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Inventor(s)	Goergen; Joel Richard et al.

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### Bi-directional power over ethernet for digital building applications

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#### Abstract

A system includes a plurality of network devices comprising a plurality of ports, a power bus connecting the network devices, wherein power is shared between the network devices over the power bus, and a controller for identifying available power and allocating power to the ports. The ports include a plurality of PSE (Power Sourcing Equipment) PoE (Power over Ethernet) ports each operable to transmit power to a device connected to one of the PSE PoE ports, a plurality of PD (Powered Device) PoE ports each operable to receive power from a device connected to one of the PD PoE ports, and a plurality of bi-directional PoE ports each configurable to operate as a PSE PoE port to transmit power to a device connected to one of the bi-directional PoE ports or as a PD PoE port to receive power from the connected device.

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**Inventors:** Goergen; Joel Richard (Soulsbyville, CA), Jones; Chad M. (Doylestown, OH), Compton, III; Charles Lacey (Palo Alto, CA)

**Applicant:** Cisco Technology, Inc. (San Jose, CA)

**Family ID:** 1000008765398

**Assignee:** CISCO TECHNOLOGY, INC. (San Jose, CA)

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*Primary Examiner: Prifti; Aurel*

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## **Background/Summary**

CROSS-REFERENCE TO RELATED APPLICATIONS (1) The present application is a continuation of U.S. patent application Ser. No. 18/063,988, filed Dec. 9, 2022, now U.S. Pat. No.

11,831,450, issued Nov. 28, 2023, which is a continuation of U.S. patent application Ser. No. 17/068,115, filed Oct. 12, 2020, now U.S. Pat. No. 11,582,048, issued Feb. 14, 2023, which claims priority from U.S. Provisional Application No. 63/053,500, filed on Jul. 17, 2020 and U.S. Provisional Application No. 63/070,110, filed on Aug. 25, 2020. The contents of these applications are incorporated herein by reference in their entireties.

## TECHNICAL FIELD

(1) The present disclosure relates generally to Power over Ethernet (PoE), and more particularly, to bi-directional PoE.

## BACKGROUND

(2) In applications such as digital building system applications, there is a need for PoE devices to connect to power devices such as solar and battery devices, which require additional capabilities of PoE systems that are not currently provided by conventional PoE systems.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

- (1) FIG. 1 illustrates an example of an integrated digital building system in which the embodiments described herein may be implemented, in accordance with one embodiment.
- (2) FIG. 2 illustrates a bi-directional PoE system in accordance with one embodiment.
- (3) FIG. 3 illustrates another example of the bi-directional PoE system, in accordance with one embodiment.
- (4) FIG. 4 illustrates the bi-directional PoE system with a plurality of switches coupled through a common shared power bus, in accordance with one embodiment.
- (5) FIG. 5 is a block diagram of a directional power control system of the bi-directional PoE system, in accordance with one embodiment.
- (6) FIG. 6 is a block diagram of a bi-directional PoE switch, in accordance with one embodiment.
- (7) FIG. 7 is a block diagram illustrating single pair multi-drop bi-directional PoE, in accordance with one embodiment.
- (8) FIG. 8 is a block diagram of a powered device in FIG. 7, in accordance with one embodiment.
- (9) FIG. 9 is a block diagram illustrating voltage conditioners at bi-directional PoE ports of a switch, in accordance with one embodiment.
- (10) FIG. 10 is an electrical schematic of a powered device (PD) circuit for the bi-directional PoE port, in accordance with one embodiment.
- (11) FIG. 11 is an electrical schematic of a power sourcing equipment (PSE) circuit for the bi-directional PoE port, in accordance with one embodiment.
- (12) FIG. 12 is a block diagram depicting an example of a network device in which the embodiments described herein may be implemented.
- (13) FIG. 13 is a flowchart illustrating a process for role reversal from PSE to PD, in accordance with one embodiment.
- (14) FIG. 14 is a flowchart illustrating a process for role reversal from PD to PSE, in accordance with one embodiment.
- (15) FIG. 15 is a power profile graph illustrating available power from solar, battery, and utility power sources over time.
- (16) FIG. 16 illustrates an example in which utility power is available for port use with battery and solar power reserved for port use or to push into utility power.
- (17) FIG. 17 illustrates an example in which utility and solar power are available for port use and the battery power is reserved for backup.
- (18) FIG. 18 illustrates an example of dynamic application of the utility, solar, and battery power.
- (19) FIG. 19 illustrates an example using only solar and battery power.

(20) FIG. 20 is a flowchart illustrating an overview of a process for identifying available power and allocating power, in accordance with one embodiment.

(21) Corresponding reference characters indicate corresponding parts throughout the several views of the drawings.

## DESCRIPTION OF EXAMPLE EMBODIMENTS

### Overview

(22) In one embodiment, a system generally comprises a plurality of network devices comprising a plurality of ports, a power bus connecting the network devices, wherein power is shared between the network devices over the power bus, and a controller for identifying available power and allocating power to the ports. The ports include a plurality of PSE (Power Sourcing Equipment) PoE (Power over Ethernet) ports, PD (Powered Device) PoE ports, and bi-directional PoE ports. The PSE PoE port is operable to transmit power to a device connected to the PSE PoE port. The PD PoE port is operable to receive power from a device connected to the PD PoE port. The bi-directional PoE port is configurable to operate as a PSE PoE port to transmit power to a device connected to the bi-directional PoE port or as a PD PoE port to receive power from the connected device.

(23) In one embodiment, an apparatus generally comprises a plurality of bi-directional PoE ports each configurable to operate as a PSE PoE port to transmit power to a device connected to one of the bi-directional PoE ports or as a PD PoE port to receive power from the connected device, a power supply unit, and a fault managed power module for receiving fault managed power on an Ethernet cable, converting the fault managed power to a power supply input power, and transmitting the power supply input power to the power supply unit.

