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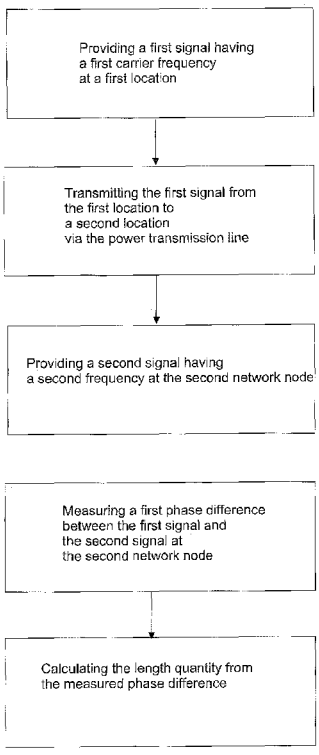


Fig. 6

(57) Abstract: The present invention concerns a method for determining a length quantity of a power transmission line, wherein the power transmission line connects a first location with a second location, wherein the method comprises: providing a first signal having a first carrier frequency (f_1) at the first location; transmitting the first signal from the first location to a second location via the power transmission line; providing a second signal having a second frequency (f_1') at the second location; measuring a first phase difference between the first signal and the second signal at the second location; calculating the length quantity from the measured phase difference. Further, the invention concerns a system for determining the length of a power transmission line (130) between a first location (110) and a second location (120), wherein a second receiver at the second location is adapted to receive a first signal having a first carrier frequency (f_1) from the first location, wherein the system comprises an frequency generator (122) for creating a second signal having a second frequency (f_1') at the second location; wherein the receiver further comprises a phase detection device (126) adapted for detecting a first phase difference between the second frequency and the first carrier frequency at the second location.

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Method and system for powerline length measurement

Description

The invention concerns a method and a system for determining a length quantity of a power transmission line, wherein the power transmission line connects a first location with a second location.

Power transmission lines expand their length due to thermal loading. A resulting sag of overhead lines is undesirable. Therefore, so the length or a length change may be monitored. An increase in length of overhead power transmission lines may lead to sag. Line sag of high voltage lines is critical, as it may lead to line faults due to flashovers to close objects such as trees.

In Wide Area Monitoring (WAM) systems for AC power transmission grids, Phasor Measurement Units (PMUs) perform measurement of voltage and current phasors. In US 2007/0038396, voltage and current phasors measured at two ends of a power transmission line are used to determine a line impedance, and specifically a line resistance. The resistance is a function of line temperature, so that the method provides a measurement of the average line temperature, which in turn affects the line length and its sag. The method requires synchronization of the PMUs.

Further, there are direct powerline sag measurement methods based on various principles, such as optical cameras, mechanical tension or inclination measurement (US 5,235,861, US 6,523,424, US 6,205,867), thermal measurements using fibres (US 6,776,522) or infrared cameras. These methods only perform local measurements.

Object of the present invention is to provide a simple and effective method and system for measuring a length quantity of a power transmission line.

According to a first aspect a method for determining a length quantity of a power transmission line, wherein the power transmission line connects a first location with a second location, wherein the method includes: providing a first signal having a first carrier frequency at the first location; transmitting the first signal from the first location to a second location via the power transmission line; providing a second signal having a second frequency at the second location; measuring a first phase difference between the first signal and the second signal at the second location; calculating the length quantity from the measured phase difference.

In a typical embodiment, the first signal with a first carrier frequency may be a sinus wave. Above method, wherein a first signal that is transmitted from a first location to a second location and the first signal is compared with a second signal at the second location may be applied remotely. Hence, local measurements of a sag, in case of an overhead transmission line may be avoided. In a typical embodiment the first and/or the second position may be any position on the power transmission line, in particular a network node.

In a typical embodiment, the power transmission line is an overhead power transmission line.

In another embodiment, which may be combined with other embodiments disclosed herein, the first signal is a power line communication signal. Thus, existing signals from a powerline communication link may be used for the length measurement.

Though, in a typical embodiment, the modulated user data may be compensated or eliminated.

