensing the carbon dioxide as a liquid flow while other elements within the flue gas remain a gas. In one embodiment, the condenser unit 115 can be configured as a cool box that is configured to cool the flue gas and condense it in multiple sequential steps or in a parallel processing of subdivided flows of the flue gas using plate heat exchangers. In some embodiments, the condenser unit 115 can be configured so that a final output temperature of the fluid output from the condenser unit 115 is within a pre-specified temperature range (e.g. -50° C or within a range of -40° C to -60° C) by using the coldness of evaporation of liquid carbon dioxide supported by a stepwise expansion of the residual uncondensed flue gas.

[0030] The condensed liquid and remaining gas from the condensed flue gas are subsequently fed from the condenser unit 115 to a separation unit 117 via a carbon dioxide separation unit feed conduit. The separation unit 117 is configured to separate the substantially carbon dioxide liquid (e.g. liquid that is between 80-100 mole percent carbon dioxide, liquid that is more than 70 mole percent carbon dioxide, or liquid that is between 92-98 mole percent carbon dioxide, etc.) received from the condenser unit 115 from the non-condensed gas. The separation unit 117 can include one or more separation columns for receiving the condensed fluid from the condenser unit 115 as well as one or more expanders for expanding off gas separated from the condensed liquid by the separation columns. The separation columns of the separation unit 117 can be configured to operate in parallel or in series.

[0031] The separated substantially carbon dioxide fluid is transported from the separation unit 117 to a storage device 19 via a storage conduit connected between the storage device 19 and the separation unit 117. A pump or series of pumps may be connected to the storage conduit for facilitating the flow of substantially carbon dioxide fluid to the storage device 19. During the transportation of the substantially carbon dioxide fluid, the fluid may be transported such that it starts as a liquid but subsequently undergoes a phase change to a gas. For instance, the liquid can be compressed, otherwise pressurized, or heated sufficiently so that the liquid changes phase into a gas or into a mixture of a liquid and a gas. Alternatively, the storage device 19 can be configured to facilitate such a phase change in the substantially carbon dioxide fluid received from the separation unit 117.

[0032] For instance, prior to being distributed to the storage device 19, portions of the separated carbon dioxide can be transported from the separation unit 117 to the flue gas compressor system 107 for use as a cooling fluid that is passed through inter stage heat exchangers used to cool compressed flue gas. For instance, a first portion of the carbon dioxide fluid separated via the separation unit 117 can be transported to a heat exchanger located between compressor stages of the flue gas compressor system 107. A second portion of the separated substantially carbon dioxide fluid can be transported via a portion of the storage feed conduit to a heat exchanger that is between another stage of compressors or is located between the last compressor stage and the purification unit 109.

[0033] The gas separated from the substantially carbon dioxide liquid condensed out of the flue gas can be referred to as off gas. The off gas can include inert elements within the flue gas (e.g. argon and nitrogen) as well as oxygen and a portion of carbon dioxide that was not condensed in the condenser unit 115 and/or otherwise separated from the rest of the flue gas. The separation unit 117 can be configured so that the separated off gas can have a composition of between 20-40 mole percent carbon dioxide, 15-25 mole percent oxygen, 5-15 mole percent argon, 30-50 mole percent nitrogen, and between 0-1 mole percent of other elements such as nitrogen oxides and/or sulfur oxides.

[0034] At least a first portion of the off gas can be transported from the separation unit 117 through the condenser 115 and to the dryer unit 111 for use in helping to cool the flue gas for facilitating condensing of the carbon dioxide from the flue gas passing through the condenser unit 115 and subsequently for passing through the dryer unit 111 as a drying fluid or part of the drying fluid. Recycling of the first portion of the off gas can help improve efficient operation of the GPU 17. A second portion of the off gas can be transported from the separation unit 117 to the regeneration unit 113 to assist in regeneration of the drying fluid after the heated drying fluid is emitted from the dryer unit 111. The second portion of the off gas can be transported to the regeneration unit via an off gas feed conduit connected between the separation unit 117 and the regeneration unit 113. A third portion of the off gas can be fed to the device 25 for subsequent use and/or emission to the atmosphere external to the plant 1 via an off gas output conduit connected between the separation unit 117 and the device 25. A portion of the regenerated fluid output from the regeneration unit 113 can also be transported to the device 25 via regenerated fluid feed conduit connected between the regeneration unit 113 and device 25 for emitting that fluid to the atmosphere.