(24) In one embodiment, a method generally comprises identifying available power from a plurality of power sources comprising a utility power source, a solar power source, and a battery power source, identifying active ports in a bi-directional Power over Ethernet (PoE) system, and allocating power from one or more of the power sources to power the active ports.

(25) In yet another embodiment, a system generally comprises a plurality of energy resource devices, a network device comprising a plurality of PD PoE ports operable to receive power from the energy resource devices connected to the PD PoE ports, and a power bus for receiving power from the network device and transmitting power to at least one other network device comprising a plurality of PSE (Power Sourcing Equipment) PoE ports for transmitting power to powered devices.

(26) Further understanding of the features and advantages of the embodiments described herein may be realized by reference to the remaining portions of the specification and the attached drawings.

### Example Embodiments

(27) The following description is presented to enable one of ordinary skill in the art to make and use the embodiments. Descriptions of specific embodiments and applications are provided only as examples, and various modifications will be readily apparent to those skilled in the art. The general principles described herein may be applied to other applications without departing from the scope of the embodiments. Thus, the embodiments are not to be limited to those shown, but are to be accorded the widest scope consistent with the principles and features described herein. For purpose of clarity, details relating to technical material that is known in the technical fields related to the embodiments have not been described in detail.

(28) New energy systems allow for low cost solar energy to power buildings and may also incorporate battery power distribution systems. Power over Ethernet (PoE) allows for communications and power distribution to electrically powered components and systems throughout the building, including for example, lights, blinds, emergency systems, building operational systems, and other powered components and systems. Conventional PoE systems provide point-to-point PSE (Power Sourcing Equipment) to PD (Powered Device) power

distribution systems. In conventional systems, the PSE powering system behind a network port only operates in one direction, thus limiting capabilities within the power distributions system. (29) Embodiments described herein provide a bi-directional PoE system that allows for PoE PSE to PD port negotiation or PoE PD to PSE port negotiation. The bi-directional PoE system may be used, for example, to allow PoE devices to connect to solar and battery devices while also providing communications on the same wires. Bi-directional PoE allows a PSE to negotiate to a PD or for a PD to negotiate to a PSE to source power to an attached network device and share power with other applications.

(30) One or more embodiments described herein provide a system, apparatus, method, or logic implementing bi-directional PoE to support multiple ports of received power or sourced power. The system may be deployed, for example, in a digital building to support integrated digital building applications. The bi-directional PoE system provides a power delivery system in which one or more ports may identify a power direction (transmitting or receiving) based on a state of power flow. Each port may independently operate as a PSE to deliver (transmit) power or as a PD to receive power. This allows for any combination of ports transmitting power or receiving power. As described in detail below, the bi-directional PoE system may include a bi-directional PoE circuit for each port to be used as a PSE or PD. One or more embodiments allow devices such as solar devices or other power sourcing devices to contribute to a PoE power load in an environmentally responsive manner. One or more embodiments provide a bi-directional PoE system that maintains compatibility with existing IEEE (Institute of Electrical and Electronics Engineer) 802.3 standards.

(31) Referring now to the drawings, and first to FIG. 1, an example of an advanced integrated digital building system in which the embodiments described herein may be implemented is shown, in accordance with one embodiment. In this example, a building **10** includes solar panels **11** in a solar roof system. The building **10** may also include energy resources other than solar, such as a wind power system, for example. The solar panels **11** are in communication with a power distribution system **14**. The power distribution system **14** may receive utility power, as shown in FIG. 1. The reusable energy sources may reduce the need for utility power and eliminate the need for a generator or central battery system. In one or more embodiments, power from reusable power sources may also be pushed back into the utility power. The power distribution system **14** is operable to transmit power (or transmit and receive bi-directional power) to a bi-directional PoE system **15**.

(32) The building **10** may be configured with one or more antennas **12** (e.g., 5G antenna) coupled to a backhaul system **13** (e.g., defining a backhaul antenna). In one or more embodiments, the power distribution system **14** is in communication with the backhaul system **13** for distributing data along with the power to the bi-directional PoE system **15**. The data may also be transmitted directly between the backhaul system **13** and the bi-directional PoE system. It is to be understood that data may also be received by means other than the antenna **12**.

(33) In one or more embodiments, the power distribution system **14** comprises an FMP (Fault Managed Power)/ESP (Extended Safe Power) distribution system that is configured to transmit and receive power or power and data. In one or more embodiments, the power distribution system **14** may be configured for Power over Ethernet (PoE) (e.g., conventional PoE or PoE+ at a power level <100 watts (W), at a voltage level <57 volts (V), according to IEEE 802.3af, IEEE 802.3at, or IEEE 802.3bt), Power over Fiber (PoF), advanced power over data, FMP, or any other power over communications system in accordance with current or future standards, which may be used to pass electrical power along with data to allow a single cable to provide both data connectivity and electrical power to network devices such as switches, routers, wireless access points, and many other network devices.

(34) The term “Fault Managed Power” (FMP) (also referred to as Extended Safe Power (ESP)) as used herein refers to high power (e.g., >100 W), high voltage (e.g., ≥56V) operation with pulse power delivered on one or more wires or wire pairs. In one or more embodiments, FMP includes

fault detection (e.g., fault detection at initialization and between high voltage pulses) and pulse synchronization between power sourcing equipment (PSE) and a powered device (PD). The power may be transmitted with communications (e.g., bi-directional communications) or without communications.