Though, the compensating or eliminating may include low-pass filtering of a phase signal obtained from a quadrature demodulator, squaring the received signal before demodulating and extracting or bandpass filtering the component at a frequency $2f_i$, and/or using a data detector to re-modulate and substrate the data-dependent phase contribution. f_i may the carrier frequency of the first signal or the frequency of the second signal.

In a typical embodiment, that may be combined with other embodiments disclosed herein, the second frequency is equal to the first carrier frequency, wherein frequency generators for generating the first carrier frequency at the first location and the second frequency at the second location are synchronized. Though, about a phase difference variation, a length variation of the power transmission line may be measured.

Though, the frequency generators may be synchronized with a navigation satellite system, in particular Global Positioning System (GPS), Gallileo, IRNSS, GLONASS and the like.

In another embodiment, which may be combined with other embodiments disclosed herein, the length quantity is the total length.

In an embodiment, the second frequency is equal to the first carrier frequency, wherein the phase and the frequency of frequency generators for generating the first carrier frequency at the first location and the second frequency at the second location are synchronized. Though, a total length may be measured.

The total length may be calculated from $d = \lambda \frac{\psi + 2\pi N}{2\pi}$, with ψ being the phase difference and λ being the wave length of the first carrier frequency and d being the length, using a reasonable value for N. In a typical embodiment, the value for N may be estimated by a direct delay measurement, in particular by measuring a message delay between the first location and the second location, and the second location and the first location, respectively.

In a further embodiment, which may be combined with other embodiments disclosed herein, the method may include providing a third signal with a third carrier frequency; transmitting the third signal from the second location to the first location; providing a forth signal having a forth frequency at the second location; measuring a second phase difference between the third signal and the forth signal at the second location. In a typical embodiment, this method may not require external synchronization.

Though, by using the phase difference variation of the first and second phase difference the length variation of the power transmission line may be measured.

In a typical embodiment, the third carrier frequency is substantially equal to the first carrier frequency.

In a further embodiment, the third carrier frequency is different to the first carrier frequency.

In a further embodiment, which may be combined with other embodiments disclosed herein, the first carrier frequency and the forth frequency at the first location are generated from the same local frequency source having a first base frequency, and wherein the third carrier frequency and the second frequency are generated from the same local frequency source having a second base frequency. Typically a frequency source may be a frequency generator, an oscillator or the like.

Though, the first carrier frequency and/or the forth frequency may be a multiple or a fraction of the first base frequency, respectively, and/or the third carrier frequency and/or the second frequency may be a multiple or a division of the second base frequency, respectively.

In another embodiment the method may further includes: providing a third signal having a third carrier frequency at a first location; transmitting the third signal from the first location to a second location via the power transmission line; providing a forth signal having a forth frequency at the second location; measuring the phase difference between the third signal and

the forth signal at the second location, wherein the third carrier frequency is different to the first carrier frequency. This embodiment may be used where the propagation speed of a signal with the first carrier frequency and the propagation speed of a signal with the third carrier frequency is substantial different.

In an embodiment, which may be combined with other embodiments disclosed herein, first carrier frequency and/or the third carrier frequency is/are in the range of 10 kHz to 2000kHz, in particular in the range of 20kHz to 1000kHz, in particular in the range of 40kHz to 500kHz.

In a typical embodiment, the method may further include calculating the length of the power transmission line based on the measured first and/or second phase difference(s).

In a typical embodiment, which may be combined with other embodiments the length quantity is the relative change in length.

In a typical embodiment, the method includes calculating the absolute length of the power transmission line from the relative change in the length of the power transmission line and an estimate of an absolute length of the power transmission line.

In a further embodiment, which may be combined with other embodiments disclosed herein, the estimate of an absolute length of the power transmission line is performed by measuring a message delay between the first location and the second location, and the second location and the first location, respectively.

According to a further aspect a method for determining the temperature of a power transmission line between a first location and a second location is provided, wherein the method includes: determining the length of a power transmission line according to the other embodiments disclosed herein, calculating the temperature of the power transmission line based on the length of the power transmission line between the first location and the second location.