[0035] The controller 23 can be configured to control and/or monitor operations of the plant 1 and/or GPU 17. The controller 23 can be configured to run a predictive model control program that is structured to configure the controller 23 to monitor and control operations of the GPU 17 to ensure the GPU 17 operates to prevent formation of dry ice and/or water ice, minimize flue gas temperature deviations, maintain a rate at which carbon dioxide is captured out of the flue gas by the GPU 17 and enhance operating flexibility. If the plant 1 is configured as a power plant, the controller 23 can also be configured to enhance the ability of the plant to adjust to load changes via the predictive model control program. The controller 23 can communicate with a computer device 31 that is configured as a distributed control system to effect operations of the plant 1 and GPU 17. Alternatively, the controller 23 can be configured such that it is a component of the distributed control system or other control system such that the model predictive control is an application run on a computer of the control system that communicates with other applications run on the controller 23 for providing control of operations of the plant 1 and GPU 17.

[0036] As may be appreciated from Figure 4, the controller 23 can be configured to receive data from different elements of the GPU 17 and other plant devices such as the ASU 3, combustion unit 9, and power generation unit 11. The controller 23 can receive data from different sensors (e.g. temperature sensors, pressure sensors, flow rate sensors, fluid composition sensors, carbon dioxide concentration detectors, etc.) from each element of the GPU 17 as well as each element of the plant 1. For example, the controller can receive data relating to disturbance variables (DVs) 301, controlled variables (CVs) 303, and constraint variables (CTs) 305. The model predictive control program can be structured to configure the controller 23 to determine parameter values associated with operations of the GPU 17, utilize the parameter values associated with the operations of the GPU 17 to determine biasing values for biasing set points by which operations of elements of the GPU 17 are controlled, and send the determined biasing values to the GPU 17 for adjusting the set points when the model predictive control program is run by the controller 23.

[0037] For example, the controller 23 can be configured to utilize a model predictive control process control algorithm defined by the code of the model predictive control program to utilize data received from different elements of the GPU 17 to determine biasing values for manipulated variables (MVs) 307 that can be subsequently sent to the distributed control system and/or used by the distributed control system for controlling operations of the plant 1 and/or GPU 17. The calculated biasing values for the MVs can be provided to the distributed control system to bias various set point values that are overseen by the distributed control system for operations of the GPU 17 and/or plant 1. If the distributed control system is also an application run on the controller 23, then the biasing values for the MVs determined via the model predictive control program can be fed to the one or more applications of the distributed control system for biasing set points used by that system.

[0038] Examples of a value for a DV 301 can include a flue gas flow rate, a demand for the load of the combustion unit (e.g. boiler load demand or furnace load demand, etc.) and/or a feedforward variable. Examples of values for CVs can include carbon dioxide purity in the substantially carbon dioxide fluid output from the separation unit 117, the carbon dioxide capture rate for operations of the GPU 17, the carbon dioxide concentration of off-gas, the temperature of inlet gas fed to a separator of the separation unit 117, or the inlet off gas temperature of an expander of the separation unit 117 and/or condenser unit 115. Examples of values for CTs include inlet flue gas temperatures at different stages or elements of the separation unit 117, outlet liquid temperatures for the substantially carbon dioxide liquid output at one or more stages of the separation unit 17 or different separation columns included within the separation unit, and off gas expander outlet temperatures for off gas separated by separation columns of the separation unit 117. In some embodiments, the CT values can be high limit values and low limit values for different parameters of the GPU and/or plant 1 that are selected to ensure safe operation of the GPU 17 or plant 1. An example of biasing values for MVs include biasing values for parameters that are to be transmitted to the distributed control system for use in biasing the set points of different parameters. The biasing values can be configured to bias separator carbon dioxide level set points for separation columns of the separation unit 117, temperature set points for one or more of the separation columns, inlet pressure set points for off gas expanders that receive off gas separated from the liquid in the separation unit 117, compressor inlet pressure set points for different compressors of the plant 1 or GPU 17, compressor outlet pressures for one or more compressors of the GPU 17 or plant 1, and temperatures of fluids at the inlets or outlets of compressors of the GPU 17 and/or plant 1. The biasing values for MVs can be determined based on the DVs, CTs, CVs, and any correlations that are determined to exist between these variables for a particular embodiment of the plant 1 and/or GPU 17. The correlations can be correlations between different parameters that are developed from test data routinely gathered during the fabrication and commissioning of a plant as well as other correlations known to exist from mass and energy balance equations relating to operations of the GPU 17 and/or plant. The CTs, CVs, DVs, and biasing values for MVs that are utilized in a particular embodiment can be any of a number of different parameters to meet a particular design objective of a particular embodiment of a plant or GPU.

