US 20020105413A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2002/0105413 A1**

Cern et al. (43) **Pub. Date: Aug. 8, 2002**

(54) **INDUCTIVE COUPLING OF A DATA SIGNAL TO A POWER TRANSMISSION CABLE7**

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(21) Appl. No.: **09/752,705**

(22) Filed: **Dec. 28, 2000**

Related U.S. Application Data

(60) Provisional application No. 60/173,808, filed on Dec. 30, 1999. Provisional application No. 60/198,671, filed on Apr. 20, 2000.

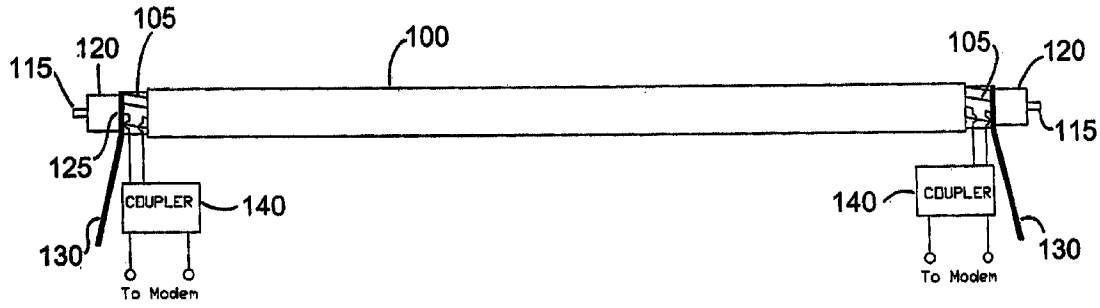
Publication Classification

(51) **Int. Cl.**[7] **H04M 11/04**

(52) **U.S. Cl.** **340/310.01**; 340/310.06

(57) **ABSTRACT**

There is provided an apparatus for enabling communication of a data signal via a power transmission cable. The apparatus comprises (a) a first winding for coupling the data signal via a conductor of the power transmission cable, and (b) a second winding, inductively coupled to the first winding, for coupling the data signal via a data port.



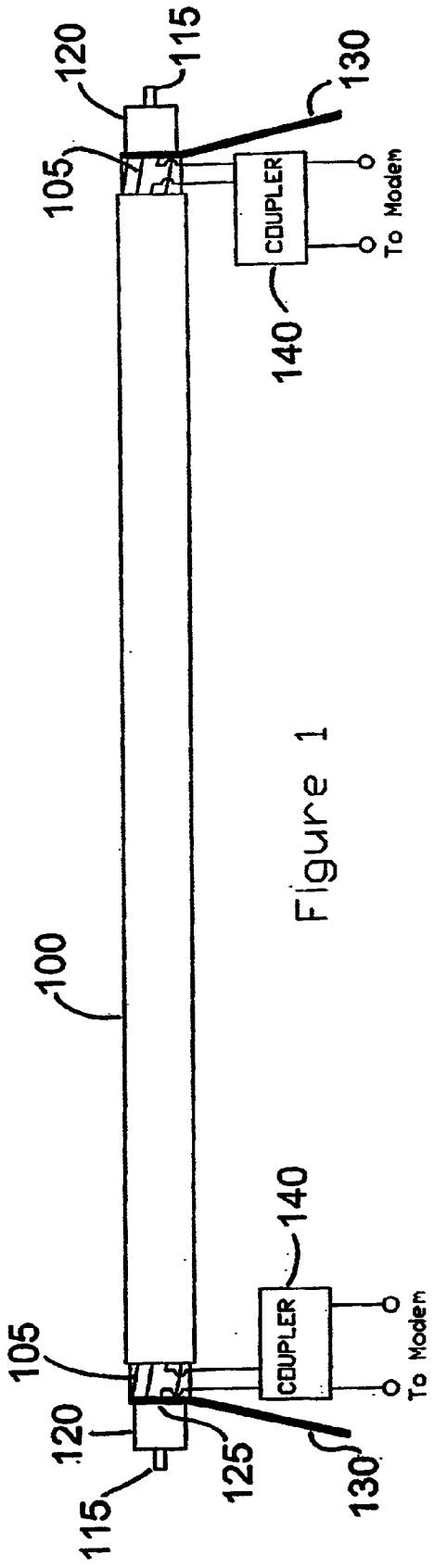

120
115
130
105
COUPLER
To Modem
140
100
140
105
COUPLER
To Modem
120
125
130
115