According to another aspect, a system for determining the length of a power transmission line between a first location and a second location is provided, wherein a second receiver at the second location is adapted to receive a first signal having a first carrier frequency from the first location, wherein the system includes an frequency generator for creating a second signal having a second frequency at the second location; wherein the receiver further includes a

phase detection device adapted for detecting a first phase difference between the second frequency and the first carrier frequency at the second location.

In a typical embodiment, the system is adapted to perform a method according to the embodiments disclosed herein.

In a further embodiment, that may be combined with other embodiments disclosed herein, the system further includes a second transmitter at the second location having a frequency generator for creating a third carrier frequency of a third signal, wherein the second transmitter is adapted to send the third signal via the power transmission line to the first location.

Though, in a typical embodiment, the second receiver and the second transmitter at the second location are adapted to use a common frequency source for creating the third carrier frequency for the third signal and for creating the second signal, wherein the common frequency source have a second base frequency, wherein in particular the third carrier frequency of the third signal is a multiple or a division of the second base frequency, and/or the second frequency is a multiple or a division of the second base frequency.

In a further embodiment, which may be combined with other embodiments, the system wherein the system includes at the first location a first receiver adapted to receive the third signal from the second location, wherein the system includes a frequency generator at the first location for creating a forth signal having a forth frequency; wherein the system further includes a phase detection device adapted for detecting a second phase difference between the forth frequency and the third carrier frequency.

Thought, in a typical embodiment, the system further includes a first transmitter at the first location having a frequency generator for creating the first carrier frequency of a first signal, wherein the first receiver and the first transmitter at the first location are adapted to use a common frequency source for creating the first carrier frequency for the first signal and for creating the forth signal, wherein the common frequency source have a first base frequency, wherein in particular the first carrier frequency of the first signal is a multiple or a division of the first base frequency, and/or the forth frequency is a multiple or a division of the first base frequency.

In another embodiment, which may be combined with other embodiments disclosed herein, the system is adapted to calculate the length of the power transmission line based on the measured first and/or second phase difference(s).

Embodiments are also directed to apparatuses for carrying out the disclosed methods and including apparatus parts for performing described method steps. Furthermore, embodiments are also directed to methods by which the described apparatus operates or by which the described apparatus is manufactured. It may include method steps for carrying out functions of the apparatus or manufacturing parts of the apparatus. The method steps may be performed by way of hardware components, firmware, software, a computer programmed by appropriate software, by any combination thereof or in any other manner.

It is contemplated that elements of one embodiment may be advantageously utilized in other embodiments without further recitation.

In the following, a method for measuring a length quantity is generally described.

From the telegraph equation, a complex amplitude of a sine wave with frequency ω propagating on a homogenous transmission line in a direction d is

$$e^{-\gamma d} = e^{-\alpha d} \cdot e^{-j\beta d} \qquad (1)$$

where

$$\gamma = \sqrt{(G'+j\omega C')(R'+j\omega L')} \approx \underbrace{\left(\frac{1}{2}R'\sqrt{\frac{C'}{L'}} + \frac{1}{2}G'\sqrt{\frac{L'}{C'}}\right)}_{\alpha} + j\underbrace{\omega\sqrt{L'C'}}_{\beta}. \quad (2)$$

In (2), R', G', C', and L' are the resistance, conductance, capacitance, and inductance per unit length of the transmission line, and the approximation is valid for a low loss line with $R' << \omega L'$ and $G' << \omega C'$. This embodiment proposes to use signals to be transmitted from a first location to a second location, in a typical embodiment from a first network node to a second network node, to measure the critical line parameters, i.e. line length and line temperature. In a typical embodiment, the carrier frequency of a powerline carrier communication (PLC) link used.

