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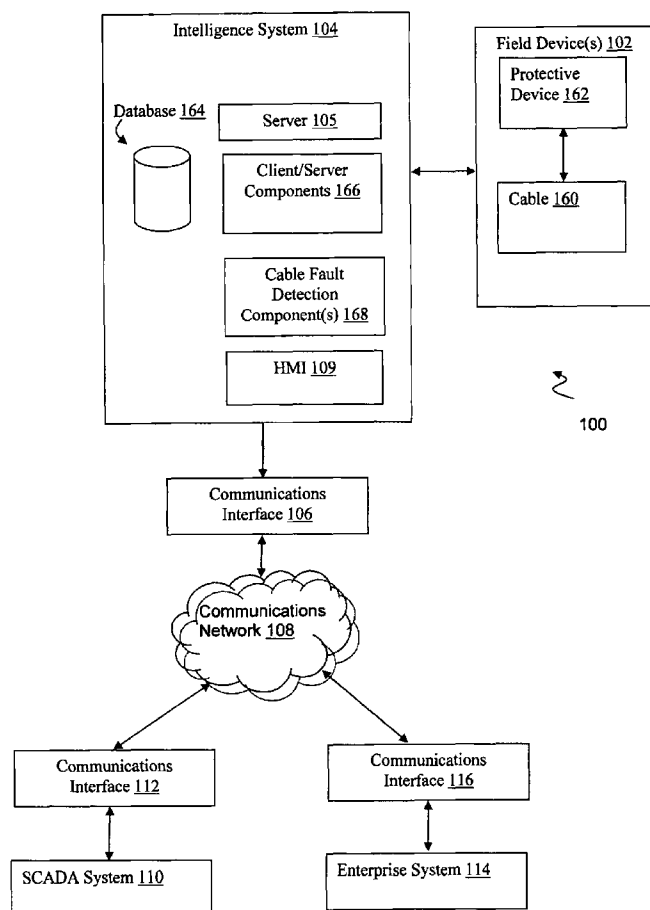
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(54) Title: CABLE FAULT DETECTION



(57) Abstract: A cable fault detection component (168) receives input data indicative of a fault in an electrical power system. The component (168) analyzes the input data to determine if the fault is indicative of a self-clearing cable fault and generates corresponding output data (276). In one implementation, the cable fault detection component (168) is implemented as a software module which operates on a computer (105) of a substation intelligence system (104).

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CABLE FAULT DETECTION

BACKGROUND

The present application relates to fault detection in electrical power transmission and distribution systems. It finds particular application to the detection and analysis of faults in underground and other cables used in the transmission and distribution of electrical power.

Underground and other cables are a key component in the transmission and distribution of electrical power. Unfortunately, however, cables can be prone to shorts or otherwise abnormally low impedance connections between two or more phases or between one or more phases and ground. These and other cable faults can be caused by a number of factors, including human error (*e.g.*, accidentally cutting or striking a cable), climatologic conditions (*e.g.*, precipitation, seismic activity, or lightning strikes), animal activity, and failure or degradation of the cable or its associated equipment. Moreover, cable faults can lead to power outages, which are inconvenient for the affected customers and which can be expensive for the electric utility involved.

One category of fault is that of self-clearing faults. While self-clearing faults can have any number of root causes, they typically have a temporal duration which is insufficient to trip the relevant protective device. In practice, the duration of most self-clearing faults is typically less than about two (2) to three (3) cycles of the power system frequency, and in many cases less than one (1) cycle.

One mechanism which can generate self-clearing cable faults is a breakdown in the insulation between cable phases or between a cable phase and ground. Such faults are often caused or exacerbated by moisture at a cable splice or joint, and are typically

characterized by an elevated or fault current having a duration of about one-quarter to one-half cycle (*i.e.*, roughly four (4) to eight (8) milliseconds (mS) in a sixty Hertz (60 Hz) system). The onset of the fault current usually occurs at or near a voltage peak. As the situation deteriorates, the frequency and severity of these faults tend to worsen with
5 time, culminating in an eventual cable failure and a resultant power outage.