Figure 1

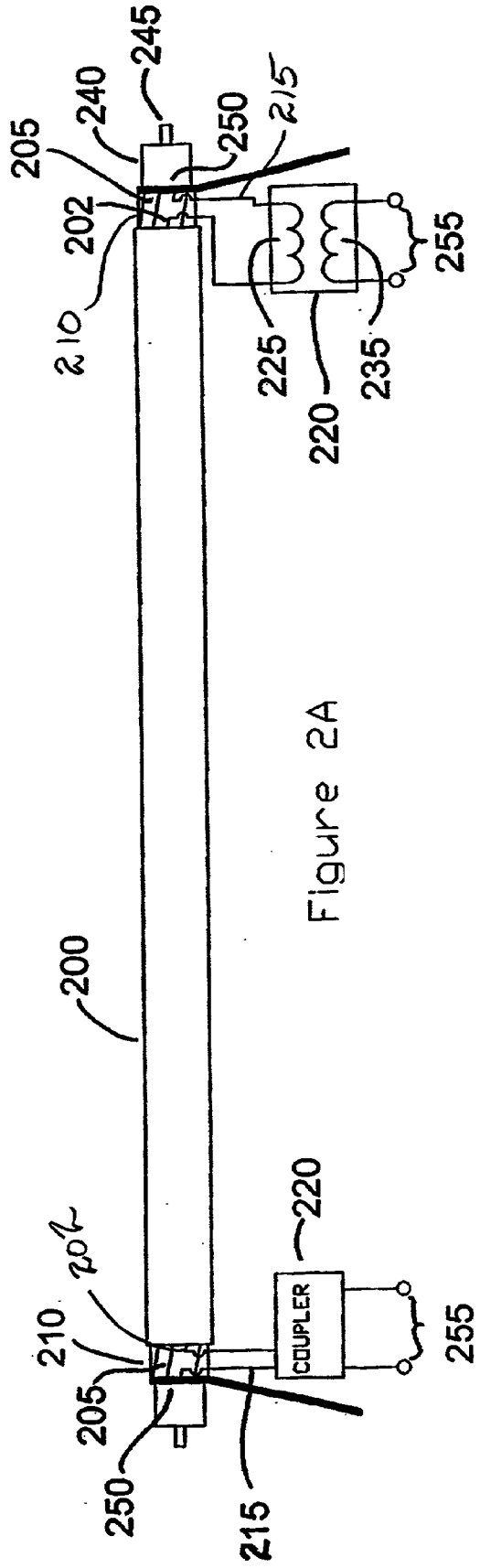

245
240
205
250
215
202
210
225
220
235
255
200
220
COUPLER
210
205
250
215
255

Figure 2A

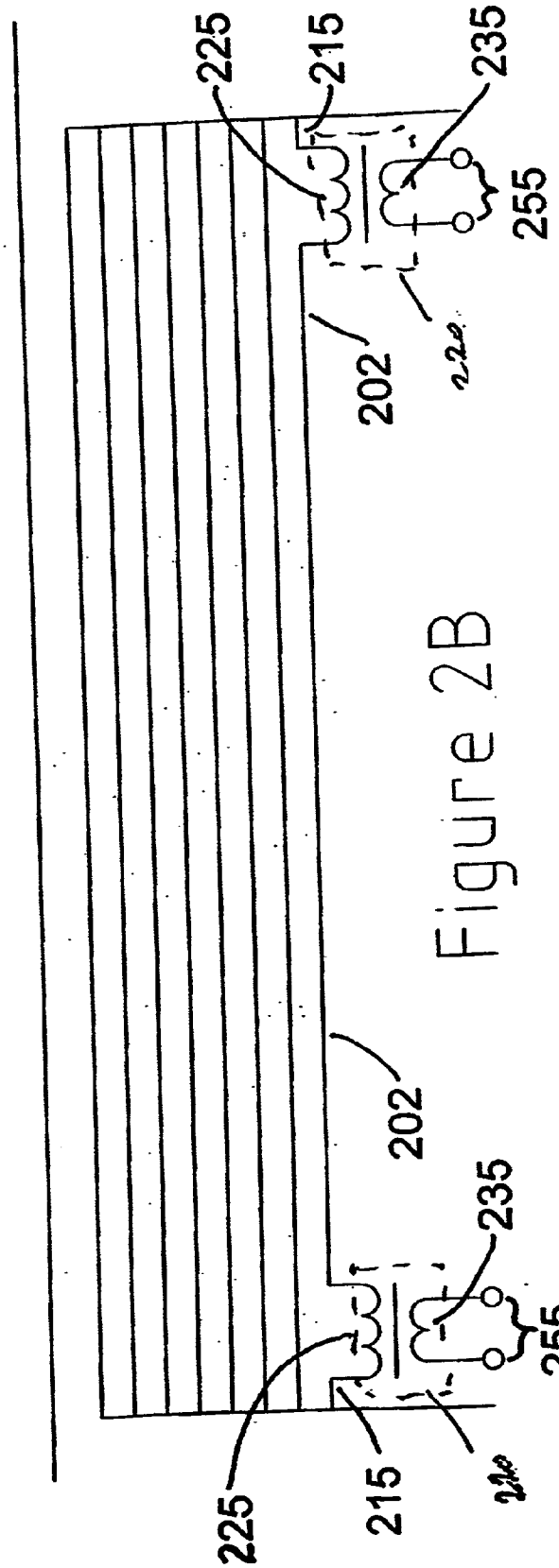


Figure 2B

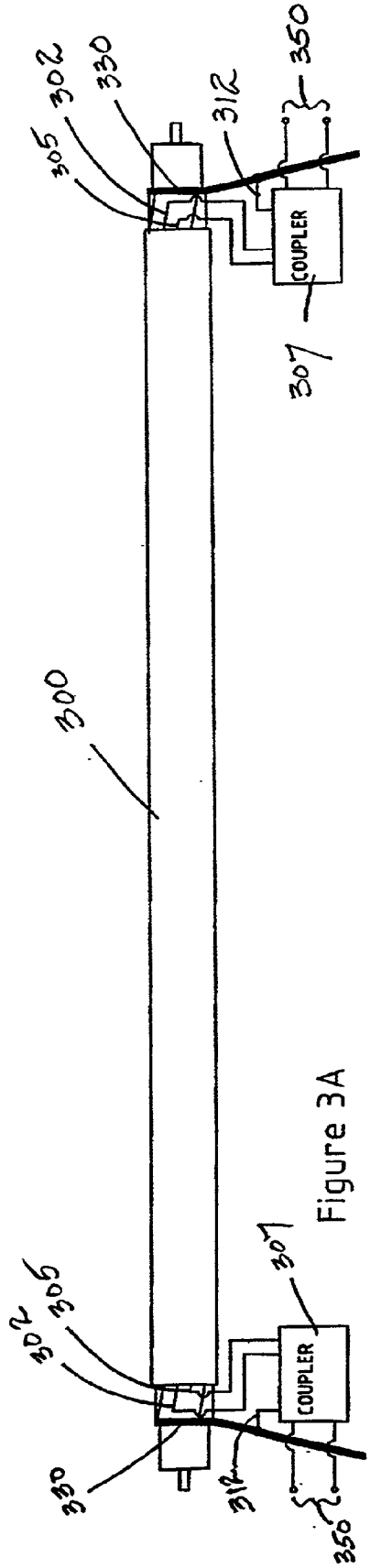

350
302
330
312
305
COUPLER
307
300
307
305
302
330
312
COUPLER
350

Figure 3A

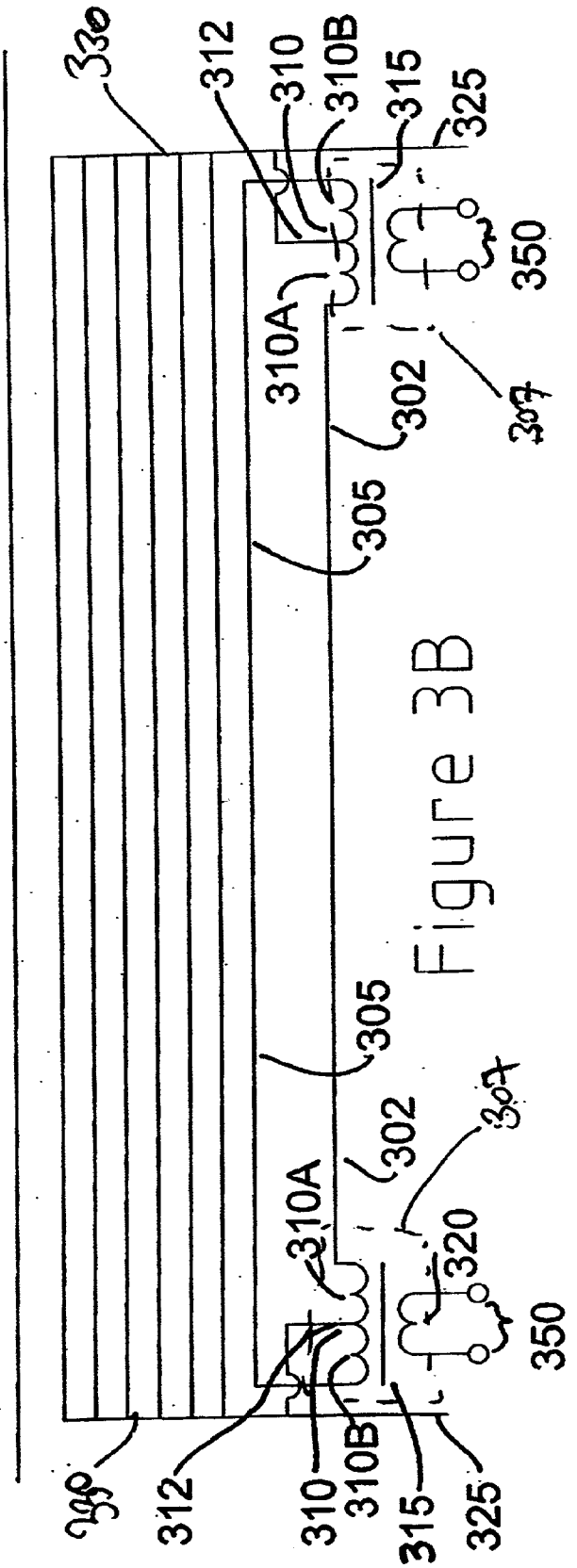

330
312
310
310B
315
325
350
310A
302
307
305
305
302
307
320
310A
350
330
312
310
310B
315
325

Figure 3B

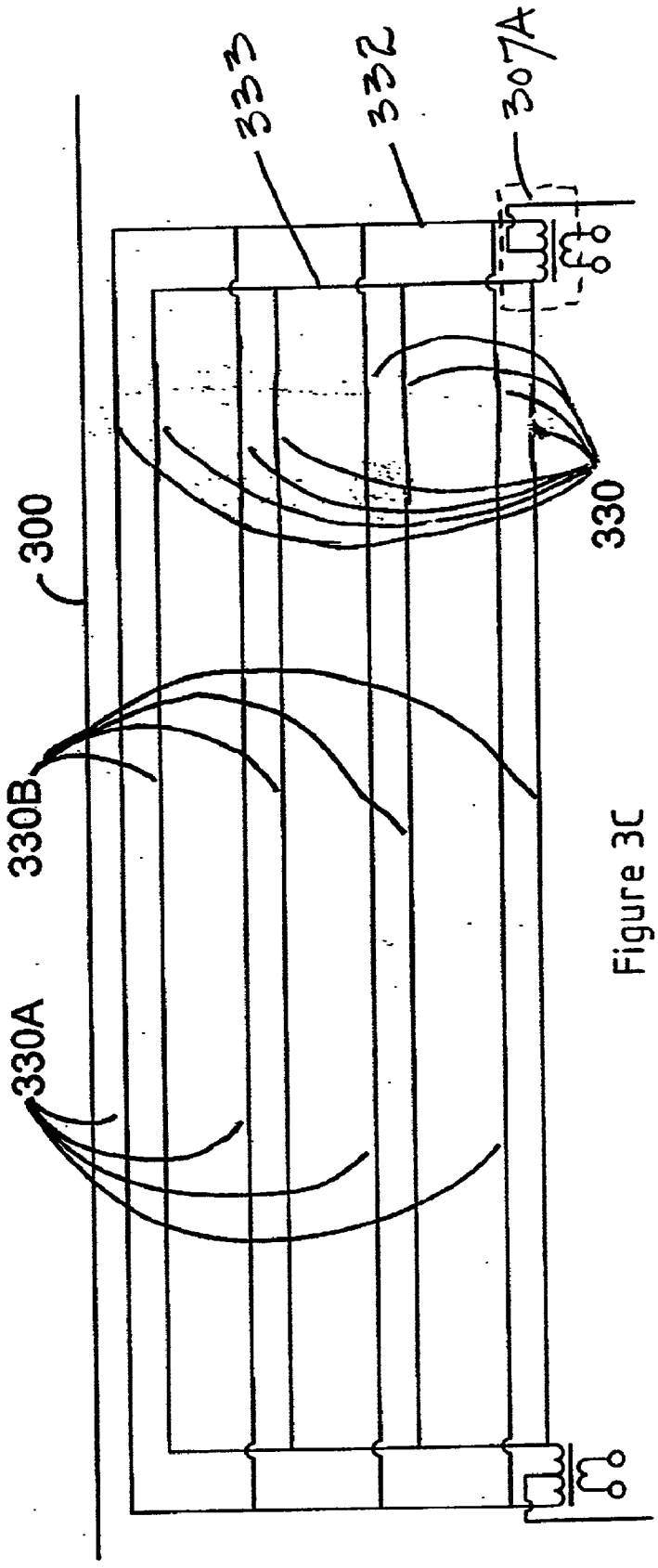


Figure 3C

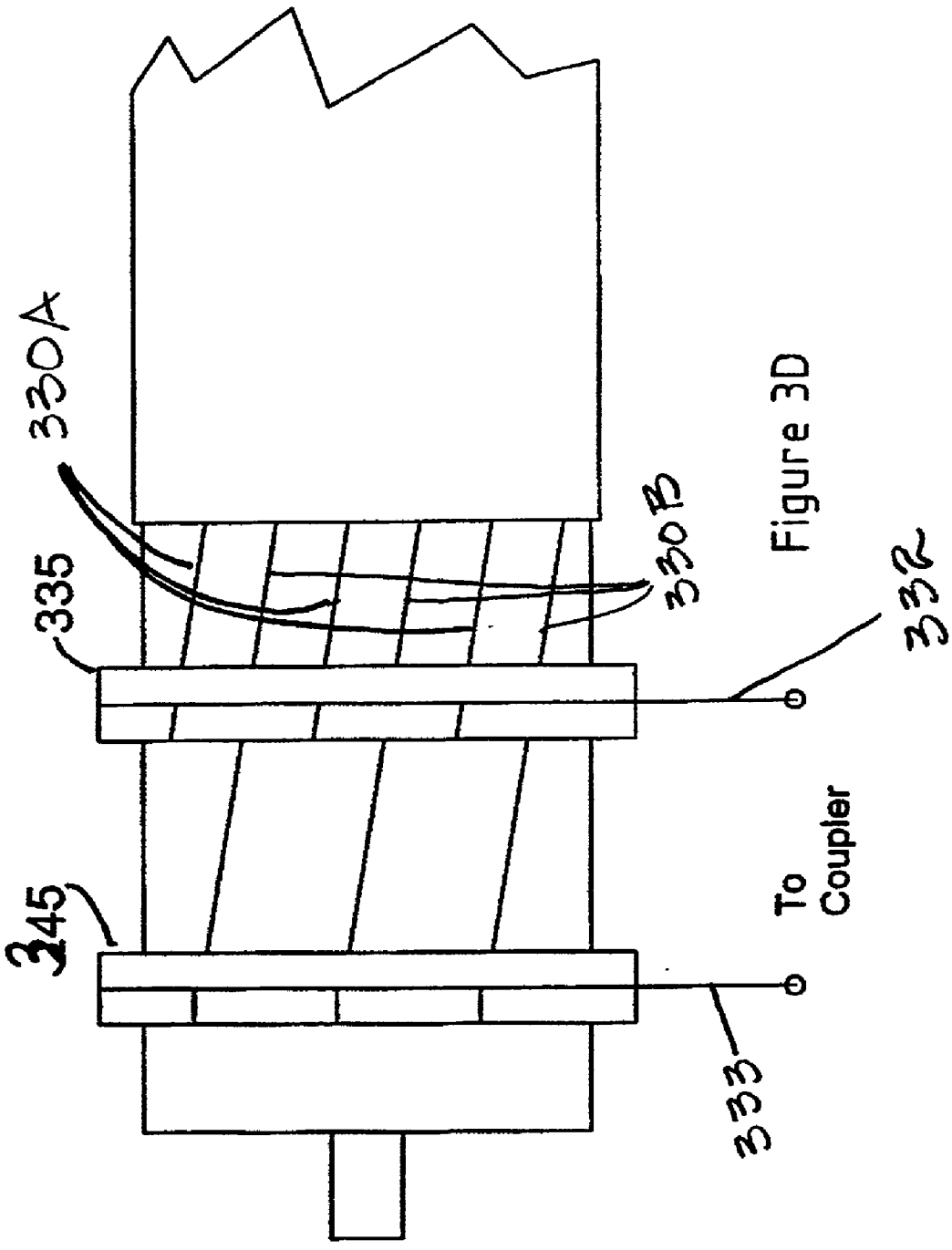


Figure 3D

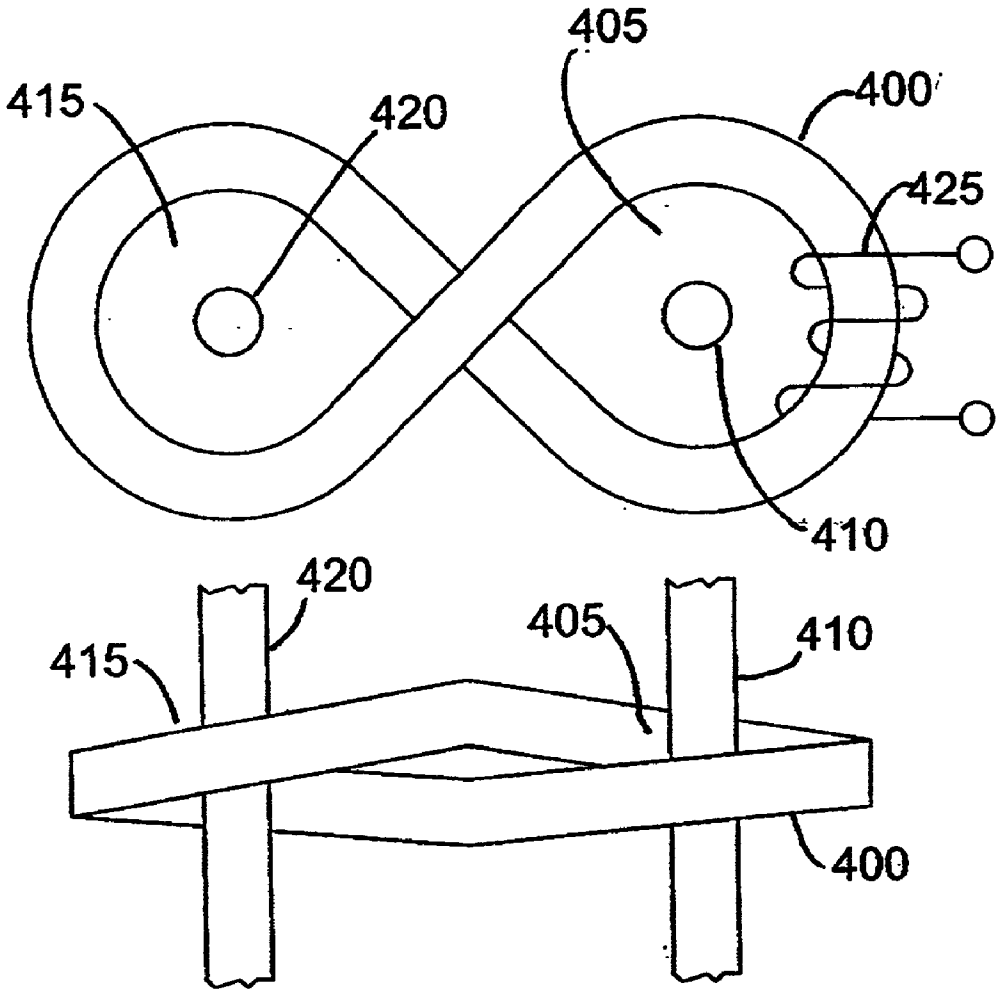


Figure 4A

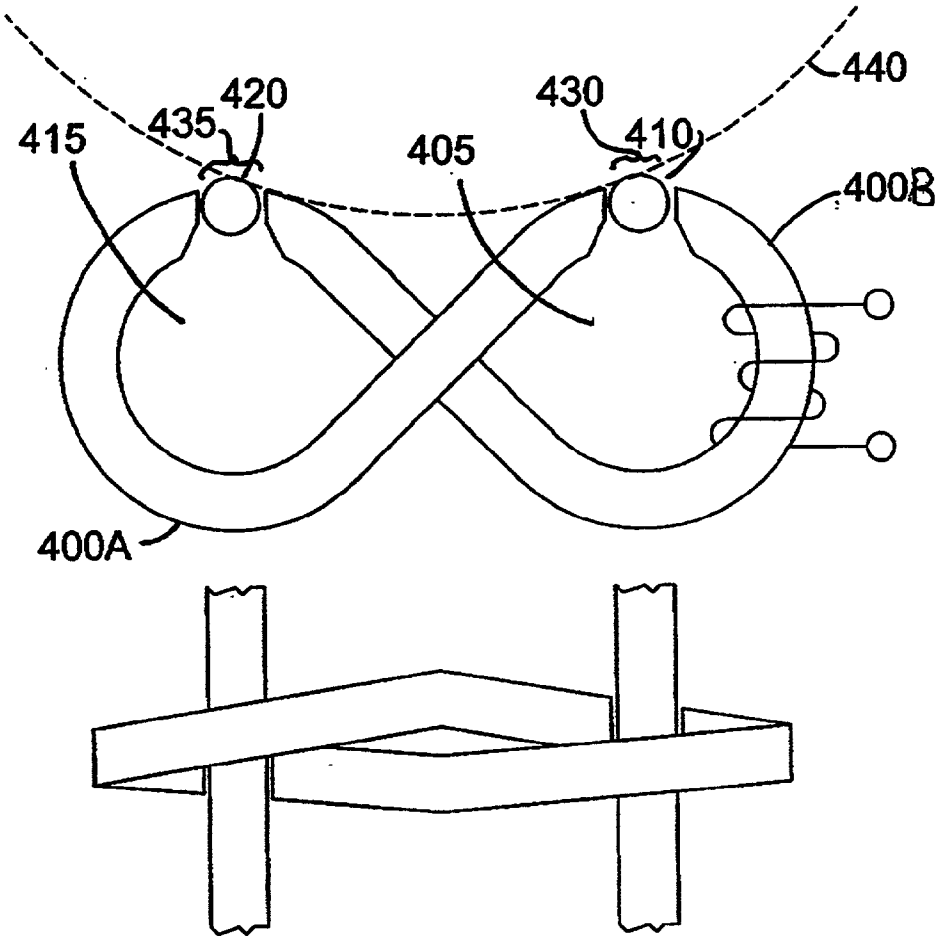


Figure 4B

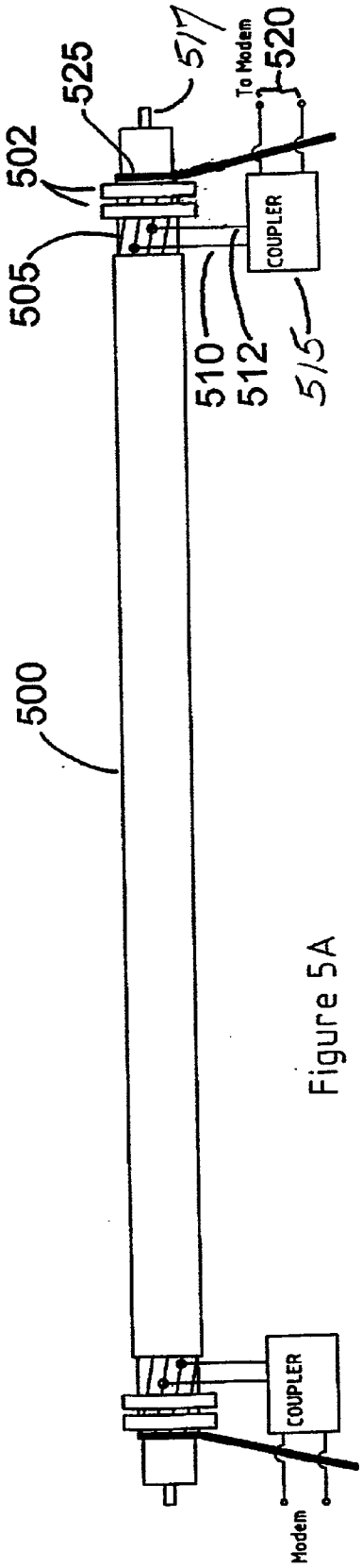

525
517
To Modem
520
502
COUPLER
505
510
512
515
500
COUPLER
Modem

Figure 5A

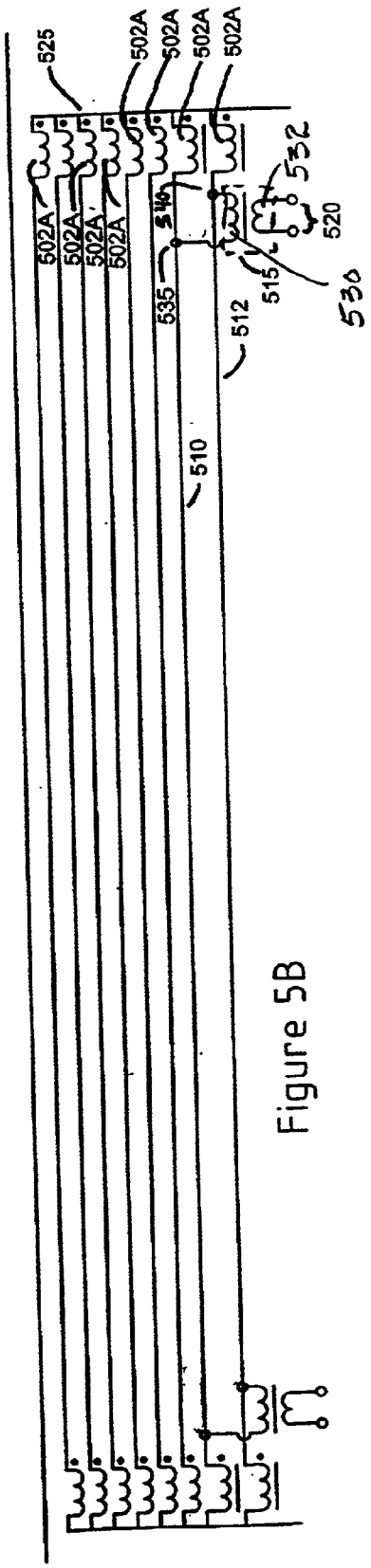