To determine the temperature of the power transmission line, a relation between the length of the power line and the temperature may be established. Line resistance: R' and hence α

increases roughly linearly against temperature, which translates to a decrease of the amplitude of the received signal, in particular a powerline communication (PLC) signal, by $e^{-\alpha d}$. Due to the skin effect, R' is considerably larger for high frequency signals, e.g. PLC signals, than for the 50/60 Hz AC power. However, the temperature-dependency is likely to be the same for the given transmission line. Given the amplitude of the transmitted signal, the receiver can measure the attenuation and thus determine the resistance *R'*. An average line temperature T_1 may be determined from the ohmic resistance R' by a relationship between the temperature and the resistance. The relationship may be linear e.g. $R'=R_2 + k_1(T_1-T_2)$, or quadratic $R'=R_2+k_1(T_1-T_2)+k_2(T_1-T_2)^2$ wherein R_2 and T_2 are a known reference and temperature values dependent on the construction of the line and k_1 and k_2 are material constants for the power line cable. Thus, the average line temperature can be inferred from this measured average line resistance. For example, the thermal resistance coefficient of aluminium is $4\cdot10^{-3}$ K^{-1}, so that an increase in the resistance *R'* by 12% implies a temperature increase of 30°C. In a further embodiment, the mapping from the measured electrical parameters such as R' to average line temperature, given the weather dependency in particular of G', is discussed in US 2007/0038396, which is incorporated herein by reference. The line temperature in turn determines the line length, as given by the thermal expansion coefficient.

There is an increase in line length *d* due the thermal expansion. The linear thermal expansion coefficient e.g. of steel is $17.3\cdot10^{-6}$ K^{-1}, and hence the thermal increase in length *d* is negligible against the thermal increase in *R'* in the term *R'·d* in equation (2). The length increase may be directly measured using a signal transmitted on the power transmission line:

In the following a method to measure the line length *d* is discribed. According to the last term in equation (2), the complex amplitude of the sine wave is rotated by $e^{-j\beta d} = e^{-j\psi}$, i.e. the *phase* ψ of the sine wave of frequency $f = \omega/2\pi$ at position *d* is

$$\psi = \omega\sqrt{L'C'}d = \omega\frac{d}{c} = 2\pi\frac{d}{\lambda} \quad (3)$$

where $c = 1/\sqrt{L'C'}$ is the propagation speed on the transmission line, and $\lambda = c/f$ is the wavelength of the sine wave. Therefore, a change of the relative phases between the end points of a transmission line indicates a change in the line length. According to an embodiment, the phase of a carrier frequency, for example the carrier phase of power line communication signals, is measured for determining the line length. Power line communication (PLC) signals employed on high voltage transmission lines have typically

carrier frequencies in the range of f = 100 kHz to 500 kHz, i.e. wavelengths of $\lambda = c/f \approx 400$ m to 2000 m. A phase measurement resolution of $\Delta\psi = 1°$ achieves a length resolution of 5.5 m or better. On a steel line length of d = 100 km, given the thermal coefficient of steel of $17.3 \cdot 10^{-6}\,K^{-1}$, this corresponds to a temperature resolution of 3°C.

Phase measurement at a given receiver location is done by comparing the phase of the received signal with the phase of a locally generated signal. Generally, it is difficult to distinguish the wanted effect of line length from the effect of unknown phase offsets between the transmitter and receiver frequency sources (oscillators).

So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments. The accompanying drawings relate to embodiments of the invention and are described in the following:

Fig 1 shows a schematic power transmission line;

Fig. 2 shows a schematic drawing of a first embodiment of a system for detecting the length of a power transmission line;

Fig. 3 shows a schematic drawing of a phase detector;

Fig. 4 shows a schematic drawing of a further embodiment of a system for detecting the length of a power transmission line;

Fig. 5 shows a schematic drawing of a quadrature demodulator; and

Fig. 6 shows a schematic method for estimating the length of a power transmission line.

Fig. 1 shows a power transmission line 1 with three phases. The power transmission line 1 is an overhead power transmission line with three phases. Due to temperature increase of the power transmission line 1 a sag s may increase. If the sag of the high voltage line is too big a flashover 10 to close objects like a tree 20 may occur. This may lead to a power transmission line fault. The sag s increases when the power transmission line length increases. In turn the power transmission line length is dependent on the temperature of the power transmission line

1. Therefore, it is important for a power network operator to monitor the length of a power transmission line.

Generally, in the following ω is used for the angular frequency and f for the normal frequency, where $\omega=2\pi f$.