(35) The term “pulse power” (also referred to as “pulsed power”) as used herein refers to power that is delivered in a sequence of pulses (alternating low direct current voltage state and high direct current voltage state) in which the voltage varies between a very small voltage (e.g., close to 0V, 3V) during a pulse-off interval and a larger voltage (e.g., >12V, >24V) during a pulse-on interval. In one or more embodiments, the FMP (or ESP) provides high power (e.g.,  $\geq 100$  W) at a high voltage (e.g.,  $\geq 56$  V). High voltage pulse power (e.g.,  $\geq 56$  VDC,  $\geq 60$  VDC,  $\geq 300$  VDC,  $-108$  VDC,  $-380$  VDC) may be transmitted from power sourcing equipment to a powered device for use in powering the powered device, as described, for example, in U.S. patent application Ser. No. 16/671,508 (“Initialization and Synchronization for Pulse Power in a Network System”), filed Nov. 1, 2019, which is incorporated herein by reference in its entirety. Pulse power transmission may be through cables, transmission lines, bus bars, backplanes, PCBs (Printed Circuit Boards), and power distribution systems, for example. It is to be understood that the power and voltage levels described herein are only examples and other levels may be used.

(36) In one or more embodiments, FMP may comprise pulse power transmitted in multiple phases in a multi-phase pulse power system with pulses offset from one another between wires or wire pairs to provide continuous power. One or more embodiments may, for example, use multi-phase pulse power to achieve less loss, with continuous uninterrupted power with overlapping phase pulses to a powered device, as described in U.S. patent application Ser. No. 16/380,954 (“Multiple Phase Pulse Power in a Network Communications System”), filed Apr. 10, 2019, which is incorporated herein by reference in its entirety. In one or more embodiments, FMP may refer to a combination of ESP (single-phase or multi-phase DC pulse power) and PoE or a power system operable to switch between ESP and PoE.

(37) The power distribution system **14** may comprise, for example, a router, switch, or other network device operable to receive power (e.g., utility power, solar power, battery power, wind power) and data (e.g., Ethernet) and transmit power and data to the bi-directional PoE system **15**. Integration and control of power from the different power sources may be performed, for example, as described in U.S. patent application Ser. No. 16/746,500 (“Method and System for Integration and Control of Power for Consumer Power Circuits”), filed Jan. 17, 2020, which is incorporated herein by reference in its entirety. As previously described, the power and data may be transmitted as PoE, FMP, ESP, or transmitted using any other suitable power over communications system. In one or more embodiments, the power distribution system **14** transmits bi-directional power and data to the bi-directional PoE system **15**. In one or more embodiments, the power distribution system **14** only receives and transmits power (or bi-directional power). As described in detail below, the bi-directional PoE system **15** may comprise one or more switches, routers, or other network devices comprising a plurality of ports with a bi-directional PoE circuit for each port to be operated as a PSE or PD. The bi-directional PoE system may also include one or more network devices with one or more FMP ports or one or more conventional network devices with only PSE or PD ports.

(38) As shown in FIG. 1, the bi-directional PoE system is connected to any number of powered devices, power sourcing equipment, and bi-directional PoE devices that may operate as PDs or PSEs. In the example shown in FIG. 1, the digital building **10** includes a plurality of APs (Access Points) **16** mounted within the building or external to the building, solar operated blinds **17a**, solar films **17b** (with photovoltaic cells), LED (Light Emitting Diode) lighting **18**, and one or more rechargeable batteries **19**. The bi-directional PoE system **15** may also be operable to power one or more emergency systems **25**. The APs **16** may be in communication with any number of network devices **20** (e.g., computer, laptop, tablet, mobile device, phone, and the like) via Wi-Fi.



(39) In the example shown in FIG. 1, the building includes an outside break area with a local charging station **21** (network device) operable to provide local Wi-Fi and charging to a defined area. The charging station **21** may be a mini bi-directional PSE/PD device powered with bi-directional PoE from the bi-directional PoE system **15** or powered with FMP from the power distribution system **14**. The charging station **21** may be configured for use in small spaces such as a break area (inside or outside) covering only a designated location. The charging station **21** may include, for example, one or more USB (Universal Serial Bus) ports **22**, a solar panel **23a**, local battery **23b**, and antenna **24**. The charging station **21** may combine, for example, light versions of PoE, Wi-Fi, hardware, charging, battery capability, solar charging, or any combination thereof. The charging station **21** may also be a stand-alone system with the solar panel **23a** and battery **23b** providing power to the charging station **21** and no bi-directional power input, to support a small number of wireless devices (e.g., one-three laptops) for a specified period of time (e.g., two hours).

(40) It is to be understood that the digital building and integrated applications shown in FIG. 1 is only an example, and the system may include any number or type of building applications (e.g., light and temperature control, video surveillance, emergency systems), digital network architecture (switching, routing, security), endpoint devices (e.g., sensors (lighting, environmental), IoT (Internet of Things) devices, access points, LED lighting, HVAC (Heating, Ventilation, and Air Conditioning) controller, security devices, video cameras, access control systems, conferencing systems, fire and safety systems), or power sources (e.g., solar, wind, battery, utility).

(41) FIG. 2 illustrates a bi-directional PoE system, in accordance with one embodiment. A bi-directional PoE network device (e.g., switch) **26** comprises a plurality of bi-directional PoE ports **28**. The ports **28** are connected to a plurality of endpoint devices **30**, **32** via Ethernet cables **29**. The network device **26** may be configured to transmit PoE to any number or type of powered devices **30** (e.g., window blinds, room lighting, television, HVAC controls, mini-bar, charging station, and the like).