[0039] If the distributed control system is run on another computer device 31 (as shown in broken line in Figure 1), then the controller 23 can be communicatively connected to that other computer device 31 to transmit the biasing values for the MVs to the computer device 31. The computer device 31 can have hardware elements such as non-transitory memory, at least one transceiver unit, and at least one processor unit connected to the memory and the transceiver unit for running one or more programs stored on the memory for running the distributed control system. The biasing values for the MVs the distributed control system computer device 31 receives from the controller 23 can be utilized by the computer device 31 to bias the set points associated with the biasing values for the MVs received from the controller 23 to adjust the set point values utilized for controlling operations of the GPU 17 and/or plant 1.

[0040] As an alternative, or in addition, the controller 23 can communicate the biasing values for the MVs to proportional-integral-derivative controllers of the different elements of the GPU 17 and/or plant 1 to bias the set points of the proportional-integral-derivative controllers associated with those MVs. For instance, the controller 23 can communicate a determined biasing value associated with a temperature monitored by a proportional-integral-derivative controller of the separation unit 117 so that the proportional-integral-derivative controller adjusts the temperature set point used by that proportional-integral-derivative controller. As another example, the controller can communicate a biasing value associated with a pressure or flow rate of an element of the GPU 17 or plant 1 to a proportional-integral-derivative controller of that element of the GPU 17 or plant 1 to function as a supervisory controller to that proportional-integral-derivative controller. By the controller 23 providing a biasing value associated with the parameter to be controlled by that proportional-integral-derivative controller, the controller 23 is able to provide input to effect an adjustment of a set point utilized by the proportional-integral-derivative controller so that operations of the element to be controlled by that proportional-integral-derivative controller are adjusted based on the biasing value received from the controller 23.

[0041] In some embodiments, the controller 23 can be configured to maximize the cost effectiveness of the operations of the GPU 17 so that operations of the GPU 17 are adjusted to meet a particular operational objective of a plant 1 or GPU 17 operator. For instance, the controller 23 can be configured to operate to prevent problems associated with ice formation in the GPU 17 (e.g. water ice or dry ice) and minimize flue gas temperature deviations while also operating the GPU 17 to maximize the economic value of carbon capture at a desired purity of carbon product in view of the costs associated with operations of the GPU to capture the carbon dioxide at the pre-specified purity levels. The effect regulatory compliance and/or the value of carbon credits that may be relevant to the operations of the GPU 17 and plant 1 can also be included within the variables weighed by the controller to determine the biasing values for biasing set points for different parameters for maximizing the economic return that can be provided by operations of the GPU 17 and/or plant 1.

[0042] In some embodiments, the controller 23 can be configured to determine biasing values for biasing set points used to control operations of elements of the GPU 17 based on utilization of the formula:

$$J = \Sigma_{i=1}^{N_{CV}} \alpha (CV_i^{SP} - CV_i^{PV})^2 + \Sigma_{j=1}^{N_{CT}} \beta (CT_j^{lim} - CT_j^{PV})^2 + \Sigma_{k=1}^{N_{MV}} \gamma \Delta MV_k^2$$

[0043] Where,

CV_i^{SP}: the reference value of the i-th control variable (e.g. required temperature set point)

CV_i^{PV}: the measured value of the i-th control variable (e.g. measured temperature)