As a consequence, a fault detection apparatus has been incorporated in a protective relay platform which can be used as an intelligent electronic device (IED). See Kojovic, et al., *Sub-Cycle Overcurrent Protection for Self-Clearing Faults Due to Insulation Breakdown* (1999); U.S. Patent No. 6,198,401 to Newton, et al., *Detection of*
10 *Sub-Cycle, Self-Clearing Faults*, issued March 6, 2001. More particularly, and as more fully described in the references, the apparatus samples the cable current signal as it occurs. Contemporaneously with detecting a current signal which exceeds a threshold value, the apparatus confirms that the circuit breaker did not operate and also evaluates succeeding current samples (again, contemporaneously with their occurrence) to
15 determine whether duration of the fault is less than one (1) cycle. If these conditions are satisfied, the device increments a fault counter. If the number and/or frequency of such faults occurrences exceeds a certain setting, the apparatus initiates an alarm, signalization, and/or a trip. In an alternate implementation, the apparatus also determines whether the fault occurred near a voltage peak.

20 However, the fault detection apparatus is provided at the level of the protective relay. One consequence of this relay-centric architecture is that the apparatus is relatively poorly integrated with the substation automation (SA), distribution automation (DA), feeder automation (FA), or other automation system. Moreover, the apparatus requires

the use of a specialized hardware platform which must be closely coupled to the protective relay, and the detection techniques have been relatively unsophisticated.

SUMMARY

Aspects of the present application address these matters, and others.

5 According to one aspect, a method includes performing a Fourier transform of a time varying signal from an electrical power transmission or feeder cable and using the Fourier transformed signal to identify a cable fault.

 According to another aspect, a computer readable storage medium contains instructions which, when executed by a computer processor, cause the processor to carry
10 out a method. The method includes using frequency domain data from a fault in an electrical power system to identify a self-clearing cable fault and generating an output signal indicative of the identified cable fault.

 According to another aspect, a cable fault detection apparatus includes a computer readable memory containing digital fault record data generated in response to a fault and
15 a computer processor in operative communication with the memory. The computer processor executes computer readable instructions which cause the processor to analyze the digital fault record data to determine if the fault is indicative of a cable fault.

 According to another aspect, a method includes obtaining oscillographic data generated in response to a power system fault and using a processor to evaluate the
20 digital fault record data to determine if the power system fault is indicative of a self-clearing cable fault.

 Those skilled in the art will appreciate still other aspects of the present invention upon reading an understanding the attached figures and description.

FIGURES

The present invention is illustrated by way of example and not limitation in the figures of the accompanying drawings, in which like references indicate similar elements and in which:

5 Figure 1 depicts components of an electrical power distribution system.

Figure 2 depicts a substation intelligence system.

Figure 3 depicts a cable fault detection module.

DESCRIPTION

With reference to Figure 1, a substation 100 includes a plurality of field devices
10 102, a substation intelligence system 104 and a communication interface 106. The field
devices 102 include transformers, capacitors, circuit breakers, intelligent electronic
devices (IEDs) and other equipment and assets as are typically encountered in the
substation environment. In the present example, the field devices 102 include one or
more cables 160 such as transmission or feeder cables and associated protective devices
15 162.

The field devices 102 are operatively connected to the substation intelligence
system 104. Depending on the architecture of a given system, the intelligence system
104 may function as one or more of a substation automation system, a feeder automation
system, or a distribution automation system. As illustrated, the substation intelligence
20 system 104 includes a server or other computer 105, a database 164, one or more client
server components 166 and cable fault detection components 168, and an optional human
machine interface (HMI) 109.

The communication interface 106 connects the substation intelligence system 104 to a wide area network (WAN), the internet, or other communications network(s) 108.

A supervisory control and data acquisition (SCADA) system 110 connects to the communications network 108 via suitable communications interface(s) 112. The
5 SCADA system 110 is typically located remotely from the substation 100 and provides supervisory control functions for a plurality of substations 100 and/or other components of the power generation and distribution system.

The substation intelligence system 104 may also be connected to one or more enterprise computer systems such as data warehouses, data marts, planning systems,
10 geographic information systems (GIS), or centralized maintenance management systems (CMMS) 114, which are likewise connected to the communications network 108 through communication interfaces 116.

As noted above, the cables 160 may include one or more transmission or feeder cables. Transmission cables are typically used to transmit high-voltage electricity from a
15 generation source or substation to another substation in the electric distribution system. Feeder cables are typically used to provide an electrical connection between the output of a substation and the input of downstream primary circuits. Feeder cables which leave the substation are sometimes termed substation exit cables. It should be noted, however, that the cables 160 are not necessarily located within the physical boundaries of the substation
20 100 and may in fact be located some distance from the substation. Depending on siting and other considerations, some or all of the cable 160 may be underground cables.