(42) One or more of the ports **28** may be coupled to an endpoint device operable as a PD or PSE based on available free power to send back into the bi-directional PoE system. As shown in the example of FIG. 2, the endpoint device comprises an energy resource device **32** (i.e., power source operable to generate power local to the endpoint device and provide the power to circuitry at the endpoint device). The energy resource device (local power source) **32** may include, for example, a rechargeable battery, photovoltaic device (e.g., solar capable blind/window system, solar panel or film), or other renewable power source or utility power source (AC power source). The energy resource device **32** may operate as a PSE or PD based on available free power to send back into the power system. If the energy resource device has excess power available after powering the local circuits in the endpoint device, the energy resource device may also provide the excess power to the network device **26** over Ethernet cable **29**. The port **28** switches between operation as a PSE port or PD port based on operating state of the energy resource device **32**. As described in detail below, each of the bi-directional ports **28** and one or more ports at the endpoint devices **32** may be configurable as responsive to an enable signal to operate as either a PSE port to source power or as a PD port to receive power. Coordination between role reversal at connected ports is described below with respect to FIGS. 13 and 14.

(43) The network device **26** may include any number of PSUs (Power Supply Units) **34**. The PSU **34** may be a removable module (field replaceable, hot-swappable device) that is received in an opening at the rear of the chassis (or other location) and configured to provide power (e.g., 48 VDC, 54 VDC, or other regulated voltage) to the network device **26**. One or more of the PSUs **34** may receive utility power or power from an UPS (Uninterruptible Power Source) at a plug **36**. As shown in the example of FIG. 2, one of the PSUs **34** is bi-directionally coupled to a battery system (e.g., DC battery system, portable power system, wall mounted power system) **38**. The rechargeable battery **38** is operable to source power and be charged by excess system power from the network device **26**.

(44) It is to be understood that the switch **26** shown in FIG. 2 is only an example of a device that may be used to implement the embodiments described herein and that other types of devices (e.g., router, switch/router, or other network device) with any number of ports may be used. Also, any number of the ports may be configured for bi-directional PoE (both PD and PSE operation), PD operation, PSE operation, or FMP operation at one or more power levels. For example, the system may be configured as a 90 watt system with bi-directional PoE or a bi-directional 350 watt PoE system and may be powered by an FMP power system with bi-directional FMP, as described below.

(45) FIG. 3 illustrates a bi-directional PoE system utilizing FMP (also referred to as FMP/ESP). In one or more embodiments, an apparatus (network device, switch) **27** comprises a plurality of bi-directional PoE ports **28** each configurable to operate as a PSE PoE port to transmit power to a device **32** connected to one of the bi-directional PoE ports or as a PD PoE port to receive power from the connected device, the power supply unit **34**, and a fault managed power module **43** for receiving fault managed power on an Ethernet cable **44a**, converting the fault managed power to a power supply input power, and transmitting the power supply input power to the power supply unit.

(46) The network device **27** may also comprise one or more FMP ports (e.g., FMP TX **42b** as shown in FIG. 3, FMP TX/RX port, FMP RX port). The FMP TX port **42b** may, for example, transmit FMP over cable **44b** to one or more network devices or power distribution system **31** (e.g., provide power to another network device or powered device). As described below with respect to FIG. 4, the FMP TX port **42b** may be used in a bi-directional PoE system with multiple energy resource devices to add excess power back into a utility power source (e.g., through the power distribution system **14** of FIG. 1).

(47) As shown in FIG. 3 an FMP bi-directional device **40** may be interposed between the DC battery system **38** and the bi-directional PoE switch **27** to convert the DC battery power to FMP. The switch **27** may use excess PoE power to push back into the FMP device **40**. The battery system **38** includes a bi-directional connection with the FMP device **40** so that it can both source power or be charged by excess system power. In the example shown in FIG. 3, the FMP bi-directional device **40** comprises FMP transmitter/receiver (FMP TX/RX) ports **42a**, FMP transmitter (FMP TX) ports **42b**, and FMP receiver (FMP RX) ports **42c**. It is to be understood that the FMP device **40** may include any number of ports configured as a transmitter/receiver, transmitter, or receiver.

(48) The FMP device **40** has a bi-directional connection (cable **44a**) to the FMP module **43** (also referred to as a power receiver, FMP receiver, or power adapter). The fault managed power module **43** is configured to receive fault managed power on the Ethernet cable **44a**, convert the fault managed power to a power supply input power, and transmit the PSU input power to the power supply unit **34**. The bi-directional PoE switch **27** may comprise one or more PSUs **34** (two shown in FIG. 3) with one or more power adapters **43** aligned for connection with the PSUs (one adapter shown in FIG. 3). The FMP module **43** is operable to convert the FMP to a standard power supply input power (e.g., 240 VAC, 240 VDC, 380 VDC, or other standard PSU input power). The cable **44a** may comprise four-pair communications cabling, Single Pair Ethernet (SPE), or any other cable comprising one or more wire pairs. Single-phase or multi-phase pulse power input may be provided to the FMP module **43** on the cable **44a**. The FMP module **43** may comprise, for example, a power adapter as described in U.S. patent application Ser. No. 16/912,563 (“Power Adapter for Power Supply Unit”), filed Jun. 25, 2020, which is incorporated herein by reference in its entirety.

(49) FIG. 4 illustrates an example of a bi-directional PoE system comprising a plurality of network devices (e.g., switch, router, switch/router) **45**, **46**, **48** comprising a plurality of ports **52a**, **52b**, **52c**, **52d**, a power bus **49** connecting the network devices, with power shared between the network devices over the power bus, and a controller (system power controller) **47** for identifying available power and allocating power to the ports. In one or more embodiments, a system comprises a plurality of energy resource devices (e.g., battery/energy storage system **53**, PV (photovoltaic) device **54**), the network device **46**, **48** comprising a plurality of PD PoE ports operable to receive power from the energy resource devices connected to the PD PoE ports, and the power bus **49**

receiving power from the network device and coupled to at least one other network device **45** comprising a plurality of PSE PoE ports for transmitting power to powered devices **51**.