Fig. 1 shows a first embodiment of a system 100 for measuring the length of a power transmission line 1. A first network node 110 is connected to second network node 120 with a power transmission line 130. In the first network node 110 a first signal with a first carrier frequency f_1 is generated using the first frequency generator or oscillator 112 and modulating incoming data in a modulator 114. The modulated data or first signal is then transmitted via the power transmission line 130 to the second network node 120. The first signal has therefore a first carrier frequency. In another embodiment, no data is modulated such that a simple sinus wave with the carrier frequency f_1 of the first frequency generator 112 is transmitted over the power transmission line 130 to the second network node 120. In an embodiment, the frequency generator 112 may replaced by an oscillator. In another embodiment which may be combined with other embodiments disclosed herein, a frequency f_0 generated by the frequency generator or oscillator may be multiplied or divided using a frequency multiplier or divider for generating the frequency f_1 before the data to be transmitted is modulated with that frequency f_1. The first signal with is transmitted over the power transmission line 130 arrives with a delay τ at second network node 120. The delay d may be calculated from the phase difference between a locally generated second signal with the frequency f_1 and the received first signal with the first carrier frequency f_1 at the second network node 120. From the phase difference, the length of the power transmission line 130 may be deducted. The second network node 120 includes a second oscillator or a frequency generator 122 for providing the second frequency f_1 that is equal to the first carrier frequency f_1 at a demodulator 124.

The demodulator 124 in the second network node 120 may include phase detector 126 as shown in Fig. 3. The phase detector may include a frequency mixer or an analog multiplier circuit, and a low pass filter for generating a voltage signal which represents the difference in phase between the first signal and the second signal.

In an embodiment, the frequency generators 112, 122 in the first and second network node 110, 120 are synchronized. This may be done by satellite signals such as from a GPS satellite 300. Therefore, the first and second network node 110, 120 may include a GPS receiver 118,

128, respectively. In further embodiments, other methods may be used to provide a synchronization of the frequency generators 112, 122 in the first and second network node.

Thus, a clock of an oscillator in a first network node 110 for transmitting the first signal with the carrier frequency f_1 to the second network node 230 and the clock of an oscillator or frequency generator in a second network node 120 are synchronized. I.e., the frequency for modulating and demodulating in the first and second network node are synchronized and typically equal. Thus, the absolute phases can be measured (up to an ambiguity of $N \cdot 2\pi$, wherein N is a natural number) and the length d of the power transmission line can be calculated directly using equation (3). Typically, the absolute phase difference of the first signal at the first network node and at the second network node may be measured, if the also the phases of the frequency generators in the first network node and the second network node are synchronized or locked. Typically, to estimate the value of N, the length of the power carrier line may be estimated using a direct delay measurement method. An example of such a direct delay measuring method is described below.

In a typical embodiment, wherein the phases of the frequency generators in the first and second network nodes are not synchronized, but the frequencies of the frequency generator in the first and second network nodes are synchronized, typically only a length variation of the power transmission line may be measured via a phase difference variation.

In a further embodiment, that will be described in the next sections with respect to Fig. 4, the frequency differences in an unsynchronized system are simultaneously estimated, and therefore the desired length d of the power transmission line. This may be implemented, in a typical embodiment, using a power line communication (PLC) system. Typically, PLC systems use continuous frequency duplex transmissions. A duplex transmission is a bi-directional transmission, i.e. at the same time a first transmission from the first network node to second network and a second transmission from the second network node to the first network node take place. Fig. 4 shows a first network node 110 and a second network node 120.

The first network node 110 transmits to the second network node 120 a first signal on frequency $\omega_1=2\pi f_1$, as shown in the upper part of Figure 4. The frequency ω_1 is therefore a carrier frequency of the first signal. Omitting any PLC data modulation for the moment, the transmitted signal is a sine wave,

$$x_1(t) = \cos(\varphi_1(t)) = \mathrm{Re}\left(e^{j\varphi_1(t)}\right) \qquad (4)$$

where $\varphi_1(t) = \omega_1 t + \varphi_1^0$.