CT_j^{lim}: the limits of the j-th constraint variable (e.g. separation unit 117 expander outlet temperature low limit)

CT_j^{PV}: the measured value of the j-th constraint variable (e.g. separation unit 117 expander outlet temperature)

ΔMV_k: the actual change of the k-th biasing value for the k-th manipulated variable (e.g. separation unit 117 expander inlet pressure set point biasing value)

α: weighting coefficients/matrix reflecting the relative importance of the control variables

β: weighting coefficients/matrix reflecting the relative importance of the constraint variables

γ: weighting coefficient penalizing relative large changes in the biasing values for the manipulated variables

In other embodiments of the controller 23, alternative forms of cost functions can include other parameters such as parameters configured to represent penalty of constraint variable violations. Additionally, linear cost terms of MVs, etc. can also be incorporated in the calculations utilized by the controller to determine MVs.

[0044] The biasing values for MVs determined by the controller 23 can be configured for sending to the distributed control system for adjusting or biasing set points that the distributed control system utilizes to control operations of the plant and/or GPU 17. In determining the biasing values for the MVs, the controller can be configure so that the values for DVs used in its calculations to determine biasing values for the MVs can be parameter values that cannot be changed by the controller 23 when performing its calculations. For each value of the CVs, the value of the CV can be affected by both the biasing value for at least one MV and the value of at least one DV relating to that CV. For each value of the CT, the process output can be controlled by the controller 23 when determining biasing values for the MVs by adjusting the CT values within pre-specified limits (e.g. non-changeable high and low limits associated with a particular CT where the high and low limits are set for safety reasons and/or to ensure a desired operational life of a particular capital asset included within the plant 1 and/or GPU 17). For instance, the flue gas flow that enters the GPU can be configured as a feedforward signal to the controller 23. The temperatures at certain points such as expander outlets can be selected so that those temperature values are constrained to prevent dry ice formation or water ice formation that can pose maintenance issues, reduce effectiveness of the GPU 17, and reduce the life of different elements of the GPU 17. Separation column levels, expander inlet pressures, or compressor inlet pressures of the GPU 17 can be configured as manipulated variables that can be utilized to improve the transient response to different conditions within the plant and also increase the carbon dioxide purity in the substantially carbon dioxide product formed from operations of the GPU 17.

[0045] Testing was conducted to assess the value that embodiments of the controller 23 can provide to operations of the GPU 17 and/or plant 1. The conducted testing showed that use of the controller 23 configured to provide a model predictive control based oversight to the operations of the GPU 17 and/or plant 1 permitted the GPU 17 to operate with reduced maximum and standard deviations of process variables while maintaining values of different operational set points within given safety and/or capital assets preservation constraints for the different elements of a GPU 17. Reduced variance permits the GPU 17 to operate more efficiently as losses associated with changes to steady state conditions can be avoided. Further, the improved operations of the GPU 17 was found to help improve the cost effectiveness of the carbon capture operations of the GPU 17 while maintaining the stability of control and safety of operation of the GPU 17 and plant 1.

[0046] It is contemplated that embodiments of the plant 1 and GPU 17 can be configured to improve carbon dioxide concentration (e.g. increase the carbon dioxide content within the product) in the substantially carbon dioxide product output by the GPU 17 for storage in the storage device 19. Embodiments can also save on power consumed by operations of the GPU 17 while maintaining a desired carbon dioxide capture rate provided by the GPU 17. Embodiments can also be configured to prevent process conditions that can cause formation of dry ice and/or water ice from occurring while also improving the stability of operations, controlled response to deviations in the value of one or more DVs or other operations of the plant, and reduce deviations of process variables that can occur during transient upsets that may arise during GPU 17 operations. Embodiments of the controller 23 can permit the GPU 17 to operate such that the optimum operating point for the GPU at steady state to produce liquid carbon dioxide product from the separation unit 117 for sending to storage device 19 is achieved with highest purity while simultaneously maintaining a required minimum carbon capture rate with the minimum consumption of power and/or minimum economic cost associated with operations of the GPU 17.