(50) In one example, the power bus **49** is configured for transmitting power in a voltage range of 54 VDC (Volts Direct Current) to 60 VDC. The power bus **49** may be configured to transmit PoE (power and data) at any suitable voltage level. As shown in the bi-directional PoE system of FIG. **4**, the controller **47** is located at one of the network devices. The controller may also be located at a management device coupled to the power bus or may be a distributed control system located at one or more of the network devices. The plurality of ports comprise a plurality of PSE PoE ports **52b** each operable to transmit power to a powered device **51** (e.g., lighting, IoT device, or other PD) connected to one of the PSE PoE ports, a plurality of PD PoE ports **52c** each operable to receive power from a device **54** connected to one of the PD PoE ports, and a plurality of bi-directional PoE ports **52a**, each configurable to operate as a PSE PoE port to transmit power to a device **53** (e.g., rechargeable battery, energy storage system, or other storage device) **53** connected to one of the bi-directional PoE ports or as a PD PoE port to receive power from the connected device. Each network device **45**, **46**, **48** may include only one type of port (e.g., only PD ports, only PSE ports, or only bi-directional ports) or any combination of ports. The ports may support all twisted pair speed types.

(51) In the example shown in FIG. **4**, three network devices **45**, **46**, **48** are coupled together over the common shared power bus **49**. A first network device **45** (top unit in FIG. **4**) is shown with ports operating as (defined as) PSE ports (e.g., 90 W or other power level ports). In this example, the network device **45** includes an FMP TX port **52d**, which may be used to transmit FMP to a device or transmit excess power back to utility.

(52) A second network device **46** (middle device in FIG. **4**) is configured with bi-directional PoE ports **52a**, PSE PoE ports **52b**, and PD PoE ports **52c**. The bi-directional PoE ports **52a** are shown coupled to the battery or energy storage system **53**.

(53) A third network device **48** (bottom device in FIG. **4**) is configured for micro-grid input and comprises a plurality of the PD PoE ports **52c**. The third network device **48** may comprise, for example, a low power switch configured to pass basic commands, data, and other information to a primary network device (e.g., network device **46** coupled to the bus **49**). In this example, the third network device **48** has a plurality of PV devices **54** (e.g., thin solar panel or film with connected electronics) coupled to the PD PoE ports **52c** for transmitting power to the network device **48**. The network device **48** may be referred to as a PD aggregator and may combine power received from the energy resource devices **54** at the PD PoE ports **52c** and transfer the combined power over the power bus **49** to another network device (e.g., network device **45**) comprising the PSE PoE ports **52b**.

(54) A side view of the PV device **54** is shown in FIG. **4**. The PV device may include, a thin solar panel or film **54a** (e.g., transparent, semi-transparent, opaque, or sun blocking) configured for mounting on a window, or any other device comprising photovoltaic cells operable to convert light into electricity. The solar panel **54a** may be connected to a PoE device comprising a PSE port **54b** or a bi-directional PoE port **54c**. For example, a solar window blind may receive power for use in rolling up or down the window blind and transmit power generated when the sun is out to the network device **48**. Thus, one or more of the PD PoE ports **52c** may be configured as a bi-directional PoE port **52a** operable to transmit power to the PV device **54** or receive power from the PV device.

(55) It is to be understood that the system shown in FIG. **4** is only an example and the bi-directional PoE system may include any number of network devices (e.g., switches, routers, switch/routers) comprising any number, type, or combination of ports (PD PoE, PSE PoE, bi-directional PoE, FMP TX, FMP RX, FMP TX/RX) in any arrangement. One or more of the network devices **45**, **46**, **48** may receive utility power or FMP, as previously described with respect to FIG. **3**. The network devices may be mounted in a rack, cabinet, or ceiling, for example.

(56) FIG. 5 is a simplified block diagram illustrating an overview of bi-directional PoE operation, in accordance with one embodiment. A front end power distribution system **55** provides power to one or more bi-directional PoE ports **56**. Each port comprises a PD circuit **57a** and a PSE circuit **57b** coupled to a controller **58** operable to detect power direction and enable PD or PSE operation. The controller **58** transmits an enable (EN) signal to enable PD operation at PD circuit **57a** or PSE operation at PSE circuit **57b**. The port will transmit power to a load or receive power from a source (load/source **59**). In one or more embodiments, the system incorporates a PD block **57a** and a PSE block **57b** with FET (Field Effect Transistor) bridging (described below with respect to FIGS. **10** and **11**) to enable a negotiated direction of power (transmitting or receiving). An enable pin may be provided in a controller chip along with a state diagram set identifying basic PoE PSE and PD direction specific negotiations.

(57) FIG. 6 is a block diagram of a bi-directional PoE network device **60** (e.g., switch or other network device), in accordance with one embodiment. In this example, two PSUs (Power Supply Units) **61** and an FMP unit **62** are coupled to a bi-directional PoE port **63**, which supports PSE or PD operation, a PSE PoE port **64**, and a PD PoE port **65**. The PSU **61** may receive utility power or PSU input power from the FMP module (power adapter) **43** described above with respect to FIG. 3. In this example, the components (ports **63**, **64**, **65**, PSU **61** and FMP unit **62**) are coupled to an internal system **77** providing regulated and isolated 54 VDC distribution (or any voltage up to 60 VDC), for example. The PSUs **61** receive utility power (e.g., AC, DC, or FMP input) at block **66**, which passes through isolation circuit **67** to provide regulated output power at block **68**. The FMP unit **62** receives power from an isolation circuit **69**, which is transmitted to a power converter operable to convert 54 VDC (or other regulated power) to HVDC (high voltage DC) at block **70**. FMP is transmitted at block **71**.