The protective devices 162 typically include one or more protective relays and associated circuit breakers or reclosers. The protective relays are advantageously

implemented as IED-based devices which, among other functions, monitor the voltage, current, and other relevant parameters of their associated cables 160, for example to detect various fault conditions, such as those caused by current, voltage, and/or frequency disturbances and which may or may not be caused by a cable fault.

5 Upon detecting a fault condition, the protective relays capture digital fault record (DFR) data such as voltage, current, and other oscillographic data and set a DFR flag indicating the occurrence of the fault. The DFR data is formatted for transmission in the known common format for transient data exchange (COMTRADE) or other suitable file format. Depending on the nature and severity of the fault, the protective relay may also
10 trip the associated breaker.

 With ongoing reference to Figure 1, the client/server components 166 are advantageously implemented as software or firmware modules which are stored in a memory or other computer readable storage medium accessible to the computer 105. Execution of the components 166 is typically driven by either a timer (timed polling) or
15 trigger-based (interrupting) mechanism so as to operate substantially in real time. Thus, for example, a client/server component 166 may from time-to-time poll a particular protective device 162 to obtain information relating to its status. Where the protective device 162 has set a DFR flag, the client/sever component 166 obtains the DFR data from the protective device 162 and generates an alarm or fault log in which the DFR data is
20 stored at an appropriate location in the database 166, again in the COMTRADE or other suitable format. In the case of a trigger-based implementation, receipt of a DFR flag from a protective device triggers acquisition of the DFR data and generation of the fault log.

With still further reference to Figure 1, the cable fault detection component 168 is likewise implemented as a software or firmware module which is stored in a memory or other computer readable storage medium accessible to the computer 105. The component 168 is also executed by the computer 105 on a polled, triggered, or other suitable basis.

5 As will be described in further detail below, the cable fault detection component 168 analyzes the DFR and/or other relevant input data to detect a signature associated with a cable fault. Upon detecting such a signature, the component 168 generates one or more outputs indicative of the fault for storage in the database 164.

The HMI 109, which may be implemented in a software layer or otherwise in
10 software which is distinct from that of the various components 166, 168, provides desired operator interface functionality, for example to allow a user to interact with the various modules 166, 168, the database 164, or other components of the substation intelligence system 104. In one implementation, the HMI 109 is implemented as software or other computer readable instructions which implement a graphical user interface (GUI) on a
15 suitable computer. User interfaces implemented in connection with the SCADA system 110 or the enterprise system 114, if any, may also allow a user to mine the data from one or more sources or otherwise provide desired HMI functionality.

A functional block diagram depicting an exemplary cable fault detection component 168 in relation to its input 262 and output 276 data is shown in Figure 2. The
20 input data 262 includes oscillographic record data 268 such as time and sample data vectors, the number of sampled data points in the oscillographic record 266, time stamp data 264 such as the date and time at which the record was acquired, the number and

identification of the sampled signals 272 (*e.g.*, the number and identification of the sampled phase or phases), the system frequency 274, and other relevant data 292.

As illustrated, the detection component 268 includes an analysis engine 288 which operates in conjunction with a Fourier processor 246, cable fault signature criteria 238, and alarm criteria 290.

The Fourier transform processor 246, which is again advantageously implemented using suitable computer readable instructions, performs a discrete Fourier transform (DFT) of the voltage and/or current samples in the oscillographic record 268. In one implementation, the DFT is calculated over sample windows or time periods which begin at intervals corresponding to one quarter ($1/4$) cycle of the power system frequency and which have a duration corresponding to one half ($1/2$) cycle of the system frequency, although different window intervals and durations are also contemplated. As will be appreciated, performing a DFT of the time varying cable current samples generates frequency domain data indicative of the frequency component(s) of the cable current during a particular sampling window. The frequency domain data includes a peak at the power system frequency, the magnitude of which is indicative of the cable current during the period covered by the DFT.

The cable fault signature 238 includes internal power system qualifiers 242 and optional external qualifiers 244 which are indicative of a cable fault. In the exemplary case of a cable fault signature 238 associated with a self-clearing fault resulting from an insulation breakdown at a cable splice or joint, the internal qualifiers 242 include a threshold cable current value, a threshold fault duration, and a fault onset criterion, although additional or different qualifiers may also be considered. Again in the case of a

joint insulation breakdown, the external qualifiers 244 may include meteorological data such as precipitation, humidity, and/or ambient temperature.