525
502A
502A
502A
502A
532
520
502A
502A
502A
502A
535
515
530
512
510

Figure 5B

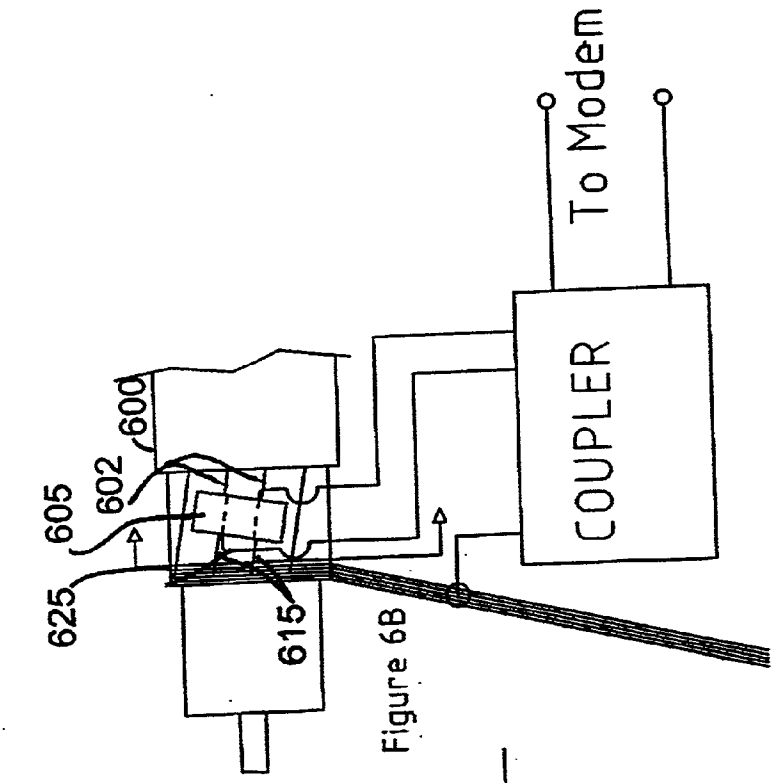


Figure 6B

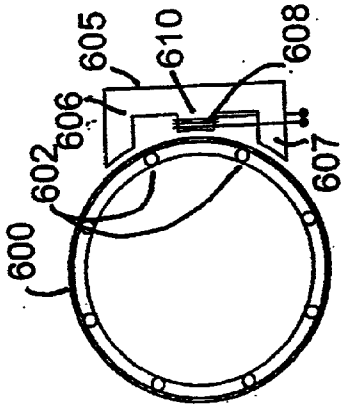


Figure 6A

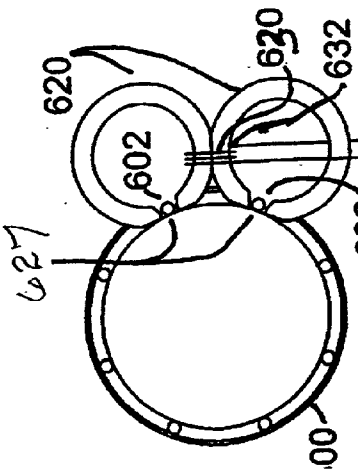


Figure 6C

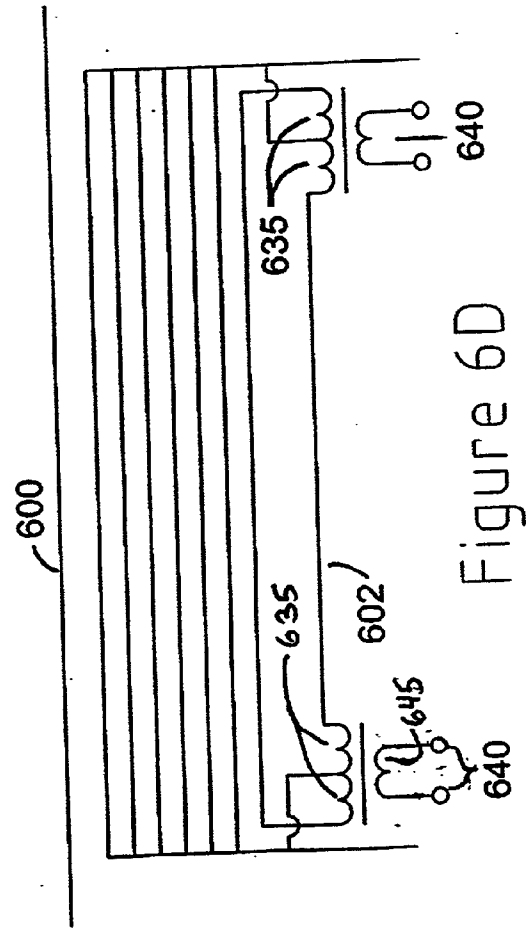


Figure 6D

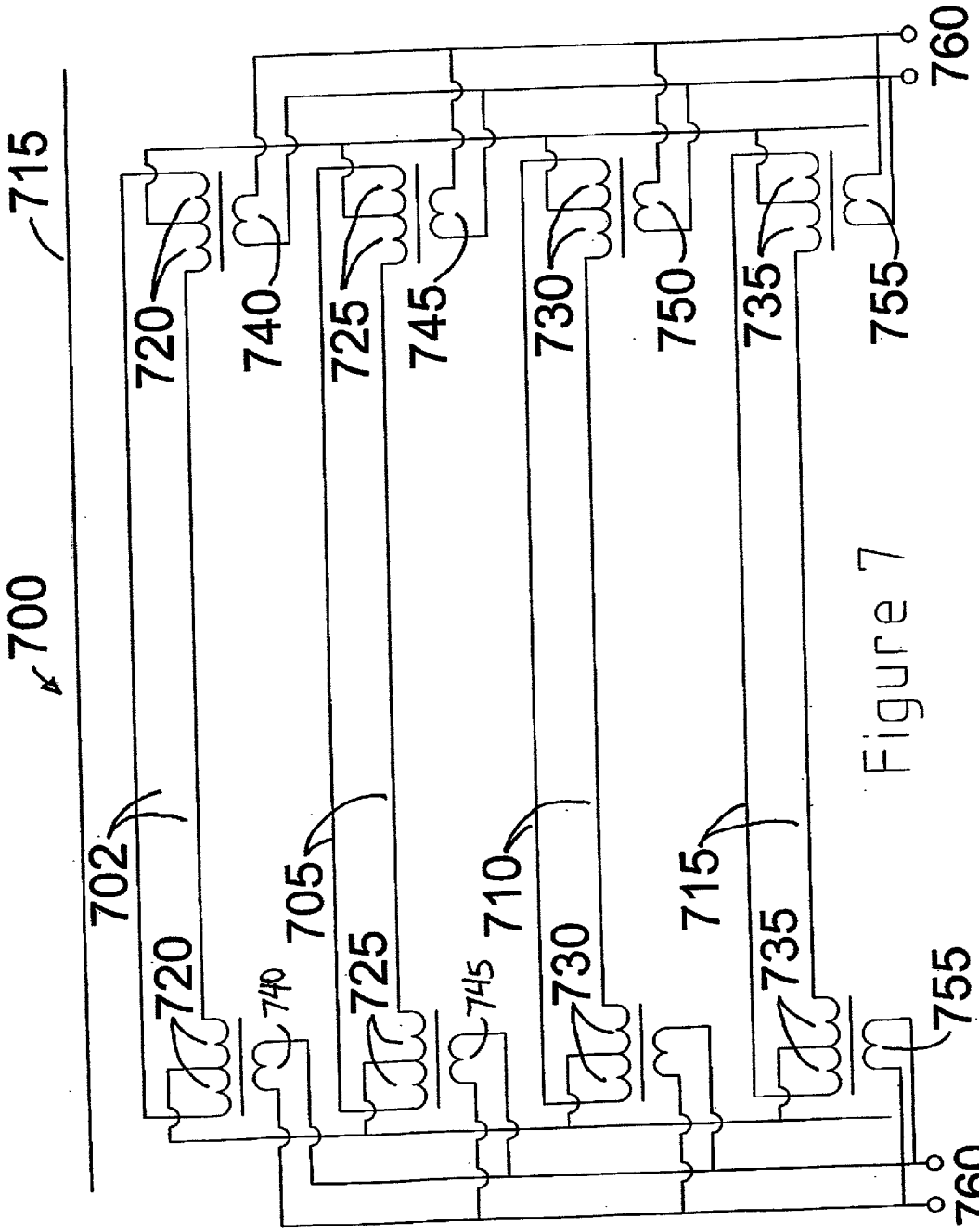

700
715
720
740
725
745
730
750
735
755
760
702
705
710
715
720
740
725
745
730
735
755
760

Figure 7

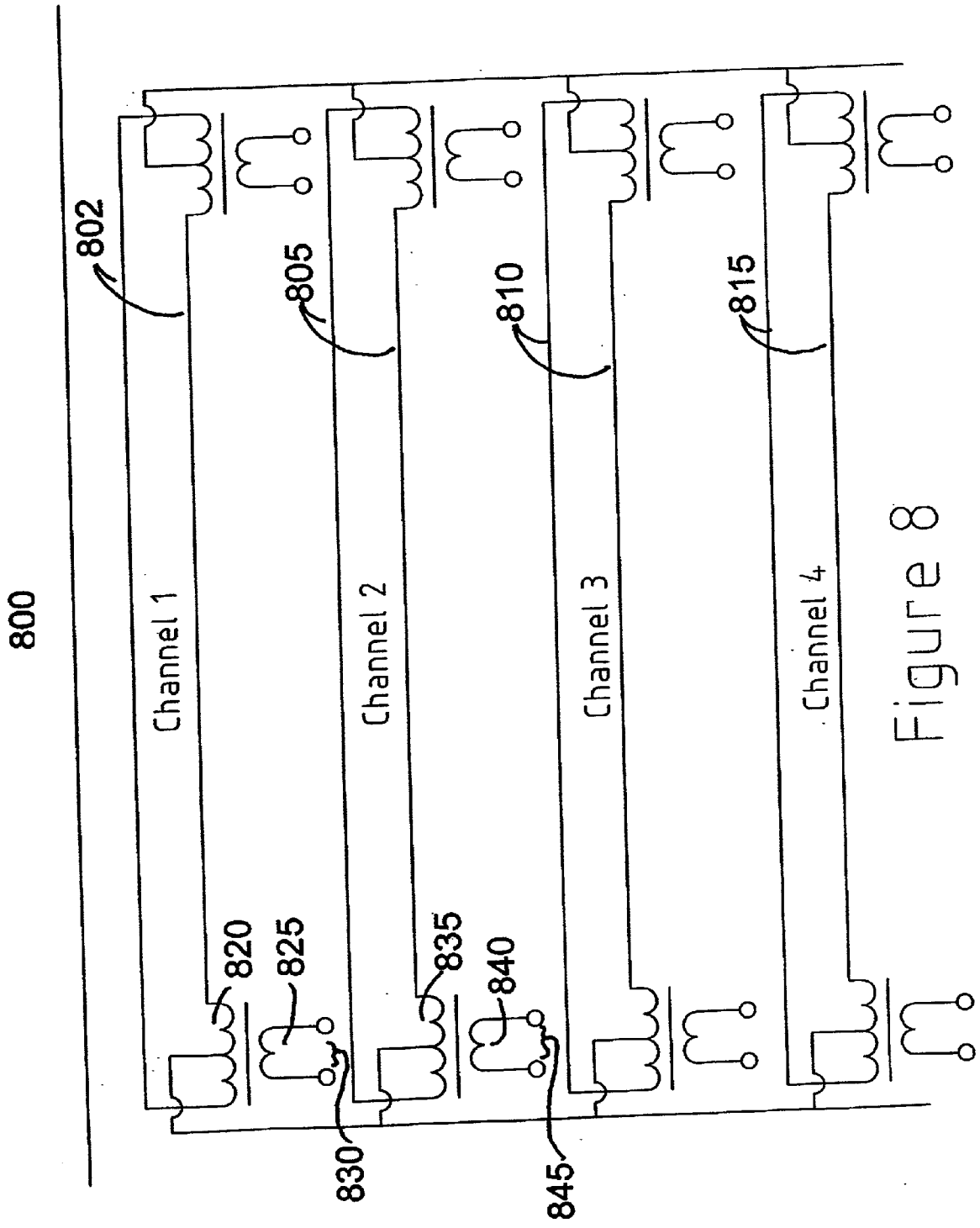

800
802
805
810
815
Channel 1
Channel 2
Channel 3
Channel 4
820
825
830
835
840
845

Figure 8

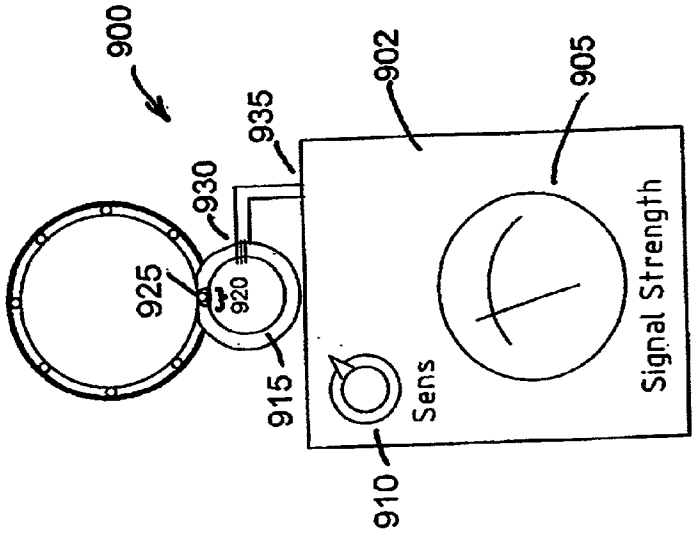


Figure 9B

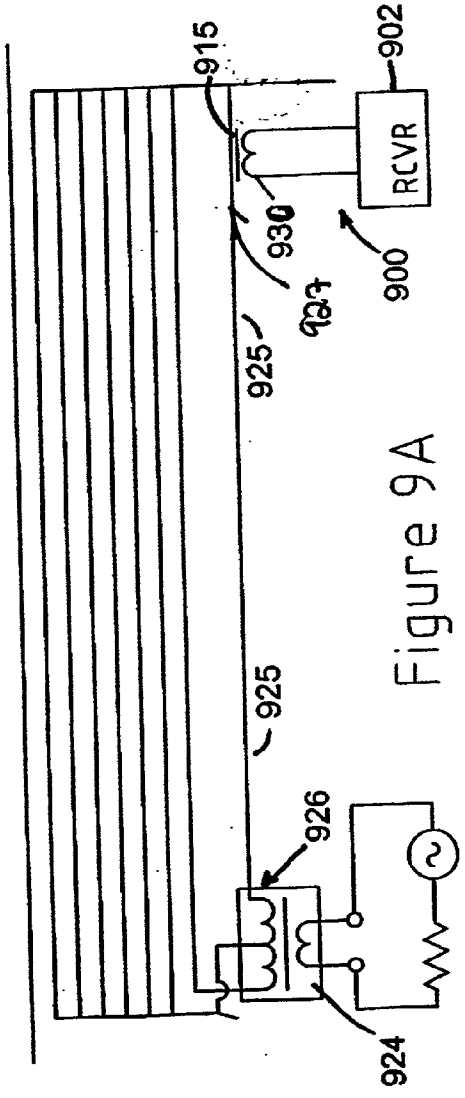


Figure 9A

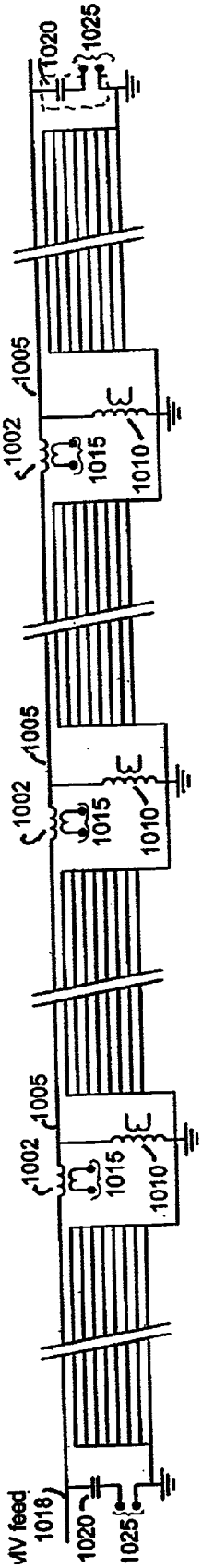

1020
1025
1005
1002
1015
1010
1005
1002
1015
1010
1005
1002
1015
1010
RV feed
1018
1020
1025