(58) The network device **60** includes a POL (Point-of-Load) **72** coupled to the internal system **77** via an isolation circuit **73** and regulated power block **74**. The POL **72** provides power over multiple rails to one or more integrated circuits (e.g., switching/routing ASIC (Application Specific Integrated Circuit) **75**). The ASIC **75** is coupled to the bi-directional PoE port **63** through a PSE/PD power controller **76** operable to enable PSE or PD operation, as previously described with respect to FIG. 5. The ports **63**, **64**, **65** receive regulated and isolated power from the internal power distribution system and data from the ASIC **75**. As previously noted, the network device **60** may include any number or combination of bi-directional, PD, PSE, or FMP ports. Each PoE port comprises a PoE connector (e.g., RJ-45 or other suitable connector) for transmitting PoE (bi-directional PoE port **63**, PSE PoE port **64**) or receiving PoE (bi-directional PoE port **63**, PD port **65**). Each port also comprises a PSE circuit **78a**, PD circuit **78b**, or both PSE and PD circuits.

(59) FIG. 7 illustrates an example of a single pair multi-drop (SPMD) bi-directional system, in accordance with one embodiment. In this example, a PSE port **90** transmits power and data over a cable **91** to a plurality of powered devices **92** (PD.sub.1, PD.sub.2, PD.sub.3, PD.sub.4, . . . PD.sub.X). SPMD provides PSE simplification as voltage regulation is done at the PD. Power per segment may be more restricted due to a larger current on the single wire pair. The PSE port **90** and PDs **92** are configured for bi-directional PoE operation.

(60) FIG. 8 is a simplified electrical schematic of the powered device **92**, in accordance with one embodiment. In this example, a voltage conditioner **93** is coupled to a solar device **94** and senses polarity and adjusts as needed. A PD IC (Integrated Circuit) **95** is coupled to a load and a diode bridge **96**. The voltage conditioner **93** may also sense voltage and regulate voltage at power in/out (A/B). The voltage conditioner **93** may include PSE functionality so that it can disable PD operation at the PD IC **95** to prevent self-discovery.

(61) In order to account for different cable lengths connecting the bi-directional PoE ports to the connected devices, which will result in different voltages at the PSE (for reverse power system), voltage conditioner **93** is inserted into a switch **99** with bi-directional ports, as shown in FIG. 9. In this example,  $V1 \neq V2 \neq V3 \neq V4$  due to the different cable lengths L1, L2, L3, and L4 connecting bi-

directional PDs **92** (PD.sub.1, PD.sub.2, PD.sub.3 PD.sub.4), respectively to the switch. The voltage conditioners **93** are coupled to the internal system regulated and isolated distribution system **97** through voltage line (V.sub.out) **98a** and current sense line **98b**.

(62) FIGS. **10** and **11** illustrate PD and PSE circuits for the bi-directional PoE port, in accordance with one embodiment. For simplification and clarity, the circuits are shown separately in FIGS. **10** and **11**, however, it is to be understood that the PD and PSE circuits are both located at the bi-directional PoE port and are connected to the same set of transformers **103** coupled to the twisted pairs **102** of the cable.

(63) FIG. **10** is an electrical schematic of a PD circuit for bi-directional PoE, generally indicated at **100**. In this example, a connector (e.g., RJ-45 connector) is coupled to a cable comprising four twisted pairs **102**. The PD circuit **100** includes two bridge rectifiers **105** coupled to a PD chip (PD IC) **104** comprising an N-FET. The PD chip **104** is coupled to a PD load **108** and PD operation is enabled at the PD chip with a PD enable signal. The PD chip **104** provides detection, presents classification, and controls the hot swap FET. The circuit also includes a regulator **106**.

(64) FIG. **11** is an electrical schematic of a PSE circuit for bi-directional PoE, generally indicated at **110**. PSE enable is provided by a control signal at a PSE controller **112**. In one or more embodiments, an enable signal is used to avoid problems with combining both PD and PSE to the same eight pins in which case the PSE may self-detect. The circuit **110** includes two P-FETs **114** and an N-FET **115**.

(65) The port includes center-tap transformers **103** that operate in a phantom power mode to either separate data from power when combined data and power are received (for PD operation shown in FIG. **10**) or combine data with power and then transmit the combined data and power (for PSE operation shown in FIG. **11**). Combined data and power is carried over the twisted pair conductors **102** in the Ethernet cable. The PoE power is carried bi-directionally on the same connector and pins at the port and along the same pairs of twisted wires in the cable.

(66) FIG. **12** illustrates an example of a network device **120** (e.g., switch, router, and the like) that may implement one or more embodiments described herein. In one or more embodiments, the network device **120** is a programmable machine that may be implemented in hardware, software, or any combination thereof. The network device **120** includes one or more processor **122**, memory **124**, interface **126**, and bi-directional PoE controller (power controller) **128**.

(67) Memory **124** may be a volatile memory or non-volatile storage, which stores various applications, operating systems, modules, and data for execution and use by the processor **122**. The network device **120** may include any number of memory components.

(68) Logic may be encoded in one or more tangible media for execution by the processor **122**. For example, the processor **122** may execute codes stored in a computer-readable medium such as memory. The computer-readable medium may be, for example, electronic (e.g., RAM (random access memory), ROM (read-only memory), EPROM (erasable programmable read-only memory)), magnetic, optical (e.g., CD, DVD), electromagnetic, semiconductor technology, or any other suitable medium. In one or more embodiments, logic may be encoded on one or more non-transitory computer readable media for execution and when executed operable to perform the steps described below with respect to FIGS. **13**, **14**, and **20**. The logic may be in the form of software executed by the processor, digital signal processor instructions, or in the form of fixed logic in an integrated circuit, for example. The network device **120** may include any number of processors **122**.