[0047] It should be appreciated that any of the above noted features of a plant such as an industrial plant or an energy production plant in any particular embodiment expressly discussed herein may be combined with other features or elements of other embodiments except when such a combination would be mutually exclusive or otherwise incompatible therewith as may be appreciated by those of at least ordinary skill in the art. It should also be appreciated that different variations to the above discussed embodiments may be made to meet a particular set of design criteria. For instance, a combustor can be configured as a furnace of a boiler unit that is configured to combust fuel in multiple combustion zones. The furnace of such a boiler unit may include only one burner or may include a plurality of spaced apart burners. As another example, the composition of off gas from the separation unit 117 can be any of a number of suitable compositions that meet a particular set of design criteria. As yet another example, heat exchangers, pumps, fans, valves, measurement sensors, conduit elements (e.g. tubes, pipes, ducts, vessels, etc.) and other elements may also be added to embodiments of the system to facilitate fluid movement or help control changes in the operation of the system. As yet another example, an air separation unit may be configured to provide oxygen or an oxidant air flow to a combustor of the energy production system. The air separation unit may have multiple storage tanks, such as multiple oxygen retaining vessels, for retaining oxygen gas or storing such gas until that gas is needed to be fed to a boiler unit or a combustion unit.

[0048] While the invention has been described with reference to various exemplary embodiments, it will be understood by those skilled in the art that various changes can be made and equivalents can be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications can be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

Claims

1. A method of operating a plant having a gas processing unit (GPU), comprising:

determining parameter values associated with operations of the GPU;
utilizing the parameter values associated with the operations of the GPU to determine biasing values for biasing set points used to control operations of elements of the GPU; and
sending the biasing values for adjusting the set points.

2. The method of claim 1, comprising:

adjusting the set points based upon the biasing values using proportional-integral-derivative controllers that monitor operations of the GPU.

3. The method of claim 1, comprising:

determining the biasing values via the formula:

$$J = \Sigma_{i=1}^{N_{CV}} \alpha (CV_i^{SP} - CV_i^{PV})^2 + \Sigma_{j=1}^{N_{CT}} \beta (CT_j^{lim} - CT_j^{PV})^2 + \Sigma_{k=1}^{N_{MV}} \gamma \Delta MV_k^2$$

where, CV_i^{SP}: is a reference value of an i-th control variable,

CV_i^{PV}: is a measured value of the i-th control variable,

CT_j^{lim}: is a limit of a j-th constraint variable,

CT_j^{PV}: is a measured value of the j-th constraint variable

ΔMV_k: is an actual change of the k-th biasing value,

α : is a weighting coefficient reflecting relative importance of the control variables,

β : is a weighting coefficient reflecting relative importance of the constraint variables, and γ: is a weighing coefficient penalizing changes of at least a pre-specified value in biasing value.

4. The method of claim 3, wherein the plant is configured to generate electricity or power, and the method comprises:

capturing, via the GPU, carbon dioxide from flue gas output by a combustion unit of the plant.

5. The method of claim 3, wherein:

the control variables comprise: (i) carbon dioxide content of a substantially carbon dioxide fluid to be sent from a separation unit of the GPU to a storage device, and (ii) a rate of capture of carbon dioxide from the flue gas; and the constraint variables comprise: (i) an off gas expander outlet temperature, (ii) an outlet temperature for substantially carbon dioxide liquid output from at least one separation column of a separation unit of the GPU, and (iii) at least one flue gas temperature.

6. The method of claim 3, wherein the biasing values comprise:

(i) compressor inlet pressure set point values, (ii) off gas expander temperature set point values, and (iii) at least one separation unit temperature set point value.

7. The method of claim 3, comprising:

determining at least one biasing value utilizing at least one disturbance variable value.

8. The method of claim 7, wherein the disturbance variable value comprises:

a flow rate of flue gas fed to the GPU.

9. The method of claim 3, wherein values of the constraint variables are selected to prevent formation of dry ice and water ice in the GPU.

10. An apparatus comprising:

a gas processing unit (GPU); and
a controller having a processor connected to non-transitory memory, a model predictive control program being stored in the memory;
the GPU being configured to connect to a combustion unit such that flue gas emitted from the combustion unit will be fed to the GPU, the GPU being configured to separate carbon dioxide from the flue gas to capture the carbon dioxide from the flue gas;
the controller being communicatively connected to the GPU to control operations of the GPU with the model predictive control program.