The alarm criteria 290 include those criteria which are used to signal an alarm condition. In the case of a signature 238 associated with an insulation breakdown, the
5 alarm criteria may include a fault rate or frequency and/or a number of faults, although additional or different criteria are also contemplated. Note that one or more of the cable fault signature 238 and alarm 290 criteria may be adjustable, for example by the user via a GUI implemented on the HMI 109 or otherwise.

The analysis engine 288 evaluates the input data 262 to determine whether the
10 fault satisfies the cable fault signature criteria 238. Again in the exemplary case of a cable fault caused by an insulation breakdown, the analysis engine 288 evaluates the Fourier transformed current signal to determine whether the magnitude of the cable current exceeds the threshold value. The analysis engine 288 also determines whether the duration of the fault is less than the threshold fault duration, whether the onset of the fault
15 occurred at or near a voltage peak, and whether the fault was self-clearing. In an implementation which includes external qualifier(s) 244, the analysis engine 288 also evaluates the relevant other input data 292, for example to determine whether the relative humidity exceeds a desired value. Where the component 168 includes alarm criteria 290, the analysis engine also determines whether the desired alarm criteria have been satisfied,
20 for example to determine whether the rate or frequency of the cable faults exceeds the specified fault rate.

The cable fault detection component 168 uses the results of the evaluation to generate output data 276 such as one or more of a cable fault detected signal or flag 280,

a cable fault rate or frequency 282, the number of cable faults 283, a cable fault alarm signal or flag 284, digital fault record data 286 such as the magnitude and duration of the fault, the phase or phase(s) affected by the fault 278, or other data 294. The output data is advantageously stored as one or more points in the substation intelligence system
5 database 164 together with a suitable time stamp.

Various alternatives and extensions are also contemplated. For example, the detection component 168 may, alternatively or additionally, use other operational or non-operational data 262 as inputs to the cable fault analysis, with the cable fault signature criteria 238 selected accordingly. In one such implementation, the sampled voltage
10 waveform is also be considered, for example to determine whether a period of increased current is accompanied by a dip in the sampled voltage.

If, as another example, heating caused by relatively higher values of cable current is expected to contribute to a cable fault, the average current values may be considered as appropriate. As still another example, other ambient or meteorological data such as
15 lightning strikes, seismic activity, or the like may also be considered.

The detection component 168 may also calculate a probability or likelihood that a particular cable fault results from a particular fault mechanism, for example by assigning relative weights to the various signature criteria 238. The detection component 168 may include or otherwise access an internal or external database containing empirically or
20 heuristically derived cable fault signatures 238 indicative of various cable fault mechanisms. In such a case, the cable fault output signal or flag 280 may also indicate the most likely fault mechanism or mechanisms. Separate outputs or flags may also be provided.

The detection component 168 may be utilized in intelligence systems 104 such as those described in commonly-owned U.S. Patent Application Serial Number 11/555,393 by Stoupis, et al., and entitled *Electrical Substation Monitoring and Diagnostics*, which application was filed on November 1, 2006 and is expressly incorporated by reference in
5 its entirety herein.

As noted above, the detection component 168 advantageously operates on data having the COMTRADE or other desired format. Thus, the detection component 168 component may be executed on a computer or process other than the server computer. For example, the detection component may be executed on a computer associated with
10 the SCADA system 110 or the enterprise system 114, or otherwise on another suitable general purpose or dedicated processor which has access to the desired input data 262 over the communication network 118. Some or all of the component 168 may also be implemented in digital and/or analog hardware.

Various alternative Fourier transform algorithms are also contemplated.
15 According to one such alternative, the discrete Fourier transform may be implemented using a suitable fast Fourier transform (FFT) algorithm. While the above discussion has focused on an analysis engine 288 which operates on frequency domain data, other analysis engines are contemplated. Thus, for example, the analysis engine 288 may perform one or more of time-domain based, rule-based, neural network, expert system,
20 analytical, or other suitable analyses.

Operation will now be described in relation to Figure 3. A fault is detected at step 302. More particularly to the exemplary implementation described above, a protective

device 162 sets a DFR flag and generates DFR data in the COMTRADE or other suitable format.

The DFR data is obtained at step 304. Thus, for example, the DFR data is obtained by the intelligence system 104 and stored in the database 164 for use by the
5 detection component 168. Alternately, the input data 262 is obtained directly by the detection component 168.