(69) The network interface **126** may comprise any number of interfaces (line cards, ports, bi-directional PoE ports, PD ports, PSE ports) for receiving power and data or transmitting power and data to other network devices.

(70) The bi-directional PoE controller **128** may be used to detect power direction, negotiate PoE, and enable PD or PSE operation, for example. The controller **128** may also perform PSE operations including, for example, PD detection and classification when the port is configured to operate as a

PSE port or perform PD operations including, for example, presenting to the PSE valid detection and classification signatures in response to the PSE operations. The controller **128** may selectively activate (enable) the PD circuit shown in FIG. **10** or the PSE circuit shown in FIG. **11**. The controller **128** may also monitor local power related parameters, current flows, or telemetry information, track power flow direction, and initiate a role reversal at the bi-directional PoE port. The power flow direction may be changed, for example, if excess power availability is identified at the PD.

(71) It is to be understood that the network device **120** shown in FIG. **12** and described above is only an example and that different configurations of network devices may be used. For example, the network device may further include any suitable combination of hardware, software, algorithms, processors, devices, components, or elements operable to facilitate the capabilities described herein.

(72) As previously described, the bi-directional PoE ports perform dynamic switching between PSE and PD roles of the ports at opposite ends of a cable so that power can flow bi-directionally. FIGS. **13** and **14** are flowcharts illustrating an overview of a process for PSE/PD and PD/PSE role reversal, in accordance with one embodiment. FIG. **13** describes a process in which the network device port starts out as a PSE (PSE mode) and switches to PD mode. FIG. **14** describes a process in which the network device port starts out as a PD (PD mode) and switches to PSE mode.

(73) Referring first to FIG. **13**, the bi-directional PoE port starts in PSE mode at step **130**. The system waits for PoE standard negotiation at step **131** and once PoE negotiation is complete, the PSE powers the PD (step **132**). If the PSE receives a request from the connected PD to become a PSE (step **133**), the PSE will switch from a source (PSE mode) to a sink (PD mode) (step **134**) and accept power (step **135**) from the connected device, which is now operating as a PSE. If there is a failure or the connected device is no longer providing sufficient power (step **136**), the device switches back to PSE mode (step **137**) and powers the PD (step **132**).

(74) Referring now to FIG. **14**, the bi-directional PoE port starts in PD mode (step **140**). The port negotiates a power class (step **141**) and receives power from the PSE (step **142**). If power is available to source at the device (step **143**), the PD may send a request to the PSE to switch modes (step **144**). Upon receiving approval to switch modes (step **145**), the device negotiates available power to source and a power source class (e.g., 15 W, 30 W, 45 W, 60 W, 90 W, 150 W, 200 W, 350 W, or any other suitable power level) (step **146**). The device switches from PD mode to PSE mode (step **147**) and delivers power to the connected device (step **148**). If there is a failure or the device no longer has available power to source (or available power drops off) (step **149**), the device switches back to PD mode (step **150**) and receives power from the PSE (step **142**).

(75) It is to be understood that the processes shown in FIGS. **13** and **14** are only examples and steps may be added, deleted, modified, reordered, or combined, without departing from the scope of the embodiments.

(76) FIG. **15** illustrates power management in a bi-directional PoE system operable to receive power from utility power, solar energy, or battery energy. In a graph shown in FIG. **15**, solar power varies throughout the day as illustrated at trace **151**. In this example, utility power provides 80% of available power, as shown at **154**, and battery power provides the remaining 20% of available power, as shown at **152**. It is to be understood that the power sources described in FIGS. **15-19** are only examples and additional power sources or different power sources may be used, without departing from the scope of the embodiments. Based on the available power and the number of active ports (active PSE ports), the ports may shed power, limit power, or add power to the system. In one or more embodiments, power may be shared among ports using an isolated distribution bus, as previously described.

(77) FIGS. **16-18** illustrate different examples of power availability and usage. In a first example, shown in FIG. **16**, utility power provides 80% of the maximum port power as indicated at **164**. The available battery power shown at **162** is based on a battery in fully charged state. The solar power

**161** and battery power **162** may be reserved for port usage or pushed into utility power.

(78) In a second example shown in FIG. **17**, battery power **172** is reserved for backup. 100% power is available for port use for at least part of the day using a combination of utility power **174** and solar power **171**. When the solar power exceeds the needed power, the extra power may be pushed into utility. When the solar power drops off, power may be reduced at one or more ports.

(79) In a third example shown in FIG. **18**, 100% of power is available from utility **184** and battery **182** and may be dynamically applied. Extra solar power **181** at peak solar time may be used to charge the battery or pushed into utility power.

(80) In a fourth example shown in FIG. **19**, only solar power **191** and battery power **192** are used, with no utility power. Power may need to be reduced at one or more ports when available power is less than 100%.

(81) Various algorithms may be implemented to determine how to use available power and how to allocate power to the active ports. The system may be configured to shed power (turn off one or more ports, reduce power at one or more ports), limit power, reserve power, add excess power back to utility, or any combination thereof. The controller may use any type of algorithm (e.g., default, user defined) to determine how to allocate available power to active ports. The controller may take into account the time of day, weather conditions (cloudy, sunny), battery charge status, priority of one or more network devices or ports, or any other parameters or variables in allocating power to the active ports. Connected devices may collect data that provides information such as energy usage or building occupancy, which may be used in system analytics. The system may also include smart services with analytics (e.g., IoT enabled smart control applications at endpoint devices) with any number of sensors or type of monitoring. The power controller may communicate with one or more devices using any suitable power management communication protocol, including for example, LLDP (Link Layer Data Protocol), which may also be used to signal role reversal of the bi-directional PoE ports.