11. The apparatus of claim 10, wherein the model predictive control program is structured to configure the controller to determine parameter values associated with operations of the GPU, utilize the parameter values associated with the operations of the GPU to determine biasing values for biasing set points by which operations of elements of the GPU are controlled, and send the determined biasing values to the GPU for adjusting the set points when the model predictive control program is run by the controller.

12. The apparatus of claim 11, wherein the biasing values are determined by the formula:

$$J = \Sigma_{i=1}^{N_{CV}} \alpha (CV_i^{SP} - CV_i^{PV})^2 + \Sigma_{j=1}^{N_{CT}} \beta (CT_j^{lim} - CT_j^{PV})^2 + \Sigma_{k=1}^{N_{MV}} \gamma \Delta MV_k^2$$

where,

CV_i^{SP}: is a reference value of an i-th control variable,

CV_i^{PV}: is a measured value of the i-th control variable,

CT_j^{lim}: is a limit of a j-th constraint variable,

CT_j^{PV}: is a measured value of the j-th constraint variable

ΔMV_k: is an actual change of the k-th biasing value,

α : is a weighting coefficient reflecting relative importance of the control variables,

β : is a weighting coefficient reflecting relative importance of the constraint variables, and γ: is a weighing coefficient penalizing changes of at least a pre-specified value in manipulated variables.

13. The apparatus of claim 12, wherein the GPU comprises:

a cooling unit, a flue gas compressor system, a purification unit, a dryer unit, a condenser unit, and a separation unit;
the cooling unit being configured to receive flue gas emitted by the combustion unit to cool the flue gas to within a pre-specified temperature;
the flue gas compressor system being connected to the cooling unit to receive the cooled flue gas from the cooling unit, the flue gas compressor system being configured to compress the flue gas to a pre-specified pressure;
the purification unit being connected to the flue gas compressor system to receive the compressed flue gas, the purification unit being configured to remove heavy metals from the flue gas;
the dryer unit being connected to the purification unit to receive the flue gas from the purification unit, the dryer unit being configured to remove water from the flue gas to reduce a dew point of the flue gas;
the condenser unit being connected to the dryer unit to receive the flue gas from the dryer unit, the condenser unit being configured to condense carbon dioxide from the flue gas such that liquid carbon dioxide will be formed from the flue gas; and
the separation unit being connected to the condenser to receive the flue gas and the liquid carbon dioxide from the condenser unit, the separation unit being configured to separate the liquid carbon dioxide from the flue gas.

14. The apparatus of claim 13, comprising:

a storage device connected to the separation unit to receive a substantially carbon dioxide fluid from the separation unit.

15. The apparatus of claim 13 in combination with a plant, the plant comprising:

a combustion unit connected to the GPU of the apparatus;
wherein the flue gas separated from the liquid carbon dioxide will be an off gas; and
the separation unit being connected to the dryer unit such that the off gas will be fed from the separation unit to the dryer unit as a drying fluid to pass through the dryer for removing water from the flue gas.