Figure 10A

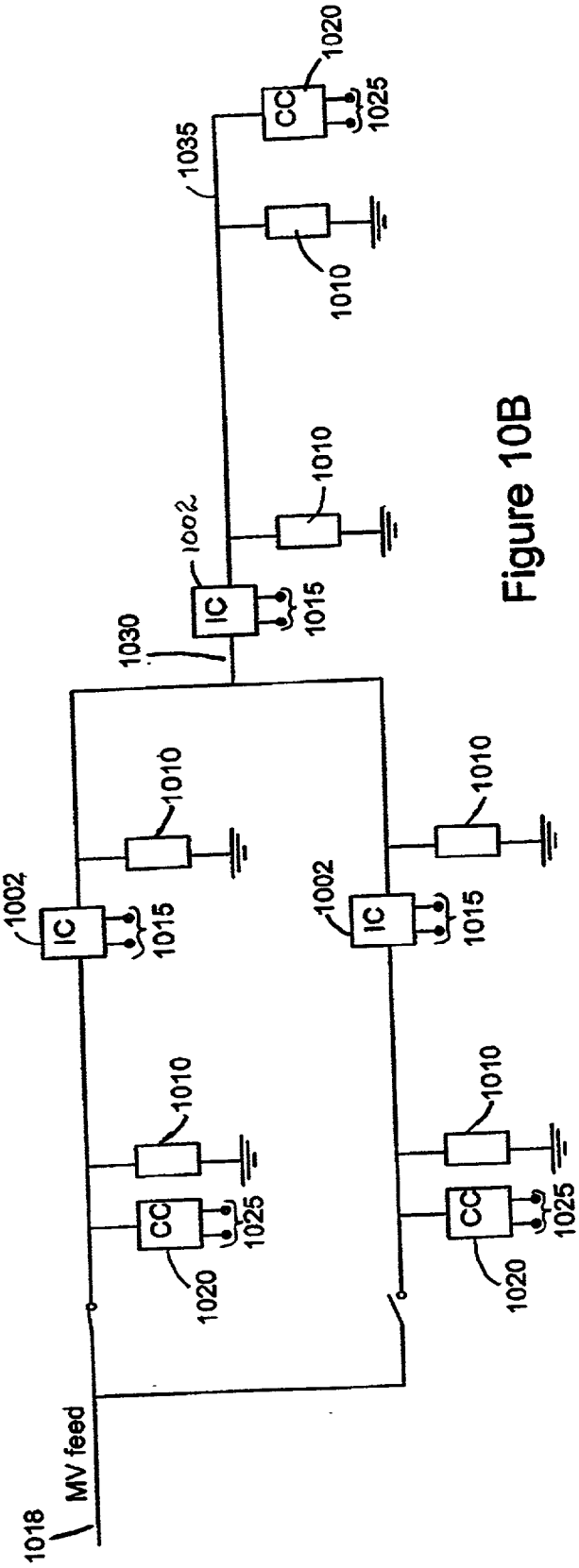


Figure 10B

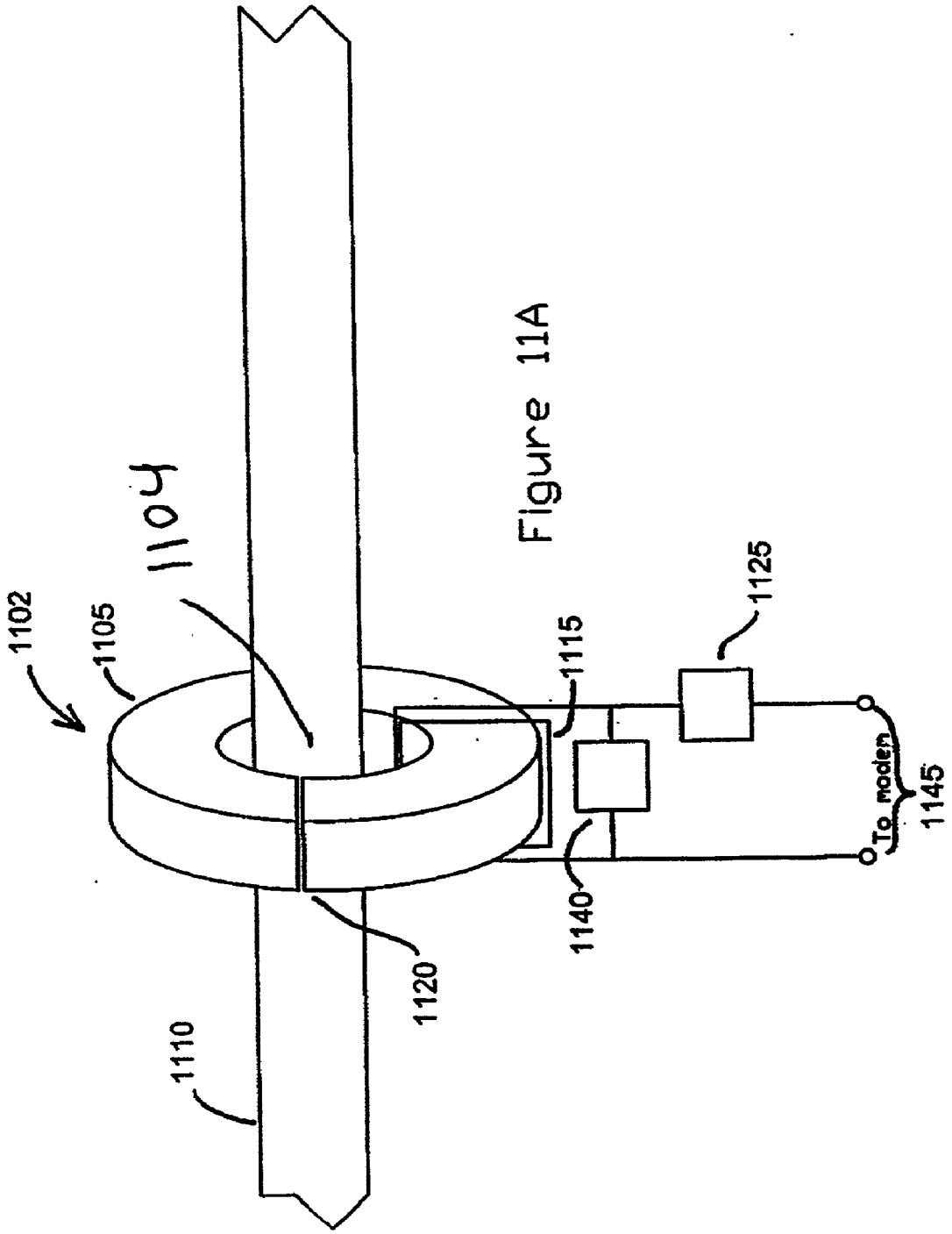


Figure 11A

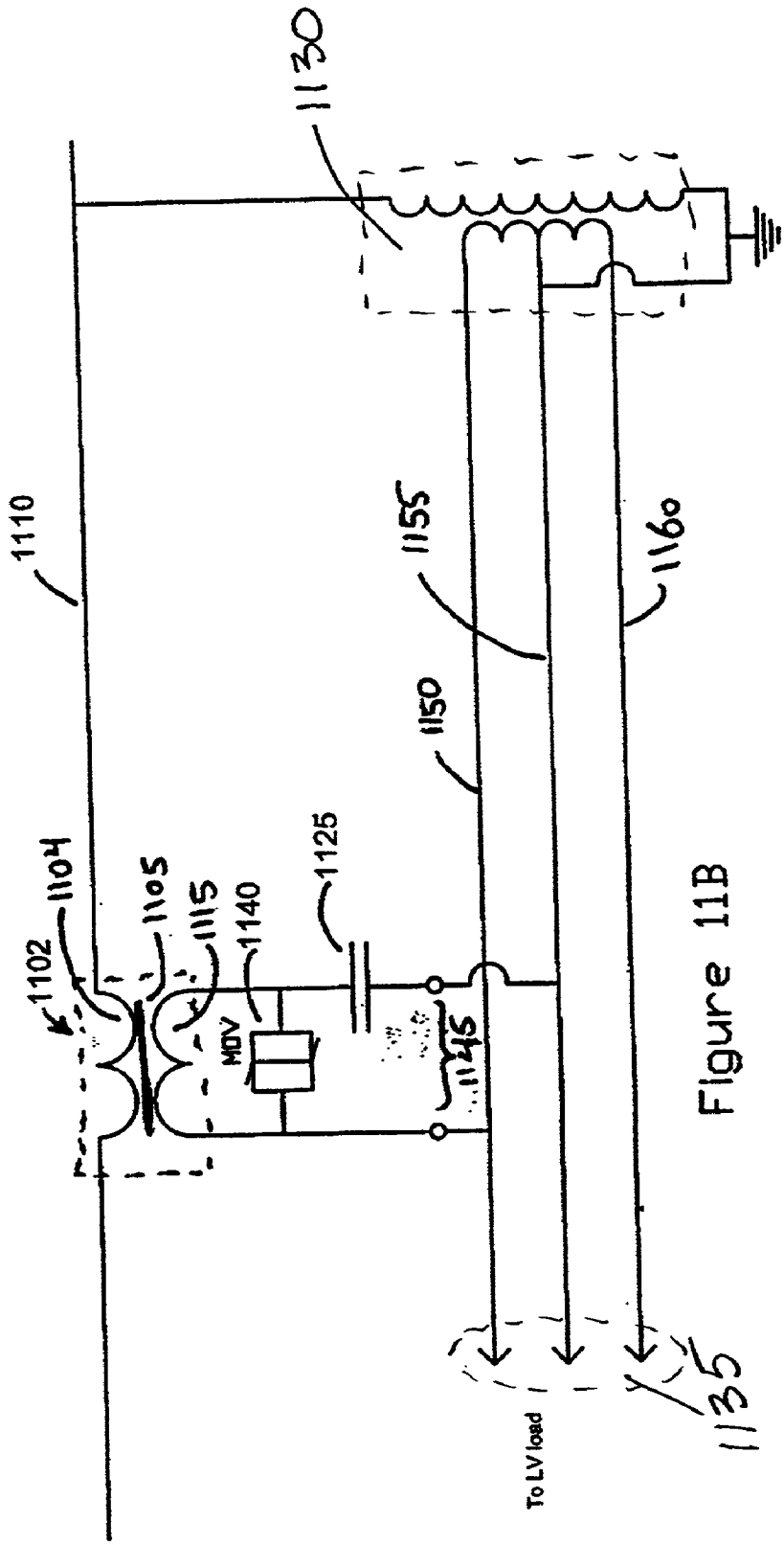

1130
1110
1155
1160
1150
1125
1104
1105
1115
1140
1102
MOV
1145
To LV load
1135

Figure 11B

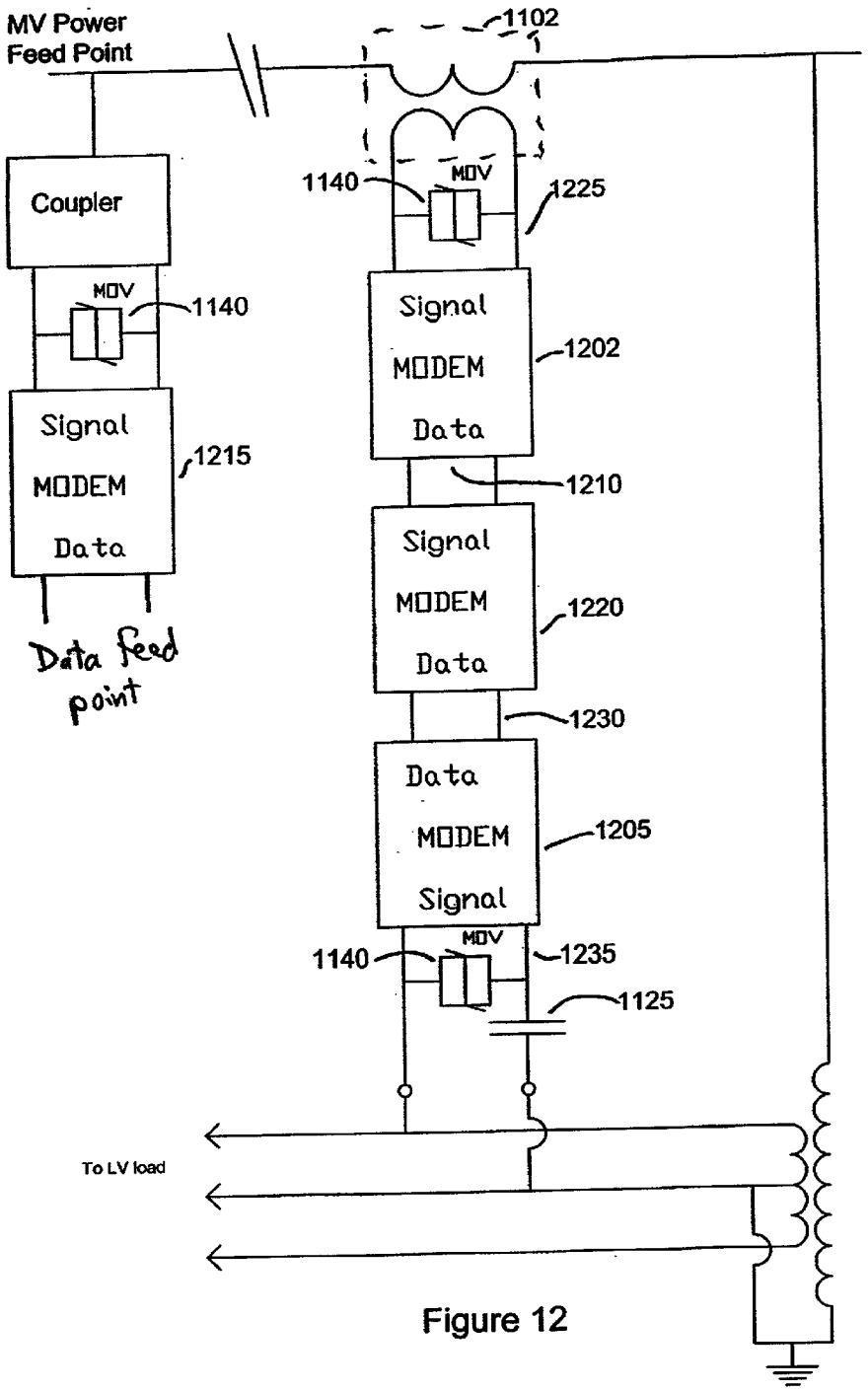

MV Power
Feed Point
1102
Coupler
MOV
1140
1225
Signal
MODEM
Data
1202
1140
Signal
MODEM
Data
1215
1210
Signal
MODEM
Data
1220
Data feed
point
1230
Data
MODEM
Signal
1205
MOV
1140
1235
1125
To LV load

Figure 12

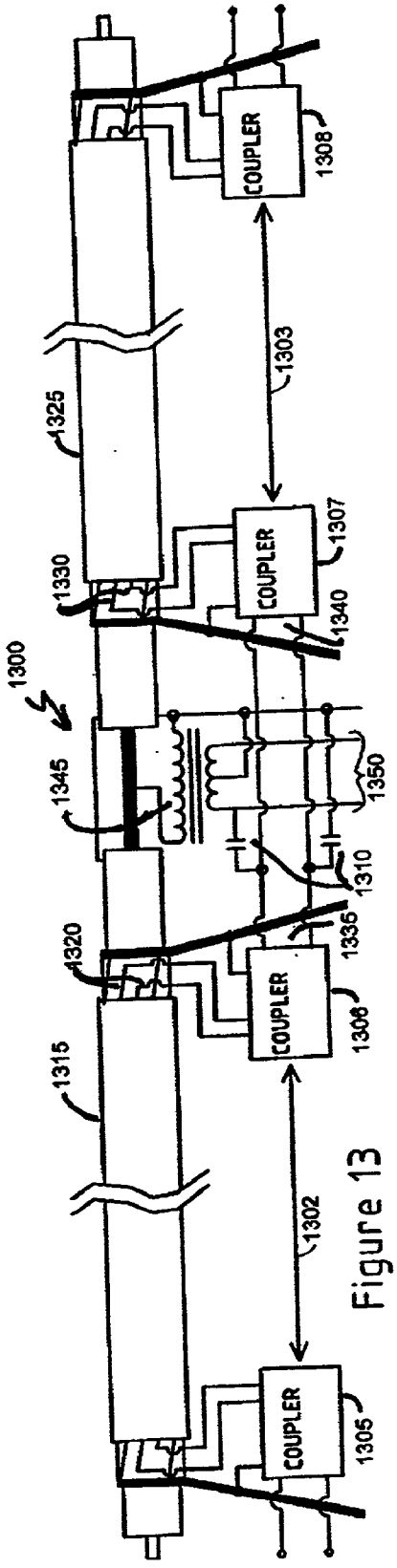

COUPLER
1308
1303
1325
1307
1330
1340
1300
1345
1350
1310
1336
1320
1306
1315
1302
1305

Figure 13

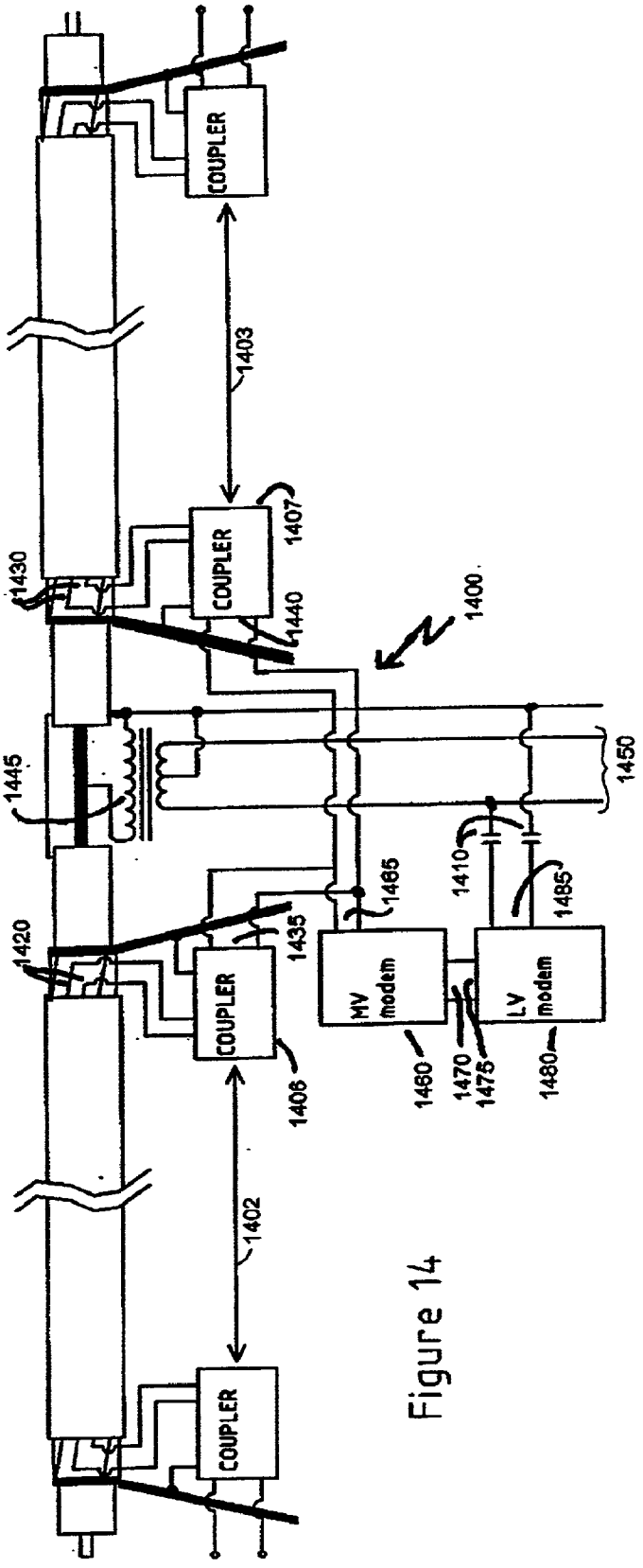

COUPLER
1403
COUPLER
1407
1430
1440
1400
1445
1450
1410
1485
1465
1420
1435
COUPLER
MV modem
LV modem
1406
1460
1470
1475
1480
1402
COUPLER

Figure 14

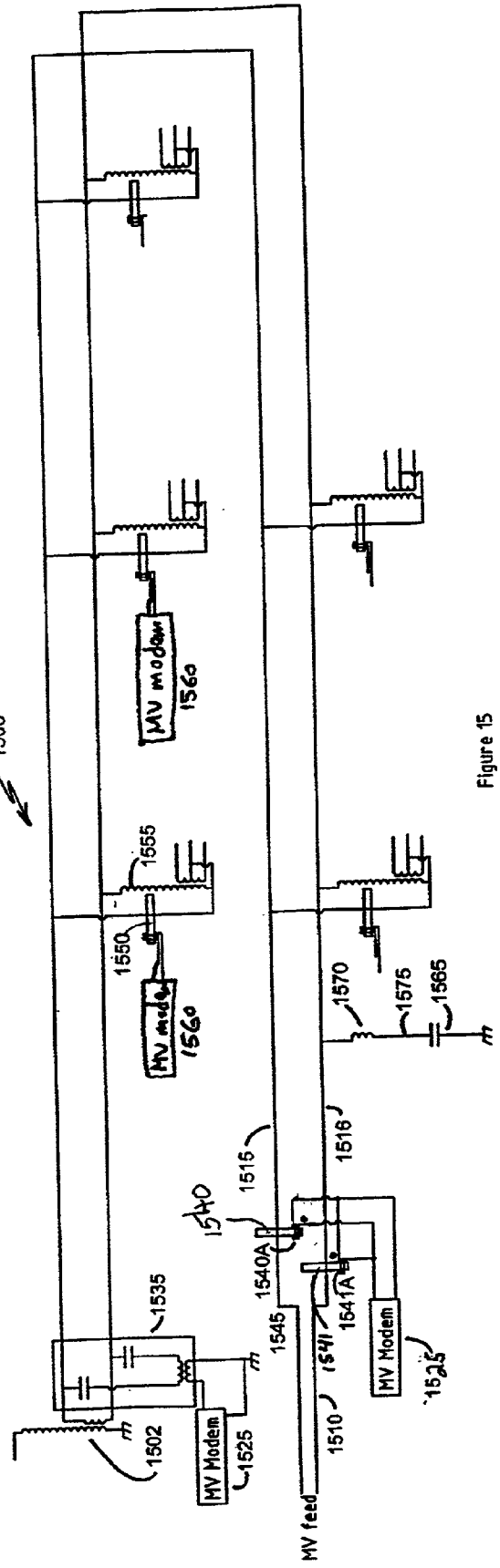

1500
MV modem
1560
1555
1550
MV modem
1560
1570
1575
1565
1516
1515
1540
1540A
1541A
1545
1541
1535
1502
MV Modem
1525
1510
MV feed
MV Modem
1525

Figure 15

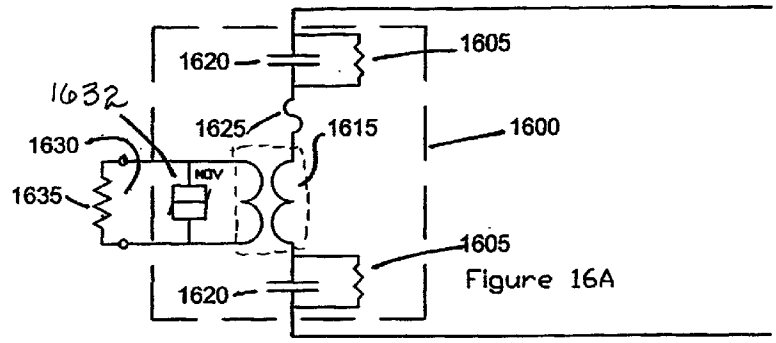


Figure 16A

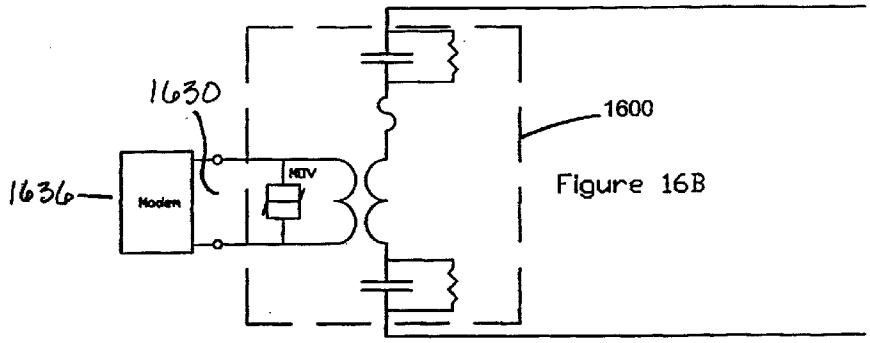


Figure 16B

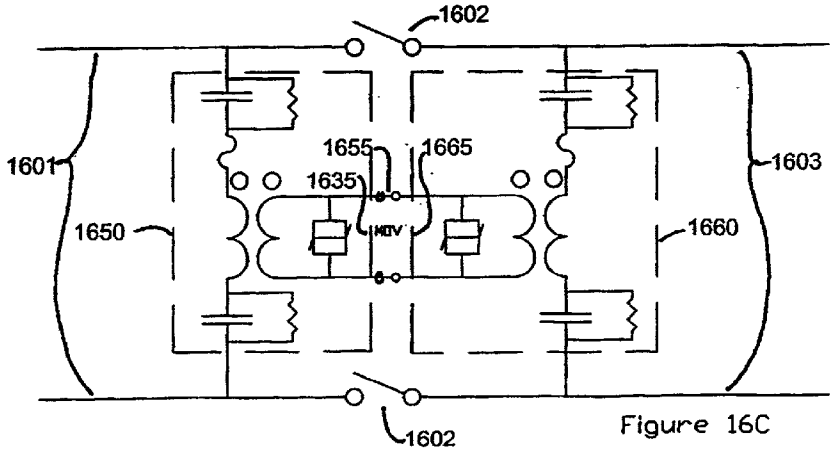


Figure 16C

INDUCTIVE COUPLING OF A DATA SIGNAL TO A POWER TRANSMISSION CABLE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is claiming priority of U.S. Provisional Patent Application Serial No. 60/173,808, filed on Dec. 30, 1999, and Serial No. 60/198,671, filed on Apr. 20, 2000.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates to communication of a data signal over a power distribution system, and more particularly, to a use of an inductive coupler for coupling a data signal via a conductor in a power transmission cable.