(82) FIG. **20** illustrates an overview of a process in which available utility power, solar power, and battery power is identified and allocated for any number of ports. Power allocation may be based on any number of parameters including, time of day, power availability, port priorities, etc.

Available power from a plurality of power sources comprising a utility power source, a solar power source, and a battery power source is identified at step **200**. Active ports in the bi-directional PoE system are identified (e.g., PSE ports or bi-directional ports operating as PSE) (step **202**). A portion (0-100%) of each power source may be selected to power the ports or for another use (e.g., extra solar power pushed into utility power, extra power used to charge battery) (step **204**). A controller allocates power from one or more of the power sources to power the active ports (step **206**). Power may be reduced at one or more ports if available power is less than needed at all ports operating at full capacity. This may include turning off one or more ports or limiting power at one or more ports. This process may be continually updated as power levels change (e.g., available solar power varies throughout the day or changing weather conditions, battery charged) and adjusted to meet varying needs at the ports. For example, one or more powered devices may have available power to put back into the bi-directional PoE system, thereby reducing system power needs. The power identification and allocation may be updated periodically or upon sensing a change in power usage or availability.

(83) It is to be understood that the process shown in FIG. **20** is only an example and steps may be modified or added without departing from the scope of the embodiments. Also, any combination of power sources may be used (e.g., utility, battery, solar, wind) to power any number or type of ports.

(84) Although the method and apparatus have been described in accordance with the embodiments shown, one of ordinary skill in the art will readily recognize that there could be variations made without departing from the scope of the embodiments. Accordingly, it is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

## Claims

1. A system comprising: a plurality of network devices comprising a plurality of ports; a power bus connecting said plurality of network devices; and a controller for identifying an available power and allocating the available power to said plurality of ports; wherein said plurality of ports comprises: a plurality of PSE (Power Sourcing Equipment) fault management power (FMP) ports, each operable to transmit the available power to a first device connected to one of the PSE FMP ports; a plurality of PD (Powered Device) FMP ports each operable to receive the available power from a second device connected to one of the PD FMP ports; and a plurality of bi-directional FMP ports each configurable to operate as a PSE FMP port to transmit the available power to a third device connected to one of the bi-directional FMP ports or as a PD FMP port to receive the available power from the third device, wherein the FMP includes a fault detection between pulses of the available power.
2. The system of claim 1, wherein the power bus is a common isolated bus.
3. The system of claim 1, wherein the power bus includes a plurality of common bus bars.
4. The system of claim 1, wherein the power bus is configured to couple together the plurality of network devices such that the available power received via a first network device of the plurality of network devices is provided to a second network device of the plurality of network devices.
5. The system of claim 1, wherein the third device connected to one of the bi-directional FMP ports comprises one of a solar device, a rechargeable battery, or a reusable power source.
6. The system of claim 1, wherein the controller is located at one of the plurality of network devices.
7. The system of claim 1, wherein the controller is a system power controller that identifies the available power in the system and allocates the available power to the plurality of ports of the plurality of network devices.
8. The system of claim 1, wherein: at least one of the plurality of network devices receives utility power, the third device comprises a rechargeable battery and the second device comprises a solar device, and the controller is configured to: identify available utility power, available battery power, and available solar power, and determine a portion of each of the available utility power, the available battery power, and the available solar power to use for powering the plurality of ports.
9. The system of claim 1, wherein at least one FMP port of the plurality of ports is configured to transmit excess power back to a utility power source.
10. The system of claim 1, wherein one of the first device, the second device, and the third device is a power source equipment and another one of the first device, the second device, and the third device is a powered device.
11. An apparatus comprising: a plurality of bi-directional fault managed power ports, each configurable to operate as a PSE (Power Sourcing Equipment) fault managed power port to transmit power to a device connected to one of the bi-directional fault managed power ports or as a PD (Powered Device) fault managed power port to receive the power from the device; a power supply unit; and a fault managed power module having one of the plurality of the bi-directional fault managed ports for receiving fault managed power and transmitting the fault managed power to the power supply unit, wherein the fault managed power includes a fault detection between power pulses.
12. The apparatus of claim 11, wherein the fault managed power module is aligned for connection with the power supply unit.
13. The apparatus of claim 11, wherein at least one of the plurality of bi-directional fault managed power ports supports an Ethernet cable or at least one twisted pair.
14. The apparatus of claim 11, wherein the power supply unit is a removable module.
15. The apparatus of claim 11, wherein at least one of the plurality of bi-directional fault managed



power ports is operable to transmit or receive the fault managed power from a plurality of devices connected to the bi-directional fault managed power port on a single pair cable in a multi-drop arrangement.

16. The apparatus of claim 11, wherein each of the plurality of bi-directional fault managed power ports comprises a voltage conditioner to account for different cable lengths connecting the bi-directional fault managed power ports to the connected devices.

17. A method comprising: identifying an available power from at least two power sources, wherein the at least two power sources are different power source types; identifying active ports in a fault managed power (FMP) system and performing a fault detection between pulses of the available power; and allocating the available power from one or more of the at least two power sources to power the active ports by determining a portion of the available power to select of the at least two power sources for powering the active ports or for charging one of the at least two power sources.

18. The method of claim 17, wherein the at least two power sources include: a battery power source or a utility power source, and at least one reusable energy power source.

19. The method of claim 18, wherein the at least one reusable energy power source includes a solar power source and a wind power source and wherein allocating the available power further comprises allocating the available power to charge the battery power source or add to the utility power source.

20. The system of claim 1, wherein the FMP includes a pulse synchronization between the plurality of bi-directional FMP ports for the fault detection.

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