For the described method it is not necessary to send data from the first network node 110 to the second network node 120. The measurement of the length of the power transmission line may in an embodiment use signals without transporting data. That means that the first signal $x_1(t)$ is sent from the first network node 120 and received at the second network node 120 after a propagation delay of τ. The propagation delay τ leads to a phase change of $-\omega_1 \cdot \tau = -\omega_1 \cdot d/c_1$, where c_1 is the known speed of propagation for the frequency ω_1, and d is the distance (length of the power transmission line) to be determined. Typically, the speed of propagation c *is* approximately $2 \cdot 10^8$ m/s, and only weakly dependent on frequency of the signal to be transmitted from the first network node 110 to the second network node 120, in particular for lossless or low loss lines. The demodulator at the second network node 120 "down-mixes" (e.g. multiplies and filters) or demodulates the received first signal with a locally generated second signal having a second frequency $\omega_1' = 2\pi f_1'$, in order to shift the high-frequency first signal to the base band, as it will be described in more detail below. Typically, the oscillator or frequency generator 122 at the second network node 120 generates the same frequency ω_1' as the oscillator or frequency generator 112 at the first network node 110 generating the frequency ω_1. In practice, however, $\omega_1' = \omega_1 + y \cdot \omega_1$, where y is a small relative frequency error, typically $y \approx 10^{-6}$ (1 ppm).

In complex notation, the first signal demodulated with the second signal corresponds to

$$\mathrm{Re}\left[z_1(t) \cdot \exp\left(-j(\omega_1' t + \psi_1^0)\right)\right] \qquad (5)$$

where $z_1(t) = x_1(t - \tau)$. In equation (5) noise and distortion effects are neglected. It may be seen that $(\omega_1' \cdot t + \psi_1^0)$ is subtracted from the received phase due to the demodulation or frequency mixing of the received first signal with the second signal. ψ_1^0 accounts for the unknown relative phase between the transmitter and receiver oscillators. The phase after the demodulator is thus

$$\psi_1(t) = \varphi_1(t) - \omega_1 \frac{d}{c_1} - \left(\omega_1' t + \psi_1^0\right) = \left(\omega_1 - \omega_1'\right) t - \left(\omega_1 \frac{d}{c_1} - \varphi_1^0 + \psi_1^0\right) \qquad (6)$$

In addition to the wanted parameter d, i.e. the length of the power transmission line, the received phase $\psi_1(t)$ contains the unknown nuisance parameters $(\omega_1' - \omega_1)$ and $(-\varphi_1^0 + \psi_1^0)$, due to the frequency and phase offsets from the frequency generator in the first network node and the frequency generator in the second network node. As there are many unknown causes contributing to the phase offset $(-\varphi_1^0+\psi_1^0)$, it is not possible in practice to recover the absolute length of the transmission power line *d* from the measured phase in (6). It is however possible to measure the relative change in the length *d* of the transmission power line from $\psi_1(t)$, if the frequency offset $(\omega_1' - \omega_1)$ can be compensated. The following describes a method to estimate d or a relative change in d, while taking any frequency offset into account.

In a typical embodiment, a second measurement of a phase difference may be performed in the reverse direction and/or on a different frequency. For example a second measurement of a phase difference is performed on the same power transmission line using a third signal that is sent from the second network node 120 to the first network node 110. This is shown in the lower part of Fig. 4.

A continuous PLC signal or another third signal is transmitted from the second network node 120 with the third carrier frequency ω_2'. The phase of the transmitted phase is thus

$$\varphi_2(t) = \omega_2' t + \varphi_2^0 .$$

Using the same derivation as above, the phase or the phase difference of the demodulated third signal in the first network node 110 is

$$\psi_2(t) = \varphi_2(t) - \omega_2' \frac{d}{c_2} - \left(\omega_2 t + \psi_2^0\right) = \left(\omega_2' - \omega_2\right)t - \left(\omega_2' \frac{d}{c_2} - \varphi_2^0 + \psi_2^0\right) \qquad (7)$$