[0004] 2. Description of the Prior Art

[0005] Low voltage (LV) power lines within the confines of a home or business have been used as a medium for point to point or network communications using so called "carrier" systems in which a data signal is modulated onto a high frequency (HF) carrier and transmitted over the power lines. Internet access, which requires "last mile" connectivity between the Internet data trunk and each domicile, would greatly enhance the utility of such networks.

[0006] A medium voltage (MV) typically 4-66 kV is reduced to a low voltage (LV) typically 100-500 volts, through an MV-LV distribution transformer. A medium voltage power distribution grid feeds many homes and businesses via distribution transformers. If data is present on the medium voltage power grid, it would be desirable to couple broadband data streams from transformer substations to entire sections of a neighborhood, but the distribution transformers effectively block high frequency energy and thus block the data from getting to the LV drop lines.

[0007] In countries using nominal low voltages of 125 volts or less, such as in North America, drop lines from the distribution transformer to the electrical load in the home or business are usually kept shorter than about 50 meters, so as to minimize voltage drop across the lines and to preserve adequate voltage regulation. Typically, only one to ten homes or businesses are supplied from each distribution transformer. For such a small number of potential users, it is not economical to procure an expensive high data rate feed, such as fiber or T1, and couple it via power line communications devices to the low voltage side of the transformer. Accordingly, in order to exploit the medium voltage distribution grid as a data backhaul channel, a device is required to bypass the distribution transformer.

[0008] In a power distribution system, a high voltage (HV) typically 100-800 kV, is stepped-down to a medium voltage through an HV-MV step-down transformer at a transformer substation. The high frequency blocking characteristics of distribution transformers isolate the medium voltage power distribution grid from high frequency noise present on both the low voltage and the high voltage (HV) lines. The medium voltage grid is thus a relatively quiet medium, ideal for communicating high speed data as a data distribution system or "backhaul line."

[0009] The above-mentioned transformers block practically all energy in the megahertz frequency range. In order to couple high frequency modulated data from the MV lines to the LV lines, a bypass device must be installed at each transformer site. Devices are presently available and used for low frequency, low data rate data coupling applications. Such applications are often termed Power Line Communications (PLC). These devices typically include a high voltage series coupling capacitor, which must withstand a Basic Impulse Loading (BIL) voltage, typically above 50 kV. Such devices are thus expensive, bulky, and have an impact on overall power grid reliability. Furthermore, in some cases, during their installation they require disconnecting power from the customers.

[0010] In countries having a nominal low voltage in the 100-120 volt range, such as Japan and the US, the number of distribution transformers is especially large. This is because the MV-LV distribution transformers are placed relatively close to the load to keep the feed resistance low. Low feed resistance is desired to maintain reasonable level of voltage regulation, that is, minimal variation in supply voltage with varying load currents. LV feed lines for distances much in excess of 50 meters would require impracticably thick wires.

[0011] For a data coupler to be effective, it must be considered in the context in which it operates in conjunction with the high frequency characteristics of the MV power lines and with other components connected to these lines, such as transformers, power factor correction capacitors, PLC coupling capacitors, and disconnect switches. These components operate at different voltages in different countries and regions. The operating voltage level has a direct impact on the geometry of the construction of medium voltage power devices and the terminal impedance of these devices at Megahertz frequencies. Other factors affecting high frequency signals on MV power lines include the geometry of the network, e.g., branching, the use of very low impedance underground cables that connect to high impedance overhead lines, and the possibility of a splitting of a network into sub-networks due to an actuation of a disconnect switch. Therefore, the suitability of an MV-LV coupler device must be considered in the context of the specific characteristics of the equipment used in each country and the MV voltage level.

[0012] Overhead transmission lines are characterized by two or mores wires run at essentially constant spacing, with air dielectric between them. Such lines have a characteristic impedance in the 300 to 500 ohms range, and very low loss. Coaxial underground cables comprise a center conductor surrounded by a dielectric, over which are wound neutral conductors. Such cables have a characteristic impedance in the range of 20 to 40 ohms, and display loss for Megahertz signals that may be as low as 2 dB per hundred-meter length, depending on the loss properties of the dielectric.

[0013] An MV-LV distribution transformer, whether designed for operation from single phase to neutral or from phase to phase in a three phase grid, has a primary winding on the MV side that appears as having an impedance in the 40 to 300 ohm range for frequencies above 10 MHz. Power factor correction capacitors have large nominal capacitance values (e.g. 0.05-1 uF), but their high frequency impedance is primarily determined by series inductance inherent in their

construction. PLC coupling capacitors have lower nominal capacitances, for example, 2.2-10 nF, but may have high frequency impedances that are relatively low relative to the power cable's characteristic impedance. Any of the aforementioned devices may produce a resonance in the megahertz range, i.e., the imaginary part of a complex impedance becomes zero ohms, but the devices do not have high Q factors at these frequencies, and so the magnitude of the impedance typically does not approach zero for a series resonance or an extremely high value for a parallel resonance.

[0014] Another device used on MV grids, especially in Japan, is a remotely controlled three phase disconnect switch. When a data signal is transmitted over a phase line that passes through such a switch, continuity of the data needs to be maintained even when the phase line is opened through the switch.

SUMMARY OF THE INVENTION

[0015] It is an object of the present invention to provide an improved coupler for coupling a data signal to a conductor in a power transmission cable.

[0016] It is another object of the present invention to provide such a coupler that is inexpensive and has a high data rate capacity.

[0017] It is a further object of the present invention to provide such a coupler that can be installed without interrupting service to power customers.

[0018] It is still a further object of the present invention to provide such a coupler using only passive components that have a virtually unlimited service life.

[0019] These and other objects of the present invention are achieved by an apparatus for enabling communication of a data signal via a power transmission cable, comprising (a) a first winding for coupling the data signal via a conductor of the power transmission cable, and (b) a second winding, inductively coupled to the first winding, for coupling the data signal via a data port.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] **FIG. 1** is an illustration of a typical underground coaxial medium voltage distribution cable, showing a neutral wire being used as a communication medium, in accordance with the present invention.

[0021] **FIG. 2A** is an illustration of an arrangement of a single-ended transmission line using a single neutral wire for data communication, in accordance with the present invention.

[0022] **FIG. 2B** is a schematic representation of the arrangement of **FIG. 2A**.

[0023] **FIG. 3A** is an illustration of a power transmission cable in which two neutral wires are used as a transmission line for communication of a data signal, in accordance with the present invention.

[0024] **FIG. 3B** is a schematic representation of the arrangement shown in **FIG. 3A**.

[0025] **FIG. 3C** is a schematic representation of an alternative to the arrangement shown in **FIG. 3A** using a plurality of neutral wires to form a data transmission line.

[0026] **FIG. 3D** is an illustration of a technique for implementing the arrangement shown in **FIG. 3C**.

[0027] **FIGS. 4A and 4B** illustrate embodiments of a magnetic core topology for a coupler for use with a pair of neutral conductors that are differentially driven with a data signal.

[0028] **FIG. 5A** is an illustration of an arrangement of a cable having a high impedance introduced by placement of a magnetic toroid core.

[0029] **FIG. 5B** is a schematic representation of the arrangement of **FIG. 5A**.

[0030] FIGS. **6A-6C** are illustrations of several arrangements of a balanced transmission line using two neutral wires and magnetic induction, in accordance with the present invention.

[0031] **FIG. 6D** is a schematic representation of the arrangements of **6A-6C**.

[0032] **FIG. 7** is a schematic of a balanced transmission line using a magnetic induction, in accordance with the present invention.

[0033] **FIG. 8** is a schematic of an embodiment of the present invention using multiple transmission lines with multiple sets of neutral wires.

[0034] **FIG. 9A** is a schematic of a system for identifying one of a plurality of wires of a power transmission cable.

[0035] **FIG. 9B** is an illustration of a system for identifying one of a plurality of wires of a power transmission cable.

[0036] **FIGS. 10A and 10B** are schematics of portions of a data communication network implemented over a power distribution system, where the data is carried on a phase conductor of the power distribution system, in accordance with the present invention.

[0037] **FIG. 11A** is an illustration of an embodiment of an inductive coupler for coupling data via a phase conductor, in accordance with the present invention.

[0038] **FIG. 11B** is a schematic representation of the embodiment shown in **FIG. 11A**.

[0039] **FIG. 12** is a schematic of a portion of a network having back-to-back modems at an inductive coupler.

[0040] **FIG. 13** is a schematic of a technique for passively coupling modulated data between segments of a power grid, in accordance with the present invention.

[0041] **FIG. 14** is a schematic of a technique for coupling modulated data between segments of a power grid using back-to-back modems.

[0042] **FIG. 15** is a schematic showing several techniques for coupling data to a phase conductor of a power distribution system in an implementation of a data communication network, in accordance with the present invention.

[0043] **FIG. 16A** is a schematic for a capacitive coupler for terminating a transmission line dead end, in accordance with the present invention.

[0044] **FIG. 16B** is a schematic using a capacitive coupler for connecting a modem to a transmission line dead end, in accordance with the present invention.

[0045] **FIG. 16C** is a schematic of an arrangement of a capacitive coupler for maintaining continuity of a data signal across a grid disconnect switch, in accordance with the present invention.

DESCRIPTION OF THE INVENTION

[0046] Overhead and underground medium voltage transmission lines may be used for the bi-directional transmission of digital data. Such transmission lines cover the path between a power company's transformer substation and one or more MV-LV distribution transformers placed throughout a neighborhood. The MV-LV distribution transformers step the medium voltage power down to low voltage, which is then fed to homes and businesses.

[0047] The present invention relates to a use of a coupler in a medium voltage grid. The coupler is for enabling communication of a data signal via a power transmission cable. It has a first winding for coupling the data signal via a conductor of the power transmission cable, and a second winding, inductively coupled to the first winding, for coupling the data signal via a data port.

[0048] One embodiment of the present invention is employed with a power transmission cable having one or more neutral wires, i.e., conductors, wrapped around an outer layer of the cable, similarly to a coaxial cable. One or more of the neutral wires of the power transmission cable serves as a conductor for one or more data signals.

[0049] Another embodiment is employed with a phase conductor of a power transmission cable. In this case, the phase conductor of the power transmission cable serves as a conductor for one or more data signals.

[0050] **FIG. 1** is an illustration of a typical underground coaxial medium voltage distribution cable **100** with an inductive coupler coupled thereto, in accordance with the present invention. Cable **100** has a multiplicity of N neutral conductors **105** wrapped spirally around a core insulator **120**, which surrounds a phase conducting wire **115**. For example, in a Pirelli Cable X-0802/4202/0692 TRXLPE 25KV 260 mils 1/0 AWG Al cable, which is available from Pirelli Cavi e Sistemi S.p.A., Viale Sarca, 222, Milano, Italy 20126, there is a phase conducting wire surrounded by insulation around which are wound 8 strands of 2.8 mm diameter copper. Cables having 12 to 16 neutral conductors are also common.

[0051] Neutral conductors **105** are separated and insulated from each other in a cable segment. At an end of cable **100**, a strand of each neutral conductor **105** is exposed and wrapped tangentially, forming a ring of copper wire **125** a short distance from the end of the cable, to form a terminus. These strands are gathered together into a single stranded wire **130** and connected to a grounding post at an MV-LV distribution transformer.

[0052] A coupler **140** is already insulated from phase conductor **115**, the latter certified to withstand both the steady state and transient voltages for which the cable is rated. Exploiting existing insulation obviates the expense of providing it again for the coupler. The coupler can be packaged with ordinary plastic materials.

[0053] Coupler **140** includes a first winding (not shown in **FIG. 1**) and second winding (not shown in **FIG. 1**). The first winding is provided by the cable itself while the second winding can comprise one or two turns of stranded, small diameter hookup wire, with minimal insulation.

[0054] In an underground cable, such as cable **100**, the use of inductive coupler **140** is particularly cost effective, as it takes advantage of the existing insulator **120** to provide isolation from the medium voltage lines.

[0055] An inductive coupler in accordance with the present invention is also suitable for use with an overhead power transmission cable. The inductive coupler is generally less expensive than a capacitive coupler, as increasing the thickness of the inductive coupler's insulation does not substantially degrade the coupler performance, while increasing the insulation thickness in the capacitor directly decreases its capacitance per unit area, and necessitates a larger plate area. Therefore, in comparison to a capacitive coupler, the inductive coupler is considerably less expensive to manufacture.

[0056] There are several alternative embodiments of the invention. For underground cable, one can enlist one or more of the neutral wires of the underground cable, which can form high frequency transmission lines, while the power conduction function of the selected neutral wire(s) is preserved.

[0057] **FIG. 2A** is an illustration of an arrangement of a single-ended transmission line using a single neutral wire for data communication, in accordance with the present invention. **FIG. 2B** is a schematic representation of the arrangement of **FIG. 2A**. A cable **200** includes a multiplicity of neutral conductors **205**, e.g. wires, that can be considered as a flat data transmission line, wrapped in a gentle spiral around a high voltage insulator **240** and a center phase conductor **245**.

[0058] One selected strand of neutral conductors **205**, i.e., neutral conductor **202**, is isolated to act as a data transmission line conductor for a data signal, and the remaining neutral conductors **205**, mainly two neutral conductors **205** that are adjacent to neutral conductor **202**, serve as a second data transmission line conductor. For the cross section of the Pirelli cable described above, the characteristic impedance is estimated to be about 95 ohms with respect to signals in a frequency range of 1-50 MHz, a subrange of which is typically used in a transmission of data.

[0059] To implement the arrangement of **FIG. 2A** in an already-installed underground cable, neutral conductor **202** is selected out of the several neutral conductors **205**, and cut in an exposed section **210** at each end of cable **200**. A lead **215** of neutral conductor **202** remains connected to a ring **250** at each end of cable **200**. Neutral conductor **202** and lead **215** are connected to a first winding **225** of a coupler **220**. First winding **225** is thus connected in series between neutral conductor **202** and ground. A second winding **235** of coupler **220** is coupled to a port **255** through which data is transmitted and received. Thus, cable **200** is enlisted for use as a high frequency transmission line, which can be connected to communications equipment such as a modem (not shown), via coupler **220**.

[0060] Electrically speaking, coupler **220** is a transformer. The impedance across the primary, i.e., first winding **225**, of such a transformer is negligible at the frequencies used for conducting power. First winding **225**, which is attached to neutral conductor **202** and lead **215**, should be wound with a wire at least as thick as that of neutral conductor **202**. Under these circumstances, the selected data-carrying neutral conductor **202** has essentially the same impedance as all of the other neutral wires. It would carry essentially the same current as each of the other neutral wires, and the total ampacity and surge current capacity of the neutral circuit would not be degraded.

[0061] In **FIGS. 2A and 2B**, the neutral current of the single neutral conductor **202** passes through coupler **220**. For a 200 Amp cable with eight neutral wires, the data-carrying wire would carry a maximum steady state current of 25 Amps rms. The maximum steady-state current through a single neutral conductor is less for a smaller ampacity cable and for a cable with a larger number of neutral conductors. Coupler **220** must be capable of handling the flux generated by this current, without magnetic core saturation, in order to carry out its data coupling function.

[0062] Neutral conductor **202** carries current in a first direction for a high frequency data signal. The other neutral conductors **205** carry the data signal's return current in the opposite direction, tending to cancel and thus greatly decrease an intensity of the radiated magnetic field due to the modulated data signal. This arrangement also provides an electrostatic shielding effect against noise coupling from an external electric field.

[0063] **FIG. 3A** is an illustration of a power transmission cable **300** in which two neutral wires are used as a transmission line for communication of a data signal, in accordance with the present invention. **FIG. 3B** is a schematic representation of the arrangement shown in **FIG. 3A**.

[0064] A coupler **307**, for example, a high frequency transformer, is installed in series with two adjacent neutral wires **302**, **305**. Neutral wires **302**, **305**, which are preferably in parallel and adjacent to one another, are cut just before a point where they attach to neutral connecting ring **330**.

[0065] Referring to **FIG. 3**B, the leads of neutral wires **302**, **305** extending from cable **300** are connected to a first winding **310** of coupler **307**. First winding **310** is thus connected in series between neutral conductor **302** and neutral conductor **305**. First winding **310** includes a center-tap **312** and a magnetic core **315**. Center-tap **312** is connected to neutral connecting ring **330**.

[0066] A portion **310**A of first winding **310** is connected to neutral wire **302** and wound in a first direction around core **315**, and a second portion **310**B of first winding **310** is connected to neutral wire **305** and wound in the opposite direction around core **315**. Portions **310**A and **310**B are made of wires of slightly larger diameter than the power cable neutral wires, and are therefore capable of carrying steady state and surge currents at least as well as the unselected neutral conductors. Each of portions **310**A and **310**B may itself be considered a winding.

[0067] The arrangement of **FIG. 3A** ensures that only a negligible impedance is inserted in series with two neutral wires **302**, **305**, and does not disturb the essentially equal division of power frequency current among all of the neutral wires. For the Pirelli cable described earlier, the characteristic impedance of the parallel wires **302** and **305** acting as a parallel wire transmission line is estimated to be approximately 130 ohms. Also, at power frequency, the arrangement shown in **FIGS. 3A and 3B** results in flux cancellation due the neutral currents' flowing in opposite directions in windings **310**A and **310**B, resulting in a negligible net flux through core **315**.

[0068] Another winding **320** is connected to a port **350** through which data is transmitted and received. Winding **320** is insulated from the power circuit neutral **325**, thus avoiding a ground loop that could induce spurious noise and fault surges into the data circuits.

[0069] Cable **300** can be thought of as a high frequency transmission line, which can be connected to communications equipment via coupler **307**. In this configuration, a data signal is driven differentially through neutral conductors **302**, **305**. Such a transmission line should emit even lower electromagnetic radiation than the singe-ended arrangement described in **FIG. 2**A, for a given drive power level.

[0070] **FIG. 3C** is a schematic representation of an alternative to the arrangement shown in **FIGS. 3A and 3B** using a plurality of neutral wires to form a data transmission line. Cable **300** has a plurality of neutral wires **330** that are substantially parallel to one another, with individuals of a first subset **330**A of the plurality of neutral wires **330** alternating with individuals of a second subset **330**B of the plurality of neutral wires **330**. The first subset **330**A is collectively regarded as a first neutral conductor and joined together to form a first stranded lead **332** to a coupler **307**A. The second subset **330**B is collectively regarded a second neutral conductor and joined together to form a second stranded lead **333** to coupler **307**A. Preferably, the plurality of neutral wires **330** is configured as N/2 transmission lines connected in parallel, where N is the number of neutral wires **330**, and N/2 is the number of neutral wires in each of subsets **330**A and **330**B. The effect of such a parallel connection is to reduce the attenuation produced by cable **300** by a factor of approximately N/2 , and to lower the characteristic impedance by the same factor.