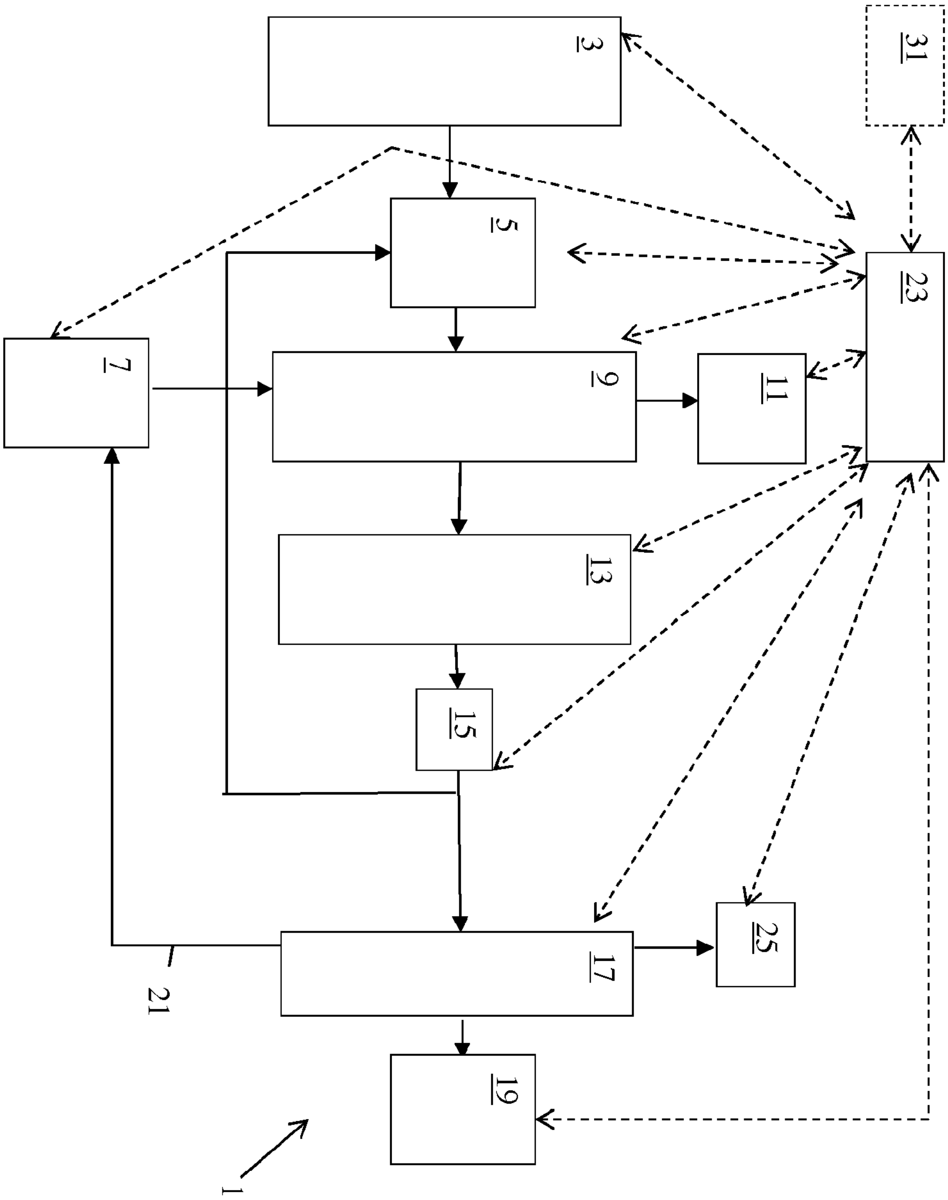

FIG. 1

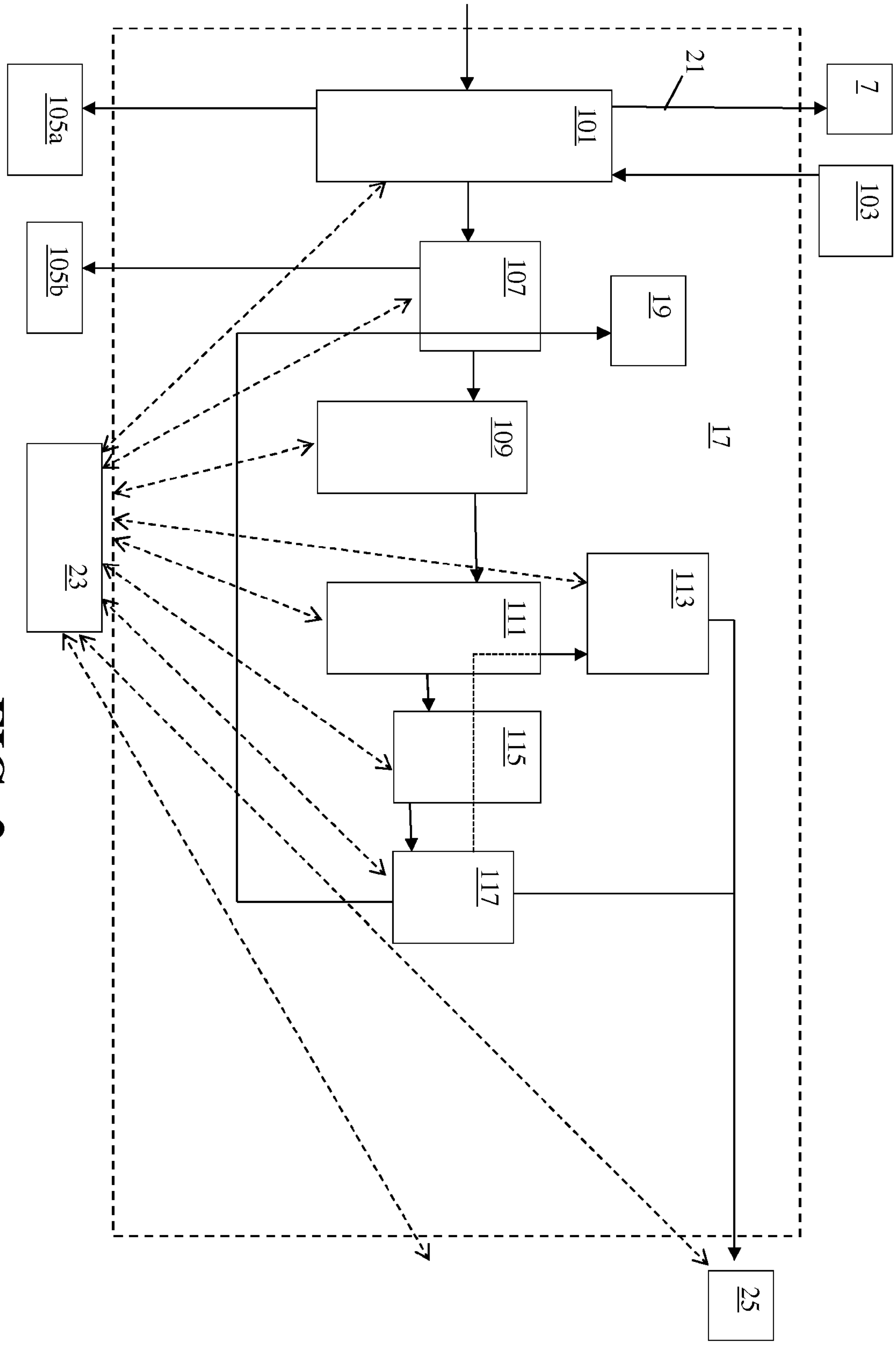

FIG. 2

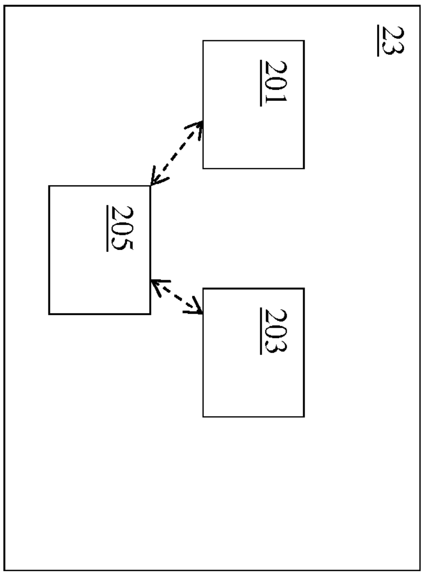

FIG. 3

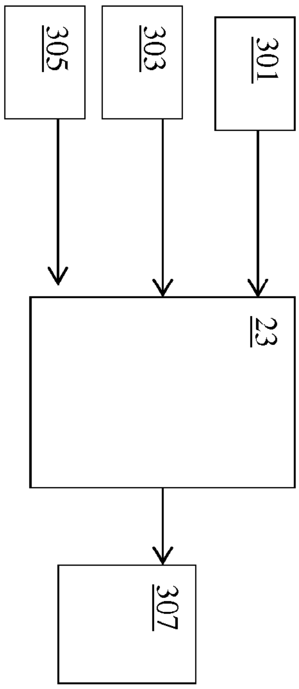

FIG. 4

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EUROPEAN SEARCH REPORT

Application Number
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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	14 October 2015	Hauck, Gunther

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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A : technological background
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