The DFR and other relevant input data is analyzed at step 306. As described above, for example, the cable fault detection component 168 evaluates the input data to determine whether the input data is indicative of a cable fault. In an implementation in
10 which the detection component 168 considers signatures indicative of various cable fault mechanisms, the input data is evaluated against the various signatures. Depending on the results of the analysis, desired output data 276 such as one or more of a cable fault detection signal, cable fault number or rate, cable fault alarm, or cable fault mechanism output is generated.

15 At step 308, the output data 276 is stored in the database 164 or other desired location.

At step 310, the process is repeated, for example on a substantially real time basis during the operation of the power system.

Of course, modifications and alterations will occur to others upon reading and
20 understanding the preceding description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS

What is claimed is:

1. A method comprising:
performing a Fourier transform of a time varying signal from an electrical power
5 transmission or feeder cable;
using the Fourier transformed signal to identify a cable fault.
2. The method of claim 1 wherein the Fourier transform includes a discrete Fourier
transform.
- 10 3. The method of claim 1 wherein the time varying signal is a time varying cable
current signal.
4. The method of claim 1 wherein the time varying signal is generally periodic and
15 performing includes Fourier transforming current data acquired over a time period which
corresponds to about one-half cycle of the signal.
5. The method of claim 1 wherein the cable fault includes an insulation breakdown.
- 20 6. The method of claim 1 wherein using includes determining a magnitude of the
Fourier transformed signal.
7. The method of claim 1 wherein performing includes Fourier transforming
oscillographic data generated in response to a power system fault.

8. The method of claim 1 including receiving COMTRADE oscillographic data indicative of the time varying signal.
- 5 9. The method of claim 8 wherein the oscillographic data is generated by a protective relay.
- 10 The method of claim 1 including using a computer of a substation automation, distribution automation, or feeder automation system to perform the step of using the
- 10 Fourier transformed signal.
11. The method of claim 1 including obtaining oscillographic data indicative of the time varying signal over a wide area network and the step of performing includes Fourier transforming the obtained data.
- 15
12. The method of claim 1 including generating an output signal indicative of the identified fault and storing the output signal in a database of a substation automation, feeder automation, or a distribution automation system.
- 20 13. A computer readable storage medium containing instructions which, when executed by a computer processor, cause the processor to carry out a method comprising the steps of:

using frequency domain data from a fault in an electrical power system to
identify a self-clearing cable fault;
generating an output signal indicative of the identified cable fault.

5 14. The computer readable storage medium of claim 13 wherein the method includes
obtaining time varying signal data;
performing a discrete Fourier transform on the time varying signal data to
generate the frequency domain data.

10 15. The computer readable storage medium of claim 14 wherein obtaining includes
obtaining the time varying signal data from a substation automation system database.

16. The computer readable storage medium of claim 13 wherein the method includes
obtaining COMTRADE data from an IED and using the COMTRADE data to generate
15 the frequency domain data.

17. The computer readable storage medium of claim 13 wherein the method includes
determining a cable fault mechanism and wherein the output signal identifies the
determined mechanism.

20

18. The computer readable storage medium of claim 13 wherein using the frequency
domain data includes calculating a magnitude of a current in the cable and comparing the
magnitude to a threshold value.

19. A cable fault detection apparatus comprising:
a computer readable memory containing digital fault record data generated in response to a fault;
- 5 a computer processor in operative communication with the memory, wherein the computer processor executes computer readable instructions which cause the processor to analyze the digital fault record data to determine if the fault is indicative of a cable fault.
20. The apparatus of claim 19 wherein the digital fault record data includes
10 oscillographic data.
21. The apparatus of claim 20 wherein the oscillographic data includes time varying cable current data.
- 15 22. The apparatus of claim 19 wherein the data includes oscillographic data and the processor performs a discrete Fourier transform of the oscillographic data.
23. The apparatus of claim 19 wherein the processor analyzes the digital fault record data to determine whether the fault is indicative of a cable insulation breakdown.
- 20 24. The apparatus of claim 19 including means for detecting the cable fault.
25. The apparatus of claim 19 including means for generating the digital fault record.

26. The apparatus of claim 16 wherein the fault is a self-clearing cable fault.

27. The apparatus of claim 17 wherein the cable includes a substation exit cable.

5

28. A method comprising:

obtaining oscillographic data generated in response to a power system fault;

using a processor to evaluate the digital fault record data to determine if the power system fault is indicative of a self-clearing cable fault.