[0071] **FIG. 3D** is a diagram showing how the arrangement of **FIG. 3C** may be conveniently implemented. To facilitate the attachment of first subset **330**A to first stranded lead **332**, a first insulating ring **335** is placed over all neutral conductors, i.e., first subset **330**A and second subset **330**B, proximate to a point where coupler **307**A will be located. First subset **330**A is wrapped over first insulating ring **335** and joined together to form first stranded lead **332**. Likewise, second subset **330**B is wrapped over a second ring **345**, which may be insulating or not insulating, and joined together to form second stranded lead **333**. The improved geometrical symmetry of the current flow and reduced voltage levels should further reduce electromagnetic radiation, relative to that emitted with the two-wire implementation of **FIG. 3A**.

[0072] An electric utility company might object to cutting two neutral wires and reconnecting them through a coupler. In accordance with the present invention, it is possible to "wind" a magnetic core around the two selected neutral wires in a manner that is topologically and magnetically equivalent to the embodiment shown in **FIGS. 3A and 3B**.

[0073] **FIGS. 4A and 4B** illustrate embodiments of a magnetic core topology for a coupler for use with a pair of

neutral conductors that are differentially driven with a data signal. Such a core has a first region adjacent to a first neutral conductor, and a second region adjacent to a second neutral conductor. The coupler includes a winding wound around a portion of the core. Through the core, the winding induces a first current in the first neutral conductor in a first direction, and induces a second current in the second neutral conductor in a second direction that is opposite of the first direction.

[0074] Referring to **FIG. 4A, a** core **400** may be visualized as a figure "8", with no contact at the crossing point. The figure "8" forms a topological "twist". A first region comprises a first loop **405** of the figure "8". A first neutral conductor **410** is routed through first loop **405**. A second region comprises a second loop **415** of the figure "8". A second neutral conductor **420** is routed through second loop **415**. Core **400** is effectively a contiguous one-window core through which conductors **410** and **420** are passed in opposite directions, thus canceling the flux due to power frequency currents. A winding **425** induces oppositely-phased high frequency signal currents in neutral wires **410** and **420**.

[0075] The figure "8" topology can be implemented on the surface of a cable, without cutting the neutral conductors. As shown in **FIG. 4B, a** core comprising core segments **400**A and **400**B is configured with a first gap **430** in the first loop **405** and a second gap **435** in the second loop **415**. Neutral conductor **410** is routed through first gap **430** and neutral conductor **420** is routed through second gap **435**. By placing cores **400**A and **400**B against the insulation **440** of neutral conductors **410** and **420**, neutral conductors **410** and **420** are placed within the path of magnetic flux.

[0076] Another method for avoiding the physical cutting of the neutral wires is to insert a high impedance for high frequencies in series with them without cutting the wires. The present invention accomplishes this by surrounding the entire cable with one or more magnetic toroid cores.

[0077] **FIG. 5A** is an illustration of an arrangement of a cable having a high frequency high impedance introduced by placement of a magnetic toroid core over the cable. **FIG. 5B** is a schematic representation of the arrangement of **FIG. 5A**.

[0078] One or more magnetic toroid cores **502** are disposed around a portion of a power transmission cable **500**. A first winding **530** (**FIG. 5B**) of a coupler **515** is connected between a first neutral conductor **510** and a second neutral conductor **512**, inwards of cable **500** relative to magnetic toroid cores **502**. A second winding **532** of coupler **515** provides a data path to a modem port **520**.

[0079] First and second neutral conductors **510, 512** are two of a plurality of neutral conductors **505** within cable **500**. Each of neutral conductors **505** will effectively see a choke **502**A (**FIG. 5B**) just prior to a neutral collection ring **525**. Thus, magnetic toroid cores **502** insert an isolating reactance between each of neutral wires **505** and ground, preferably on the order of magnitude of a few micro-Henries.

[0080] Magnetic toroid cores **502** may be configured as a split core of two halves, with a mechanical package provided to mate the core halves accurately, and fasten the core to cable **500**. The advantage of this embodiment is that none of the neutral wires **505** need be cut during installation of magnetic toroid cores **502**.

[0081] A data signal can be transmitted to and received from a modem (not shown) connected across a port **520** of coupler **515** and coupled to neutral conductors **510, 512** upstream of magnetic toroid cores **502**. Cable **500** can be thought of as a high frequency transmission line with connection end points **535** and **540** partially isolated from ground by toroids acting as chokes.

[0082] At power frequency, the net current passing through the magnetic toroid cores **502** is essentially zero, since the phase current of a central conductor **517** flowing in one direction is balanced by the oppositely directed neutral current flowing through the multiplicity of neutral wires **505**, all passing through magnetic toroid cores **502**. Core saturation is thus obviated. Power current distribution among the neutral wires **505** is remain unchanged by the presence of magnetic toroid cores **502**, as a very small reactance is induced by the choking effect of magnetic toroid cores **502**, which affect all neutral wires equally.

[0083] FIGS. **6**A-**6**C are illustrations of several arrangements of a balanced transmission line using two neutral wires and magnetic induction, in accordance with the present invention. **FIG. 6D** is a schematic representation of the arrangements of **6**A-**6**C. Again, the advantage obtained is the avoidance of cutting or manipulating the neutral wires, for circuits that may or may not be energized.

[0084] Each of the embodiments of FIGS. **6**A-**6**D uses two neutral wires as a transmission line. Signal current is magnetically induced in the sections of the neutral wires, adjacent to a grounded collection ring. An open magnetic core (such as an "E" core) is positioned proximate and perpendicular to the two neutral wires.

[0085] As shown in **FIG. 6**A, an open magnetic core **605** has a first leg **606** positioned proximate and perpendicular to a first one of two neutral wires **602** of a cable **600**, a second leg **607** positioned proximate and perpendicular to a second one of neutral wires **602**, and a third leg, i.e., common leg **610**, located between first leg **606** and second leg **607**. Common leg **610** has a winding **608** wound thereabout.

[0086] Winding **608** is wound around common leg **610**, which is positioned between the two neutral wires **602** of cable **600**. This arrangement induces currents in the individuals of neutral wires **602** in opposite directions from each other. A segment **615** (**FIG. 6B**) of neutral wires **602** terminating together in a grounded collection ring **625** (**FIG. 6B**) may alternatively be considered a one turn coil passing through the gap between the pole faces of legs **606** and **610**, and between the pole faces of legs **607** and **610**. Thus, a signal current in winding **608** will induce signal current in the two neutral wires **602**, launching a differential signal down the transmission line formed by those two neutral wires **602**.

[0087] Referring to **FIG. 6**C, to reduce the size of the relatively large air gap between the legs in standard core shapes (e.g., "E" core), and to increase the coupling coefficient, a pair of magnetic toroidal cores **620** can be used, with gaps **627** provided through which neutral wires **602** are routed. A winding **630** is wound around a portion of each of magnetic toroidal cores **620**, e.g., a common leg **632**.

[0088] The equivalent circuit of the embodiments of FIGS. **6**A-**6**C is shown in **FIG. 6D**. The sections of neutral wires **602** in which the flux is induced act as two oppositely

phased windings **635** connected together at collection ring **625**. A winding **645** provides a port **640** for a connection to a modem (not shown).

[**0089**] Power frequency magnetomotive force (MMF) is canceled in the common leg of the core, but appears in full on each side leg. However, the air gap, which must be larger than the diameter of a neutral wire, would usually prevent these side legs from becoming saturated.

[**0090**] The advantage of the embodiments of FIGS. **6**A-**6**D is an avoidance of both interruption and physical contact with the neutral wires **602**. Current distribution among the neutral wires at power frequency would remain essentially unchanged, as the very small reactance induced by the core's choking affect would introduce a negligible reactance compared to the overall neutral wire impedance over the entire cable segment. Cable **600** can be thought of as a high frequency transmission line, connected at each terminus via a coupler, to communications equipment.

[**0091**] **FIG. 7** is a schematic of a balanced transmission line using a magnetic induction, in accordance with the present invention. This embodiment is similar to that of **FIG. 6**D, but instead of a single magnetic core or pair of toroids coupling to one pair of neutral wires, it couples to all neutral wires, organized as pairs. For a cable with an odd number of wires, one wire would be left unused. To achieve this, any of the embodiments of FIGS. **6**A-**6**D may be employed, with the number of couplers equaling the number of neutral wire pairs, and the windings of the couplers connected together. For minimum radiation, alternate neutral wires should be oppositely phased.

[**0092**] Similar to the embodiments of FIGS. **6**A-**6**D, the embodiment of **FIG. 7** includes a coupler having a first winding **720** for coupling a data signal via a first neutral conductors **702** of a power transmission cable **700** and a second winding **740**, inductively coupled to first winding **720**, for coupling the data signal via a data port **760**. Generally, the embodiment of **FIG. 7** enhances this to include a third winding **725** for coupling the data signal via a second neutral conductor **705** of power transmission cable **700**, and a fourth winding **745**, inductively coupled to third winding **725**, for coupling the data signal via data port **760**. The data signal travels in a first path via first neutral conductors **702**, first winding **720** and second winding **740**, and in a second path via second neutral conductor **705**, third winding **725** and fourth winding **745**. The first path is in parallel with the second path.

[**0093**] **FIG. 7** illustrates the use of all pairs of neutral wires, according to the embodiment of **FIG. 6D**. Wire pairs **702**, **705**, **710** and **715** all perform as transmission lines, in a manner similar to the selected pair **600** of **FIG. 6D**. The segments of the neutral wires passing through the magnetic flux of the cores act as windings **720**, **725**, **730** and **735**, and drive the neutral wire pairs as transmission lines. Windings **740**, **745**, **750** and **755** may be connected in parallel, as shown, or in any series or parallel combination providing consistent phasing, to provide a data signal to a port **760**. Since a central phase conductor **715** of power cable **700** is exposed to equal and oppositely phased flux from the coupling coils, phase conductor **715** does not affect the signal transmission.

[**0094**] Some of the advantage of the embodiment of **FIG. 7** are (a) the installation of a coupler can be performed without selecting a pair of neutral conductors, and therefore without identifying those conductors at the far end of the segment (note that a phase inversion is possible here, but would not affect data flow, as modems can tolerate phase inversion of the entire signal), (b) data transmission is possible, even if cable **700** is damaged during its run, and some of the neutral wires are accidentally grounded, (c) better cancellation of external fields and lower radiation, and (d) lower path loss over the cable segment.

[**0095**] **FIG. 8** is a schematic of an embodiment of the present invention using multiple transmission lines with multiple sets of neutral wires. This embodiment utilizes any of the embodiments represented in FIGS. **6**A-**6**D, but instead of a single signal path, it exploits a multiplicity of neutral wire transmission lines **802**, **805**, **810**, **815** to provide multiple independent transmission channels. FIGS. **8** shows four transmission channels.

[**0096**] Similar to the embodiments of FIGS. **6**A-**6**D, the embodiment of **FIG. 8** includes a coupler having a first winding **820** for coupling a data signal via a first neutral conductor **802** of a power transmission cable **800** and a second winding **825**, inductively coupled to first winding **820**, for coupling the data signal via a data port **830**. Generally, the embodiment of **FIG. 8** enhances this to include a third winding **835** for coupling a second data signal via a second neutral conductor **805** of power transmission cable **800**, and a fourth winding **840**, inductively coupled to third winding **835**, for coupling the second data signal to a second data port **845**.

[**0097**] Such a multiplicity may be exploited for achieving (a) full duplex transmission of data on one or more channels, (b) multiple unidirectional or bi-directional channels, thus increasing overall bandwidth, (c) redundant transmission of data to minimize errors, (d) implementing multi-wire interfaces that have separate clock, strobe and data lines, and (e) use of one channel for supervisory commands, error notification, or other data useful in network management.

[**0098**] For each of the embodiments shown in FIGS. **6**A-**6**D, and for the enhancements shown in FIGS. **3**-**8**, selection of one or two neutral wires at one end of a cable implies that the same wires must be identified at the distal end of the cable.

[**0099**] **FIG. 9A** is a schematic, and **FIG. 9B** is an illustration, of a system **900** for identifying one of a plurality of wires of a power transmission cable. System **900** includes a receiver **902** for sensing a signal from a selected neutral wire of the power transmission cable, and an indicator **905** of a magnitude of the signal. The signal is applied to a selected wire **925** at a first point **926** on the power transmission cable. Receiver **902** senses the signal at a second point **927** on the power transmission cable that is remote from the first point.

[**0100**] System **900** also includes a ferrite toroid **915** having a radial slot **920** through which the selected neutral wire **925** is routed, and a winding **930** that is wound around a portion of ferrite toroid **915** and connected to an input **935** of receiver **902**. The signal is inductively coupled from the selected neutral wire **925** via the ferrite toroid **915**. The signal is applied to the selected neutral wire **925** at first point **926** via an inductive coupler **924**.

[**0101**] At the first cable end to be connected, the wire(s) are selected, and a coupler attached. **FIG. 9A** shows a pair

of neutral wires being selected. The coupler is driven by a low power, high frequency oscillator, typically in the MHz range. This causes high frequency current to flow most strongly in the wire(s) selected.

[0102] At the distal end, radio receiver **900** is tuned to the same frequency. This radio receiver is special in that it is equipped with a signal strength meter **905** and manual or automatic gain control **910** for optimizing the gain. In addition, the receiver's antenna comprises a ferrite toroid **915** with a radial slot **920** slightly greater than the diameter of the neutral wire **925**, and a coil wound on the toroid **915** connected to the receiver's antenna input terminals **935**. Preferably, toroid **915** is fixed-mounted onto the receiver case.

[0103] The installer holds the receiver so as to orient the slot to be in line with and proximate to neutral conductor **925** and observes the reading on the signal strength meter **905**. The installer then moves the receiver tangentially around the cable, sensing each wire in turn. The wire(s) producing the maximum reading on the signal strength meter will be those directly excited at the other end of the cable.

[0104] Accordingly, a method for identifying one of a plurality of neutral wires of a power transmission cable, comprises the steps of (a) applying a signal to a selected neutral wire, at a first point on the power transmission cable, (b) sensing a relative magnitude of the signal on each of the plurality of neutral wires at a second point on the power transmission cable that is remote from the first point, and (c) identifying the selected neutral wire from the relative magnitudes. The identifying step identifies the selected neutral wire as the one of the plurality of neutral wires having a greatest relative magnitude. The applying step comprises inductively coupling the signal to the selected neutral wire, and the sensing step comprises inductively coupling the signal from the selected neutral wire.

[0105] Thus far, the present invention has been described in the context of a cable with multiple, separate, mutually insulated neutral wires. However, many power distribution networks do not use cables with mutually insulated neutral wires, but rather have their neutral wires in the form of a mesh or multiple wires connected together with conducting copper tape. **FIGS. 10A, 10B**, 11A and 11B and their associated descriptions, relate to an application of the present invention for other common medium voltage power girds, such as those carried on overhead wires and those carried on pseudo-coaxial underground cables with a single neutral conductor.

[0106] A coupler that avoids physical contact with a medium voltage phase conductor is desirable in that such a coupler would not need to withstand steady state and surge voltages of the phase conductor, thus simplifying construction and reducing cost of the coupler. However, the use of the currently proposed inductive coupler presupposes a circuit continuity through which current may flow, whilst the medium voltage circuits may include either physically open circuits at their ends, or be connected to transformer windings whose high impedance at radio frequencies may approximate the effect of an open circuit termination. In accordance with the present invention, inductive couplers can be used in a medium voltage data backhaul network when high frequency terminations are added using capacitive-coupled ports at the ends of the cable, and, in a large distribution network, also at a one or more intermediate positions. The phase conductors of underground power transmission lines can be used as data transmission lines when they are equipped with load terminations effective at the high frequencies used for communications for coupling data signals to and from the transmission lines.

[0107] In power distribution systems, the medium voltage grid is attached to devices that present an impedance much higher than the cable's characteristic impedance to signals at high frequencies. Such devices effectively appear as open circuits to high frequency signals. Coupling modulated data packets onto such an open-circuited cable would result in a large fraction of a coupled wave being reflected from the ends of the cable, and possibly being interpreted by data receivers as new packets. A further undesirable feature of such reflections would be to mislead the data receivers into concluding that new packets are occupying the cable, and "carrier sense" types of shared networks would suffer a loss of available transmission time.

[0108] For cables and wires with significant high frequency losses, these reflections would quickly dissipate, and not cause problems. However, for both overhead lines and some underground pseudo-coaxial lines, the losses are low, and strong reflected signals may interfere with the direct signals.

[0109] **FIGS. 10A and 10B** are schematics of portions of a data communication network implemented over a power distribution system, where the data is carried on a phase conductor of the power distribution system. The present invention uses a combination of inductive and capacitive couplers. As explained below, the network includes (a) an inductive coupler for coupling a data signal via the phase conductor, and having a data port for further coupling of the data signal, and (b) a capacitive coupler, connected between the phase conductor and ground, proximate to an end of the power transmission cable, for absorbing reflections of the data signal and optionally serving as a data port for coupling of the data signal.

[0110] Inductive couplers **1002** are used at intermediate nodes **1005** proximate to a distribution transformer **1010**. Each inductive coupler **1002** provides a port **1015** for connection to a modem (not shown) over a low voltage network being powered from the secondary of each distribution transformer **1010**. Capacitive couplers **1020** are connected between an end of a wire or cable and a local ground, to both absorb reflections and provide signal coupling nodes **1025**. That is, a signal coupling node **1025** is located between a capacitive coupler **1020** and ground, for coupling the data signal between the phase conductor and for providing another data port for the data signal.

[0111] The "end of the wire or cable" includes a point **1018** where power is fed into the cable from a high voltage to medium voltage transformer. In loop topologies, the cable returns to this location but reaches a dead end. Capacitive couplers **1020** are included at such "dead ends". Should a T-branch **1030** produce a stub **1035** in the power network, a capacitive coupler **1020** is used to terminate the distal end of stub **1035**.

[0112] **FIG. 11A** is an illustration of an embodiment of an inductive coupler **1102** for coupling data via a phase conductor, in accordance with the present invention. **FIG. 11B** is a schematic representation of the embodiment shown in **FIG. 11A**.

[0113] An inductive coupler **1102** includes a first winding **1104** for coupling the data signal via a phase conductor **1110**, and a second winding **1115**, inductively coupled to first winding **1104**, for coupling the data signal via a data port **1145**. Inductive coupler **1102** includes a core **1105** through which phase conductor **1110** is routed. This configuration of phase conductor **1110** through core **1105** serves as first winding **1104**, i.e., a winding of a single turn. Second winding **1115** is wound around a portion of core **1105**.