In the first network node 110 and in the second network node 120, the frequencies for modulating the third signal (the carrier frequency ω_2 of the third signal) or demodulating the first signal (i.e. the frequency of the second signal ω_1'), or the frequencies for modulating the first signal (the carrier frequency ω_1 of the first signal) and demodulating the third signal (i.e. the frequency of the forth signal ω_2) may be derived from the same frequency source, or from synchronized or the same frequency generators. Thus, it is possible to relate $(\omega_1 - \omega_1')$ to $(\omega_2' - \omega_2)$ using the frequency errors. In both nodes, the frequencies $f_i=\omega_i/2\pi$ and fi' are derived from local oscillators generating reference or base frequencies f_0 and f_0', in the first network node 110 and the second network node 120, respectively.

$$f_1 = k_1 f_0, \qquad f_1' = k_1 f_0' \qquad (8)$$

$$f_2 = k_2 f_0, \qquad f_2' = k_2 f_0'$$

Frequency multipliers or dividers k_1 and k_2 may be implemented, in a typical embodiment, in the first network node 110 and the second network node 120. Therefore they are known constants, and same in both nodes. All frequency errors are thus proportional to the difference $f_0' - f_0$,

$$f_0' - f_0 = f_0(1+y) - f_0 = y f_0 \qquad (9)$$

where y denotes the relative frequency offset of f_0' with respect to f_0. Therefore $(\omega_1 - \omega_1') = -y\omega_1$ and $(\omega_2' - \omega_2) = y\omega_2$.

Inserting this into equation (6) and equation (7) yields

$$\psi_1(t) = -y\omega_1 t - \omega_1 \frac{d(t)}{c_1} + \left(\varphi_1^0 - \psi_1^0\right) \qquad (10)$$

$$\psi_2(t) = +y\omega_2 t - \omega_2' \frac{d(t)}{c_2} + \left(\varphi_2^0 - \psi_2^0\right) \qquad (11)$$

$\psi_1(t)$ and $\psi_2(t)$ are the phase differences between the received first and second signal at the second network node 110 ($\psi_1(t)$), and between the received third and the forth signal at the first network node 120 ($\psi_2(t)$). These two measurements allow to eliminate the unknown frequency offset y: Solving equations (10) and (11) for d(t), while taking advantage of fact that the frequency offset is small ($|y| << 1$), so that $\omega_2' \approx \omega_2$, yields

$$d(t) = -\frac{\frac{\psi_1(t)}{\omega_1} + \frac{\psi_2(t)}{\omega_2}}{\frac{1}{c_1} + \frac{1}{c_2}} + \frac{\frac{\left(\varphi_1^0 - \psi_1^0\right)}{\omega_1} + \frac{\left(\varphi_2^0 - \psi_2^0\right)}{\omega_2}}{\frac{1}{c_1} + \frac{1}{c_2}} \qquad (12)$$

The may also obtained in an embodiment, where the frequency generators in the first network node 110 and the second network node 120 are synchronized, e.g. by Global Positioning System (GPS) signals. The second term on the right hand side of equation (12) is constant in time and due to the absolute phases. It may only be measured with exactly synchronized

clocks. However, in practice it is sufficient to measure only a relative change in the length d(t), as given by the first term in equation (12), i.e.

$$\hat{d}(t) = -\frac{\frac{\psi_1(t)}{\omega_1} + \frac{\psi_2(t)}{\omega_2}}{\frac{1}{c_1} + \frac{1}{c_2}} \quad . \qquad (13)$$

In the illustrative special case of $\omega_1 = \omega_2 = \omega$, that means the same carrier frequency is used for the first and the third signal,

$$\hat{d} = -\frac{c}{\omega}\frac{\psi_1 + \psi_2}{2}, \qquad (14)$$

i.e. d is obtained from the average of the two measurements, as a generalization of equation (3).