10

29. The method of claim 28 including storing a result of the evaluation in a computer database.

30. The method of claim 28 wherein the cable includes an electrical power system

15 transmission cable.

31. The method of claim 28 including obtaining the oscillographic data from an IED.

32. The method of claim 31 wherein the oscillographic data includes COMTRADE

20 data.

33. The method of claim 28 wherein the method includes Fourier transforming the oscillographic data.

34. The method of claim 28 wherein the fault has a duration of less than about three cycles.

5 35. The method of claim 28 wherein the processor is located at an electrical substation.

36. The method of claim 28 including determining a likelihood that the cable fault is indicative of a cable fault.

10

37. The method of claim 28 wherein using a processor includes using the processor to evaluate a signal indicative of moisture.

38. The method of claim 28 including repeating the steps of obtaining and evaluating
15 substantially in real time.

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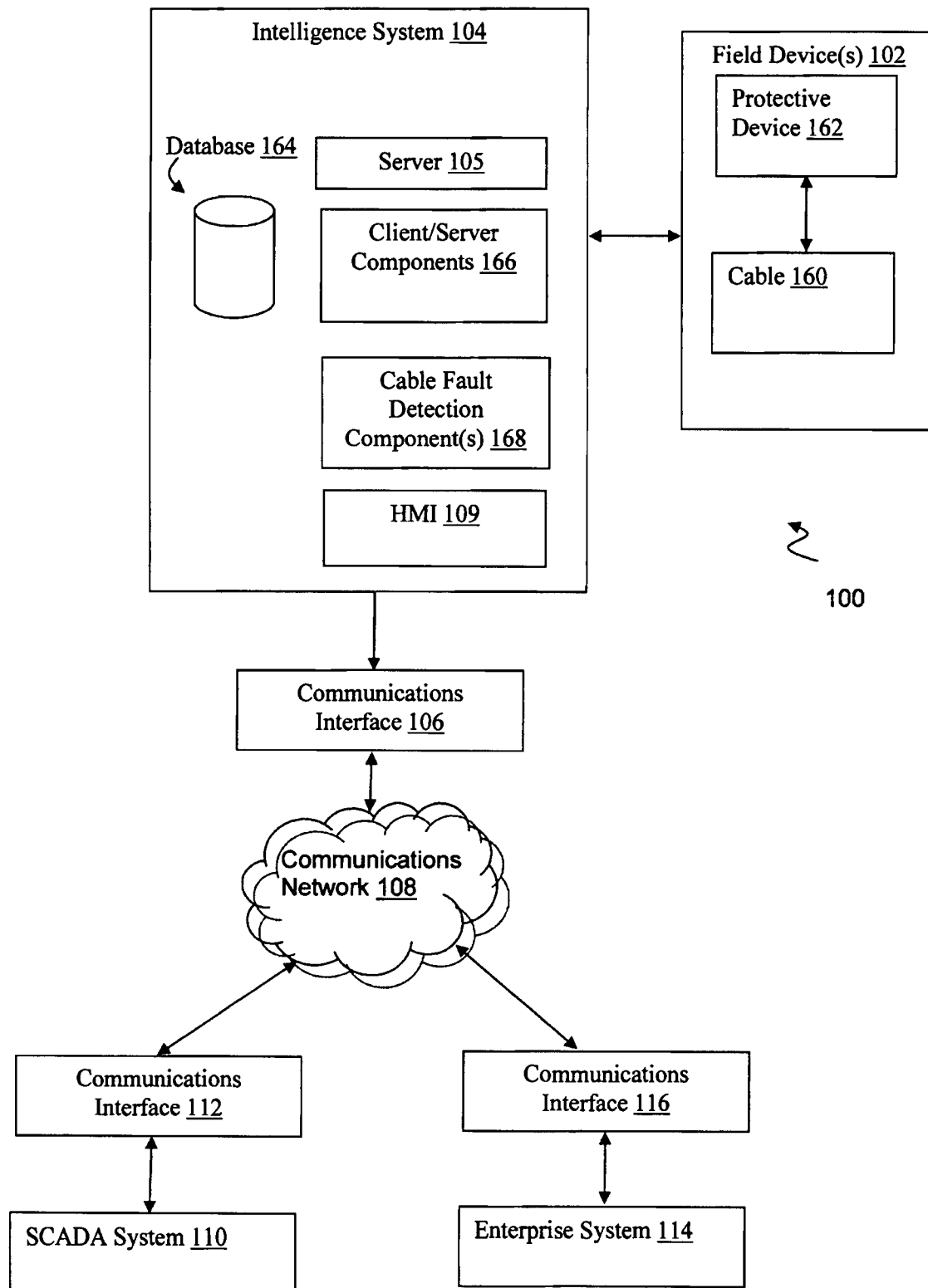
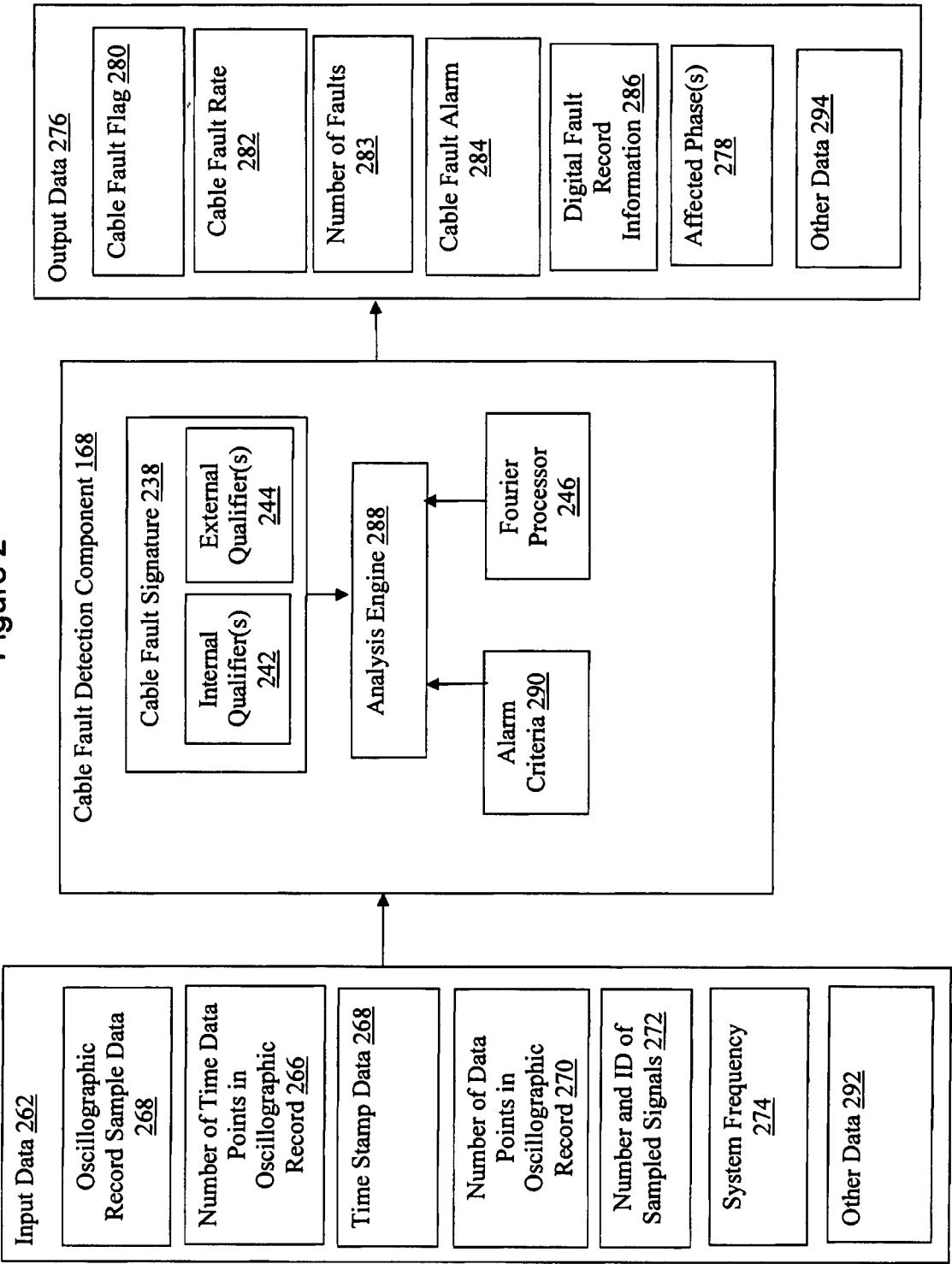
Figure 1

Figure 2



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Figure 3