[0114] Inductive coupler **1102** is a current transformer in which core **1105** is placed over a segment of phase conductor **1110**. Inductive coupler **1102** can also be used with an underground cable by placing core **1105** over a segment of an underground cable that is not also covered by a neutral conductor sheath, with the power cable phase wire passing through core **1105** as a one-turn winding.

[0115] Core **1105** is made of ferrite or other soft magnetic material with substantial permeability and relatively low loss over the frequency range required for the modulated data. Core **1105** has an air gap **1120** sufficient to allow operation of the inductive coupler **1102** without saturation, even when current through phase conductor **1110** is as high as the maximum current for which conductor **1110** is rated, e.g. 200 amps rms.

[0116] Inductive coupler **1102** has a primary magnetization inductance sufficient to present appreciable high frequency impedance to a modem transmitter over a relevant frequency range, but negligible impedance at power distribution frequencies. Inductive coupler **1102** has both a leakage inductance and a reflected-primary impedance much lower than the characteristic impedance of the transmission line of which phase conductor **1110** is a component, over the relevant frequency range.

[0117] Inductive coupler **1102** has a high voltage capacitor **1125** in series with second winding **1115** and data port **1145**, and connected to a low voltage output, i.e. power line output, of a distribution transformer **1130**, to prevent second winding **1115** from short circuiting a low voltage power circuit **1135**. Thus capacitor **1125** couples a data signal between second winding **1115** and the power line output.

[0118] Inductive coupler **1102** also has a surge protector **1140** connected in parallel with second winding **1115**, to protect the low voltage circuit **1135**, and any electronic communications equipment attached to thereto, from being affected by a high amplitude pulse that might appear on phase conductor **1110** and be coupled by inductive coupler **1102** onto the low voltage lines.

[0119] Note that while only one LV phase line **1150** and LV neutral line **1155** are connected to coupler **1102**, the other phase line **1160** will receive a slightly attenuated signal via capacitive and inductive coupling, over the length of the LV drop lines.

[0120] An important consideration, and a desirable objective, is a minimization of electromagnetic radiation from the wires and cables used for transmission of data. These lines could radiate electromagnetic interference, even if buried a few feet underground. Spurious resonances might also prevent transmission over certain narrow frequency bands.

[0121] One or more techniques should be employed to minimize radiation, tolerate resonances, and provide a robust and reliable data channel. Options for minimizing radiation include:

[0122] (A) Using spread spectrum modulation in the modems connecting to and from the medium voltage grid. Spread spectrum modulation employs a relatively low spectral power density (e.g. −55 dBm/Hz).

[0123] (B) Minimizing the power level of the modulated data. The power level should to be high enough to overcome any noise on the line, and any self-generated equipment noise, e.g., internal noise, amplifier noise, etc. By exploiting the relative isolation of the medium voltage line from the noisy low voltage and high voltage grids, line noise can be minimized. This can be accomplished by placing back-to-back modems at each inductive coupler. Back-to-back modems are for the purpose of regenerating a bit stream and remodulating the data transmission over an additional medium.

[0124] **FIG. 12** is a schematic of a portion of a network having back-to-back modems at an inductive coupler. A first modem **1202** has a first port **1225** coupled to a data port of a second winding of an inductive coupler **1102** for sending and receiving a modulated data signal, and a second port **1210** for further coupling of the digital data. A second modem **1205** has a first digital data port **1230** coupled to the second port **1210** of first modem **1202**, and a second port **1235** for further coupling of the modulated data signal. Optionally, a router **1220** may be interposed between first modem **1202** and second modem **1205**.

[0125] The advantages of the above arrangement are:

[0126] A) The noise of the LV grid does not reach the MV grid. Isolation can further be enhanced by optical isolators in series with the data connection **1210**.

[0127] B) A spread spectrum or other modem, which uses different technology or parameters than the MV modem, can be optimized for LV grids. The inductive couplers introduce additional series impedance at the coupling nodes that is small relative to the wire or cable's characteristic impedance, thus minimizing both reflections and power absorption. In this case, the modulated data may traverse a large number of intermediate nodes successfully. Preferably, the magnetization and leakage inductances are small enough to minimize impedance disturbance but large enough to provide sufficient coupling. Implied here is an intentional impedance mismatch between the modem and the impedance presented by the coupler.

[0128] C) Routers and other networking equipment **1220** can be employed for mediating between the home and external network.

[0129] One parameter at issue for minimizing radiation is an attenuation of signal level in a direction between line and coupler, as the signal level on the medium voltage power line must be strong enough to overcome this attenuation. Attenuation in the direction between coupler and line may be easily overcome without additional radiation by applying more power to the coupler driving the line so as to establish the maximum permissible transmitted power level consistent with compliance to maximum allowed radiation levels.

[0130] For example, if each coupler is designed for a 10 dB coupling loss, then the transmitted power may be

increased by 10 dB to compensate, and only the second coupler's 10 dB is deducted from the modem's loss budget.

[0131] **FIG. 13** is a schematic of a technique for passively coupling modulated data between segments of a power grid, in accordance with the present invention. **FIG. 13** shows a data communication network **1300** implemented over a power distribution system having a first segment **1302** with a first neutral conductor **1320**, and a second segment **1303** with a second neutral conductor **1330**. Network **1300** includes a first coupler **1306** for inductively coupling a data signal via first neutral conductor **1320**, and having a data port **1335** for further coupling of the data signal, and a second coupler **1307** having a data port **1340** coupled to data port **1335** of first inductive coupler **1306**, and for inductively coupling the data signal via second neutral conductor **1330**.

[0132] First segment **1302** includes a first power distribution cable **1315** on a first side of a power distribution transformer **1345**. Second segment **1303** includes a second power distribution cable **1325** on a second side of power distribution transformer **1345**. Power distribution transformer **1345** has an output to power line **1350**. Network **1300** further comprises a capacitor **1310** between data port **1335** of first inductive coupler **1306** and output power line **1350**, for coupling the data signal to output power line **1350**.

[0133] Each transformer-to-transformer segment becomes a separate link in a multi-link chain. A coupler is attached to each cable termination, thus requiring two couplers per transformer, except for the last transformer on a dead end segment.

[0134] Passive chaining of segments is achieved by connecting the data ports **1335** and **1340** of the two couplers on either side of a transformer to each other. A passive connection to the communications devices attached to LV line **1350** is made through series coupling capacitors **1310**. Similar modems would be attached at both the networks feed point, such as the power substation, and at low voltage outlets at the users' premises.

[0135] **FIG. 14** is a schematic of a technique for coupling modulated data between segments of a power grid using back-to-back modems. **FIG. 14** shows a data communication network **1400** implemented over a power distribution system having a first segment **1402** with a first neutral conductor **1420**, and a second segment **1403** with a second neutral conductor **1430**. Network **1400** includes a first coupler **1406** for inductively coupling a data signal via first neutral conductor **1420**, and having a data port **1435** for further coupling of the data signal, and a second coupler **1407** having a data port **1440** coupled to data port **1435** of first inductive coupler **1406**, and for inductively coupling the data signal via second neutral conductor **1430**.

[0136] A first modem **1460** includes a first port for modulated data signals **1465** coupled to data port **1435** of first coupler **1406**, and having a second port for digital data **1470** for further coupling of the data signal. A second modem **1480** has a first port for digital data **1475** coupled to second port **1470** of first modem **1460**, and a second port **1485** for further coupling of the modulated data signal.

[0137] The power distribution system includes a power distribution transformer **1445** having an output power line **1450**. Network **1400** further comprises capacitors **1410** between second port **1485** of second modem **1480** and output power line **1450**, for coupling the modulated data signal to output power line **1450**.

[0138] A medium voltage cable may include a long cable segment, such as from a substation to the first distribution transformer in a loop. For ease of installation and service, the long section may be segmented, with access manholes at each node. At these points, the cable segments might be terminated in medium voltage connectors (for center conductor), along with neutral wire collector rings that are grounded. This introduces a discontinuity in the data transmission line, which is carried on one or more neutral wires. To bypass this discontinuity, a pair of couplers can be installed, one on either side of the ground, with their primaries connected to each other, creating a bridging connection.

[0139] The present invention also provides for implementing a data communication network using a phase conductor across segments of a power distribution system.

[0140] **FIG. 15** is a schematic showing several techniques for coupling data to a phase conductor of a power distribution system in an implementation of a data communication network **1500**, in accordance with the present invention.

[0141] A capacitive coupler is placed on overhead lines fed by an HV-MV step-down transformer. The transformer secondary impedance is of the same order of magnitude as that of overhead lines or larger. A terminator-coupler, e.g., a capacitive coupler with a data port, may be used here that both (a) is used to couple a modem to the line, and (b) terminates the line with a resistance approximately equal to the characteristic impedance of the power transmission cable (as a modem or dummy resistor impedance is reflected through its transformer). Accordingly, **FIG. 15** shows that the power distribution system includes a substation HV-MV voltage step-down transformer **1502**. A capacitive coupler **1535**, i.e., a terminator-coupler, is located proximate to a secondary winding of voltage step-down transformer **1502**. A component, such as modem **1525**, has an impedance that when reflected through capacitive coupler **1535** is approximately equal to a characteristic impedance of the power transmission cable.

[0142] In systems such as in Japan, where the custom is to run a very low impedance coaxial underground cables for lengths up to hundreds of meters to the beginning of an overhead grid, the preferred location for inductive couplers is at the overhead side of the underground-overhead transition point. Here, the low impedance of the underground cable acts like a short circuit at the end of the overhead line, and a closed current loop is formed. Thus, the power distribution system includes a transition **1545** between an overhead cable **1515**, **1516** and an underground cable **1510**, in which underground cable **1510** has a characteristic impedance that is much lower than that of overhead cable **1515**. One or more inductive couplers **1540**, **1541** are located on overhead cable **1515**, **1516**, proximate to transition **1545**.

[0143] The placement of inductive couplers **1540**, **1541** on the three phase overhead cable **1515**, **1516** may be done symmetrically with each member of a coupler pair driven with oppositely phased current. Such a drive will substantially cancel the far field electromagnetic radiation, and ease compliance with any regulatory standards. Accordingly, network **1500** may include a pair of inductive couplers **1540**,

1541 such that a first inductive coupler, e.g., **1540**, of the pair induces a first current in the phase conductor, e.g., **1515**, in a first direction, and a second inductive coupler, e.g., **1541**, of the pair induces a second current in the second phase conductor, e.g., **1516**, in a direction opposite of the first current.

[**0144**] Alternatively, a single phase may be driven, with equal and opposite currents being induced in the other phases, at a distance exceeding one wavelength from an inductive coupler, again canceling much of the far field radiation. For example, one inductive coupler **1540** may be used, and transmission line induction effects may be relied on to balance the currents, after one wavelength down the line.

[**0145**] Inductive couplers may also be placed on the lines feeding a distribution transformer primary, since the transformer primary impedance of some types of distribution transformers may be of the same order of magnitude as that of the overhead lines, and a closed loop is formed. Since this loop carries relatively low power-frequency currents, typically in the 2-8 Ampere range, there is little tendency for core saturation, and coupler cores may be built with little or no air gap. As shown in **FIG. 15**, an inductive coupler **1550** is located on a line that feeds a primary winding **1555** of a distribution transformer of the power distribution system.

[**0146**] Since the magnitude of the circuit impedance seen by the inductive coupler **1550** may be as high as hundreds of ohms, and modems **1560** along the length of the transmission line attached to inductive coupler **1550** would typically have a 50 ohm impedance, there may be a substantial impedance mismatch.

[**0147**] As shown in **FIG. 15**, power distribution system **1500** may include a PLC capacitor and/or a power factor correction capacitor, e.g., capacitor **1565**, between a phase conductor, e.g., **1516** and ground. Capacitor **1565** may have an impedance lower than that of the power transmission cable **1516**. PLC and power factor capacitors may have a high RF impedance, in which case they will not significantly disturb HF signals passing over the power grid. For those devices having an RF impedance whose magnitude is of the same order of magnitude or lower than the characteristic impedance of the power line, such as capacitor **1565**, a series choke **1570** may be inserted in series with capacitor **1565**. Series choke **1570** may comprise an existing lead wire **1575** to capacitor **1565** by placing one or more snap-on split magnetic cores over lead wire **1575**.

[**0148**] The power-frequency current is relatively low, so core saturation will not be a problem. The micro-Henry magnitude of these chokes' inductive impedances will not affect the capacitors' power frequency functioning. Lossy cores may also be used, for they simply increase the high frequency impedance of the choke, and add to the isolation of the capacitor.

[**0149**] The effects of transmission line reflections must be considered as they produce echoes that might introduce errors in the data stream. Spread spectrum modulation is the most likely candidate for such echo-laden transmission, as it is tolerant of narrow band frequency absorption and narrowband noise, and minimizes emitted electromagnetic radiation due to its low spectral power density. For spread spectrum modems, reflected intra-packet signals that are 6-10 dB or more below the direct signal level will not affect the data reception. Intra-packet reflected signals are defined as reflections that arrive during the direct reception of the original packet.

[**0150**] Impedance disturbances on the power lines may be caused by (a) distribution transformers, with or without the addition of inductive coupler impedance, (b) line terminations, which are typically designed to be fairly well matched to line impedance, (c) T-branches, and (d) PLC or power factor correction capacitors. The reflection coefficient of these impedance discontinuities will generally not exceed 0.5, and the reflected signal is subject to outbound and return loss of the lines themselves, i.e., absorptive loss and radiation loss, so it is expected that the amplitude of reflected signals will be weaker than direct signals by more than 6-10 dB. Thus, the reflected signals that arrive during a data packet will appear as low amplitude noise, and will not prevent the intended data signals from being correctly received.

[**0151**] For couplers placed at low impedance feed points to high impedance lines, such as transition **1545**, the loss and reflections due to impedance mismatch are not desirable. Since the very heavy power wires cannot be wound around the coupler core, the secondary can have no more than one turn, and the primary can have no less than one turn. Therefore, the impedance reflected onto the power lines will be equal to the modem impedance, one quarter of that, or less, depending on the turns ratio. For modems with 50-ohm terminal impedance, this reflected impedance is much lower than their characteristic impedance. One solution to improving impedance match is to build modems with an output impedance of a few hundred ohms.

[**0152**] Another solution is to connect a phase-antiphase pair of couplers with their primaries in parallel. The secondaries (MV lines) are necessarily in series. Thus, a 50-ohm modem impedance is transformed into a 100 ohm reflected impedance by the phase-antiphase inductive coupler pair. This principle can be carried further, by using multiple couplers with their primaries paralleled, achieving a series connection of transformer (coupler) windings on the power line side, and a parallel connection on the modem side.

[**0153**] For example, **FIG. 15** shows a first inductive coupler **1540** and a second inductive coupler **1541**. First inductive coupler **1540** induces a first current in a first direction in phase conductor **1515** via a first winding **1540**A, and second inductive coupler **1541** induces a second current in the opposite direction in phase conductor **1516** via a second winding **1541**A. First winding **1540**A and second winding **1541**A are in parallel with one another. In **FIG. 15**, first winding **1540**A and second winding **1541**A are marked with dots to show this phase relationship.

[**0154**] The inductive coupler at the overhead feed point must be designed to withstand the effects of the total feed current, which may reach hundreds of Amperes. Since even a one-turn coil carrying such current will saturate the core of currently available magnetic materials appropriate for high frequency operation, this "main line" coupler must generally include an air gap in its magnetic circuit. To achieve sufficient magnetization inductance, such couplers will need a multiplicity of cores forming the equivalent of one core that is very thick in the direction of the power wire.

[0155] FIGS. **16A-16C** are schematics representing several uses of capacitive couplers in a communication network implemented over a power distribution system. These capacitive couplers are used at nodes in the network where inductive couplers might not be effective, e.g., at points where there is an effective open circuit to RF current.

[0156] A capacitive coupler **1020**, such as used in **FIGS. 10A and 10B**, is shown in **FIG. 16A**, marked there as capacitive coupler **1600**. Capacitive coupler **1600** should be capable of continuously withstanding the working voltage supplied by the phase conductor and a series of BIL pulses, e.g., 125 kV for a 15 kV working voltage, as per IEEE Specification 386. Capacitive coupler **1600** should also be constructed so as to eliminate corona breakdown as per the above specification.

[0157] Capacitive coupler **1600** connects to the MV lines via high voltage capacitors **1620**, e.g., 10 nF, whose impedance at the lowest relevant frequency is a fraction of the characteristic impedance of the power transmission cable. Optionally, capacitive coupler **1600** may include a safety fuse **1625** in series with capacitor **1620**, to avoid faulting the medium voltage line should in case of a short-circuit.

[0158] High resistance bleeder resistors **1605** are connected in parallel with each capacitor **1620** to discharge them when they are not connected to energized circuits. Charged capacitors would be a hazard to personnel. To further isolate the data port **1630** from the MV lines, a high frequency isolation transformer **1615** is used, with an optional non-unity turns ratio, if needed, for impedance transformation.

[0159] To protect devices that are connected to data port **1630**, a surge protector **1632**, such as an metal oxide varistor (MOV) may be connected across the terminals of data port **1630** to limit the amplitude of pulses that might otherwise be coupled from the MV lines to the devices.

[0160] Preferably, in the network in which the capacitor is installed, one terminal of capacitive coupler **1600** is connected to a medium voltage phase line, and the other terminal connected to neutral (for single phase lines) or to a second phase line (for multiphase lines).

[0161] When used to terminate a dead end of a transmission line, capacitive coupler **1600** may be used, together with a termination resistor **1635**, connected to data port **1630**, to match the power transmission cable's characteristic impedance.

[0162] **FIG. 16B** illustrates the use of capacitive coupler **1600** for coupling a modem **1636** onto a dead end of a power transmission cable. Modem **1636** is connected to data port **1630**.

[0163] **FIG. 16C** is a schematic of an arrangement of capacitive couplers for maintaining continuity of a data signal across a grid segmentation switch. **FIG. 16C** shows a power distribution system having a phase conductor with a first segment **1601** on a first side of a switch **1602** and a second segment **1603** on a second side of switch **1602**. A first capacitive coupler **1650** couples a data signal via first segment **1601**, and has a data port **1635** for further coupling of the data signal. A second capacitive coupler **1660** has a data port **1665** coupled to data port **1635** of first capacitive coupler **1650**, and couples the data signal via second segment **1603**. Thus, a transmission of the data signal between first segment **1601** and second segment **1603** is maintained when switch **1602** is opened.

[0164] The present invention employs a variety of network protocols to extend physical range and improve reliability. After passing through inductive couplers and encountering impedance mismatches, tee junctions, and radiation loss, the amplitude of the signal available to the modem's receiver may become very weak. Whether this weakness is relative to a modem's internal noise or to ambient electrical noise on the medium voltage lines, there will be a physical point beyond which the signal cannot be detected and demodulated into data with an acceptably low error rate.

[0165] Bi-directional modems may be added to regenerate and strengthen the signal if high impedance chokes are also used to isolate the medium voltage grid into independent segments.

[0166] The data communication network can employ communication protocols that include the passing of data tokens from node to node. At each node, the token, which provides signaling or control, or includes a data packet as payload, is stored, interpreted, and routed to either the modem's local data user or else to the next node on the network. The time required to store, interpret and retransmit a token will reduce considerably the effective net data rate of such a network, if each node is always on-line.

[0167] In accordance with the present invention, only certain nodes are programmed to be active at any given moment, namely the node to which the token is addressed and a minimum fixed subset of nodes distributed along the network that are required to maintain a minimum signal amplitude for all points on the network. When this subset of nodes is active, there will be an advantageous tradeoff of time delay and reduced net data rate in return for increased physical range and improved error rate.

[0168] The determination of identity of the permanently active node members can be achieved by manual measurements of the attenuation between all nodes of the medium voltage network. Preferably, the modems are equipped with circuits that measure the voltage amplitude and/or signal to noise ratio, and are interrogated by a network media access control layer. The nodes should also be programmed to accept a command that keeps them in a permanently active relaying mode, even for tokens or packets that are not addressed to them.

[0169] An algorithm can then be implemented that determines which nodes should be set permanently active, and issues a stream of commands to all nodes to set the appropriate nodes permanently active. The algorithm is run each time the configuration of the medium voltage grid is changed, but this is a relatively rare event.

[0170] Closely spaced nodes will enjoy a data rate equal to the maximum network rate while more distant nodes will still be serviced by reliable, low error rate service, albeit at a lower data rate. In principle, it is claimed that the described arrangement removes all distance limits from medium voltage communications.

[0171] The transmission line formed by the selected conductor and its neighbors is inherently a wide bandwidth, low loss, and low dispersion medium. For overhead lines, the

losses would be due to skin effect and radiation, the latter being relatively ineffective since the lines are not resonant at most frequencies. For underground lines, the losses would be due to skin effect and the insulation's lossiness, e.g., outer layer of plastic and inner layer of semiconducting material.

[0172] The present invention produces a low electromagnetic emission and has a low susceptibility to external noise, especially when used with spread spectrum techniques. Power levels may also be kept low, because of low cable-to-coupler loss. Susceptibility to external noise sources would be proportional to radiation, with the modes having the lowest electromagnetic interference (EMI) also being those most resistant to external noise reception, based on the reciprocity principle.

[0173] For single-ended mode (see **FIG. 2A**), the two neighbors of the selected conductor act in anti-phase to the central conductor for both electrical and magnetic radiation modes. An observer at distance would see substantial cancellation of fields.

[0174] For balanced modes, there would be both far-field cancellation and a shielding affect of the grounded neighbors. For transformer termination (See **FIG. 2B**), the coupling loss would be lowest, and drive power levels could be kept relatively low, giving the lowest EMI levels. For choke termination, drive power levels would be slightly higher.

[0175] If the modems act as repeaters, then drive power levels can be held to the minimum required for a single segment, further reducing radiation.

[0176] A data communication network in accordance with the present invention offers a capacity for very high data rates, e.g., exceeding 10 Mbps. The couplers are all magnetic and electrostatic devices with bandwidths that can reach at least tens of megahertz if high frequency magnetic and dielectric materials are used. Transmission lines that are not too lossy and that have minimal dispersion could conduct frequencies exceeding 20 MHz. Such frequencies could be used for modems using various modulation schemes, and even at one bit per Hertz, would yield high data rates.

[0177] Baseband signaling can also be employed if the data coding eliminates long strings of all-1's and all-0's. With inter-segment connections that include regeneration (repeaters), the bandwidth would be much larger than obtainable with passive linking of segments.

[0178] The couplers of the present invention can be installed with little or no interruption of power service to customers. Installation can also be accomplished without exposure to high voltages. Employing gloved linemen, the authorities may allow placing an inductive coupler around a cable, while the cable is in service. Even if the authorities insist that workmen not work on energized cables, the loop architecture of neighborhood medium voltage grids allows disconnecting a single cable segment, without interrupting service to customers. For the relatively few capacitive couplers, a single short power outage might be needed.

[0179] The present invention permits continued operation of a data communication network even during power outage. Operation continues even during interruptions in medium voltage power.

[0180] The present invention poses little or no impact on reliability of electrical grid. Inductive couplers have no fault modes that would affect power flow. The few capacitive couplers, with their fuses, would also not cause a line fault.

[0181] For the embodiments of **FIGS. 2A and 2B**, winding the coupler with a thicker wire would preclude its failure due to over-current, and using industry-standard connections between the selected neutral and the coupler should minimize connection failure. Were an open circuit to occur, it leaves (N−1)/N of the current-carrying capacity intact, or 87.5% in the case discussed. Since the cable usually runs at much below its 200 A capacity, such a failure should have no effect.

[0182] Short circuit of the coupler would impact data communications, but such would merely restore the neutral conductor to its original state. Accordingly, the power grid would not be adversely impacted.

[0183] Short circuit of the neutral or any other part of the coupler to ground would have not effect on the MV line, as its neutral is proximately connected to the ground rod. Failure of the magnetic circuit, open, short or saturation, would have no effect on the supply of electric power or the safety of system.

[0184] The couplers use only passive components, implying a virtually unlimited life of service. The inductive coupler can be any suitable transformer or inductor.

[0185] In the passive implementation, the inductive couplers use only passive components, e.g. wires wound around magnetic cores, and these have no wear mechanisms. The capacitive couplers also have no wear mechanisms.

[0186] The passive construction, and ease of installation of the inductive couplers provide a low cost solution to the problem of coupling to medium voltage power distribution lines and utilizing them a backhaul data channels. Installation time should be less than 15 minutes for the predominant inductive, and installation costs minimal.

[0187] There is a clear advantage of the embodiments that use neutral lines, as compared to capacitive bypass couplers that employ the medium voltage conductors to carry data. The latter make contact with the medium voltage line at least once each transformer, and must withstand full fault voltages. For example, a Coupler for a 15 kV rms phase-to-ground cable must be tested for 125 kV BIL. This makes the capacitive coupler very bulky and expensive, and adds many more potential points of failure to the system.

[0188] It should be understood that various alternatives and modifications could be devised by those skilled in the art. The present invention is intended to embrace all such alternatives, modifications and variances that fall within the scope of the appended claims.

What is claimed is:

1. An apparatus for enabling communication of a data signal via a power transmission cable, comprising:

a first winding for coupling said data signal via a conductor of said power transmission cable; and

a second winding, inductively coupled to said first winding, for coupling said data signal via a data port.

2. The apparatus of claim 1, wherein said conductor is a first neutral conductor of said power transmission cable.

3. The apparatus of claim 2, wherein said first winding is connected in series between said first neutral conductor and a ground.

4. The apparatus of claim 2, wherein said first winding is connected in series between said first neutral conductor and a second neutral conductor of said power transmission cable.

5. The apparatus of claim 4, wherein said data signal is driven differentially through said first neutral conductor and said second neutral conductor.

6. The apparatus of claim 5, further comprising

a core having:

a first region adjacent to said first neutral conductor; and

a second region adjacent to said second neutral conductor,

wherein said second winding is wound around a portion of said core, and

wherein said second winding induces a first current in said first neutral conductor in a first direction, and induces a second current in said second neutral conductor in a second direction that is opposite of said first direction.

7. The apparatus of claim 6, wherein said core is topographically configured as a figure "8" with no contact at the crossing point of the "8".

8. The apparatus of claim 7,

wherein said first region comprises a first loop of said figure "8",

wherein said first conductor is routed through said first loop,

wherein said second region comprises a second loop of said figure "8", and

wherein said second conductor is routed through said second loop.

9. The apparatus of claim 7,

wherein said first region comprises a first gap in a first loop of said figure "8",

wherein said first conductor is routed through said first gap,

wherein said second region comprises a second gap in a second loop of said figure "8", and

wherein said second conductor is routed through said second gap.

10. The apparatus of claim 4, wherein said first neutral conductor and said second neutral conductor are substantially parallel to one another in said power transmission cable.

11. The apparatus of claim 4, further comprising a core, wherein said first winding comprises:

a grounded center tap;

a first portion connected to said first neutral conductor, wound in a first direction around said core, and connected to said grounded center tap; and

a second portion connected to said second neutral conductor, wound in a second direction around said core, and connected to said grounded center tap.

12. The apparatus of claim 4,

wherein said power transmission cable has a plurality of neutral wires that are substantially parallel to one another, with individuals of a first subset of said plurality of neutral conductors alternating with individuals of a second subset of said plurality of neutral conductors,

wherein said first neutral conductor comprises said first subset of said plurality of neutral conductors, and

wherein said second neutral conductor comprises said second subset of said plurality of neutral conductors.

13. The apparatus of claim 4, further comprising

a magnetic toroid core disposed around a portion of said power transmission cable,

wherein said first neutral conductor and said second neutral conductor are connected to a common terminating member downstream of said magnetic toroid core, and p1 wherein said first winding is connected to said first and second neutral conductors upstream of said magnetic toroid core.

14. The apparatus of claim 13, wherein said first and second windings are disposed within a balun transformer.

15. The apparatus of claim 2, further comprising an open magnetic core having:

a first leg positioned proximate and perpendicular to said first neutral conductor;

a second leg positioned proximate and perpendicular to a second neutral conductor of said power transmission cable; and

a third leg, located between said first leg and said second leg, having said first winding wound thereabout.

16. The apparatus of claim 2, further comprising:

a first magnetic toroidal core having a gap through which said first neutral conductor is routed;

a second magnetic toroidal core having a gap through which a second neutral conductor of said power transmission cable is routed,

wherein said first winding is wound around a portion of said first magnetic toroidal core and a portion of said second magnetic toroidal core.

17. The apparatus of claim 2, further comprising:

a third winding for coupling said data signal via a second neutral conductor of said power transmission cable; and

a fourth winding, inductively coupled to said third winding, for coupling said data signal via said data port,

wherein said data signal travels in a first path via said first neutral conductor, said first winding and said second winding, and in a second path via said second neutral conductor, said third winding and said fourth winding, and

wherein said first path is in parallel with said second path.

18. The apparatus of claim 2, wherein said data signal is a first data signal, and wherein said apparatus further comprises:

a third winding for coupling a second data signal via a second neutral conductor of said power transmission cable; and

a fourth winding, inductively coupled to said third winding, for coupling said second data signal to a second data port.

19. The apparatus of claim 1, wherein said conductor is a phase conductor of said power transmission cable.

20. The apparatus of claim 19, wherein said phase conductor is part of a medium voltage grid of the power distribution system.

21. The apparatus of claim 19, further comprising a core through which said phase conductor is routed, wherein said second winding is wound around a portion of said core.

22. The apparatus of claim 21, wherein said core has an air gap.

23. The apparatus of claim 19, further comprising a capacitor in series between said second winding and a ground.

24. The apparatus of claim 19, further comprising a surge protector connected in parallel with said second winding.

25. The apparatus of claim 1, further comprising:

a first modem having a first port coupled to said data port of said second winding, and having a second port for further coupling of said data signal; and

a second modem having a first port coupled to said second port of said first modem, and having a second port for further coupling of said data signal.

26. The apparatus of claim 25, wherein said first modem and said second modem are configured back-to back.

27. The apparatus of claim 25, further comprising a data router interposed between said first modem and said second modem.

28. A data communication network implemented over a power distribution system having a power transmission cable with a phase conductor, comprising:

an inductive coupler for coupling a data signal via said phase conductor, and having a data port for further coupling of said data signal; and

a capacitive coupler, connected between said phase conductor and a ground, proximate to an end of said power transmission cable, for absorbing reflections of said data signal.

29. The data communication network of claim 28,

wherein said inductive coupler is located proximate to a distribution transformer of said power distribution system,

wherein said distribution transformer has a power line output, and

wherein said data communication network further comprises a capacitor for coupling said data signal between said data port and said power line output.

30. The data communication network of claim 28, wherein said phase conductor is part of a medium voltage grid of said power distribution system.

31. The data communication network of claim 28, wherein said end of said power transmission cable is at a medium voltage output terminal of a high voltage to medium voltage transformer of said power distribution system.

32. The data communication network of claim 28, further comprising a node, located between said capacitive coupler and said ground, for coupling said data signal between said phase conductor and a second data port.

33. The data communication network of claim 28, wherein said inductive coupler comprises a current transformer having a winding coupled to said data port.

34. The data communication network of claim 33,

wherein said current transformer further comprises a core through which said phase conductor is routed, and

wherein said winding is wound around a portion of said core.

35. The data communication network of claim 34, wherein said core has an air gap.

36. The data communication network of claim 33, further comprising a capacitor in series with said winding and said data port.

37. The data communication network of claim 33, further comprising a surge protector connected in parallel with said winding.

38. The data communication network of claim 28, wherein said capacitive coupler comprises:

a capacitor;

a high frequency isolation transformer;

a fuse;

a bleeder resistor; and

a termination resistor having a resistance approximately equal to a characteristic impedance of said power transmission cable.

39. A data communication network implemented over a power distribution system having a first segment with a first neutral conductor, and having a second segment with a second neutral conductor, comprising:

a first coupler for inductively coupling a data signal via said first neutral conductor, and having a data port for further coupling of said data signal; and

a second coupler having a data port coupled to said data port of said first inductive coupler, and for inductively coupling said data signal via said second neutral conductor.

40. The data communication network of claim 39,

wherein said first segment comprises a first power distribution cable on a first side of a power distribution transformer, and

wherein said second segment comprises a second power distribution cable on a second side of said power distribution transformer.

41. The data communication network of claim 40,

wherein said power distribution transformer has an output power line, and

wherein said data communication network further comprises a capacitor between said data port of said first inductive coupler and said output power line, for coupling said data signal to said output power line.

42. The apparatus of claim 40, further comprising:

a first modem having a first port coupled to said data port of said first coupler, and having a second port for further coupling of said data signal; and

a second modem having a first port coupled to said second port of said first modem, and having a second port for further coupling of said data signal.

43. The apparatus of claim 42,

wherein said power distribution transformer has an output power line, and

wherein said data communication network further comprises a capacitor between said second port of said second modem and said output power line, for coupling said data signal to said output power line.

44. A data communication network implemented over a power distribution system having a power transmission cable with a phase conductor, comprising:

an inductive coupler having a first port for coupling a data signal via said phase conductor, and having a second port for further coupling of said data signal.

45. The data communication network of claim 44, wherein said inductive coupler is a radio frequency (RF) transformer.

46. The data communication network of claim 44, wherein said data communication network further comprises a capacitor connected in series with said first port and said phase conductor.

47. The data communication network of claim 46,

wherein said power distribution system includes a voltage step-down transformer,

wherein said inductive coupler is located proximate to a secondary winding of said voltage step-down transformer, and

wherein said data communication network further comprises a component having an impedance that when reflected through said inductive coupler is approximately equal to a characteristic impedance of said power transmission cable.

48. The data communication network of claim 47, wherein said component is a modem.

49. The data communication network of claim 44,

wherein said power distribution system includes a transition between an overhead cable and an underground cable,

wherein said underground cable has a characteristic impedance that is lower than that of said overhead cable, and

wherein said inductive coupler is located on said overhead cable, proximate to said transition.

50. The data communication network of claim 44,

wherein said inductive coupler induces a first current in said phase conductor in a first direction,

wherein said data communication network further comprises a second inductive coupler for coupling said data signal via a second phase conductor of said power transmission cable, and

wherein said second inductive coupler induces a second current in said second phase conductor in a direction opposite of said first current.

51. The data communication network of claim 44, wherein said inductive coupler is located on a line that feeds a primary winding of a distribution transformer of said power distribution system.

52. The data communication network of claim 44,

wherein said power distribution system includes a component between said phase conductor and a ground,

wherein said component has a characteristic impedance of less than that of said power transmission cable, and

wherein said data communication network further comprises a choke in series with said component.

53. The data communication network of claim 52, wherein said component is selected from the group consisting of a power factor correction capacitor, and a power line communications (PLC) capacitor.

54. The data communication network of claim 52, wherein said choke comprises a magnetic core disposed around a length of a wire that connects said component to said phase conductor.

55. The data communication network of claim 44,

wherein said inductive coupler induces a first current in said first phase conductor via a first winding,

wherein the data communication network further comprises a second inductive coupler for coupling said data signal via a second phase conductor of said power transmission cable,

wherein said second inductive coupler induces a second current in said second phase conductor via a second winding, and

wherein said first winding and said second winding are in parallel with one another.

56. A data communication network implemented over a power distribution system having a phase conductor with a first segment on a first side of a switch and a second segment on a second side of said switch, comprising:

a first capacitive coupler for coupling a data signal via said first segment, and having a data port for further coupling of said data signal; and

a second capacitive coupler having a data port coupled to said data port of said first capacitive coupler, and for coupling said data signal via said second segment,

wherein a transmission of said data signal between said first segment and said second segment is maintained when said switch is opened.

57. A method for identifying one of a plurality of neutral wires of a power transmission cable, comprising:

applying a signal to a selected neutral wire, at a first point on said power transmission cable;

sensing a relative magnitude of said signal on each of said plurality of neutral wires at a second point on said power transmission cable that is remote from said first point; and

identifying said selected neutral wire from said relative magnitudes.

58. The method of claim 57, wherein said identifying step identifies said selected neutral wire as said one of said plurality of neutral wires having a greatest relative magnitude.

59. The method of claim 57, wherein said applying step comprises inductively coupling said signal to said selected neutral wire.

60. The method of claim 57, wherein said sensing step comprises inductively coupling said signal from said selected neutral wire.

61. A system for identifying one of a plurality of neutral wires of a power transmission cable, comprising:

a receiver for sensing a signal from a selected neutral wire of said power transmission cable; and

an indicator of a magnitude of said signal,

wherein said signal is applied to said selected wire at a first point on said power transmission cable, and said receiver senses said signal at a second point on said power transmission cable that is remote from said first point.

62. The system of claim **61**, further comprising:

a ferrite toroid having a radial slot through which said selected neutral wire is routed; and

a winding that is wound around a portion of said ferrite toroid and connected to an input of said receiver,

wherein said signal is inductively coupled from said selected neutral wire via said ferrite toroid.

63. The system of claim **61**, further comprising an inductive coupler through which said signal is applied to said selected neutral wire at said first point.

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