In a typical embodiment, above method may be implemented using a quadrature demodulator, e.g. using e.g. a quadrature amplitude modulation (QAM). The QAM is a modulation scheme which conveys data by changing the amplitude of the carrier waves. These two waves, usually sinusoids, are out of phase with each other by 90° and are thus called quadrature carriers. The two waves have usually the same frequency. The measurement of the first and second phases $\psi_i(t)$, i = 1,2 at the first and second network node, respectively, given the received signals $z_i(t)$, may be implemented by a quadrature demodulator. An example of a quadrature demodulator is shown in Fig. 5. The received signal $z_i(t)$, for example the first signal received at the second network node 120, or the third signal received at the first network node 110, is multiplied (or demodulated) by quadrature signals $\cos\left(\omega_i t + \psi_i^0\right)$ and $-\sin\left(\omega_i t + \psi_i^0\right)$ and low-pass filtered. The resulting signals are

$$u_i^I(t) = \frac{1}{2}\cos\left(\psi_i(t)\right) \qquad (15)$$

$$u_i^Q(t) = \frac{1}{2}\sin\left(\psi_i(t)\right), \qquad (16)$$

from which the phase $\psi_i(t)$ is found as the angle of the complex number $u_i(t)$, $u_i(t) = u_i^I(t) + ju_i^Q(t) = 1/2\, e^{j\psi_i(t)}$. Formally,

$$\psi_i(t) = \arctan\left(\frac{u_i^Q(t)}{u_i^I(t)}\right). \qquad (17)$$

The measurements of the phase difference $\psi_1(t)$ and $\psi_2(t)$ performed at different nodes are combined to yield an estimate of d(t), see for example equation (14). This implies that the measurement values are sent, at an appropriate rate, to a calculation unit. This unit may be located at the first network node 110 or at the second network node 120, in which case the values can be transmitted using the PLC communication link itself. Alternatively, the values can be sent by separate devices to some third unit for processing.

The description above is given in terms of unmodulated carriers. In practice, the PLC signal is modulated by the user data to be transmitted. For accurate phase measurements, this data modulation may be compensated or eliminated.

In an embodiment, the phase signal obtained from the quadrature demodulator is low-pass filtered, in order to smooth over the data-induced phase variation.

In another embodiment, the signal $z_i(t)$ is squared before demodulation and extracting (bandpass filtering) the component at frequency $2\omega_i$. Quadrature demodulation of the resulting signal yields $2\psi_i(t)$ with most data-dependent contributions removed.

In a further embodiment, a decision-feedback may be used, i.e. using the data detector to re-modulate and subtract the data-dependent phase contribution.

These schemes may introduce measurement errors which depend on the statistics of the data.

In the following a numerical example is given for a measurement of a length of a power transmission line.

Assume that d increases from say 100 km to 100.05 km in one minute due to increased thermal loading of 30°C. Hence $\dot{d}$ = 50m/60 sec = 0.83 m/s. With f_1 = 100 kHz and f_2 = 200 kHz, and a relative frequency error of y = 10^{-6} (1 ppm can be achieved by low-cost temperature-controlled quartz oscillators), it follows from equation (10) and equation (11) with $d(t) = d_0 + \dot{d}\,t$ that the frequencies measured at $\psi_1(t)$ and $\psi_2(t)$ are

$$\frac{\dot{\psi}_1}{2\pi} = -yf_1 - f_1\frac{\dot{d}}{c} = -104.2\ mHz\,, \qquad f_1\frac{\dot{d}}{c} = 0.42\ mHz$$

$$\frac{\dot{\psi}_2}{2\pi} = +yf_2 - f_2\frac{\dot{d}}{c} = +191.7\ mHz, \qquad f_2\frac{\dot{d}}{c} = 0.83\ mHz$$

(with c = $2\cdot10^8$ m/s). It is seen that contribution due to the oscillator frequency offset may be considerably larger than the frequency due to the length change of the power line. Precise measurement of the phases is thus crucial to obtain accurate length estimates from equation (13).

In a further embodiment instead of using bi-directional measurements as described above, it also possible to use two co-directional links from the first network node 110 to the second network node 120, using different frequencies $f_1 \neq f_2$. In this case, the sign of the measured frequency offsets at frequencies f_1 and f_2 are equal, and a similar derivation as above yields

$$\hat{d} = -\frac{\frac{\psi_1}{\omega_1} - \frac{\psi_2}{\omega_2}}{\frac{1}{c_1} - \frac{1}{c_2}}. \qquad (18)$$

However, this method fails if the propagation speeds c_1 and c_2 for the two frequencies are equal, as is true for lossless lines. Hence, this method may be sensitive to measurement errors.

In a further embodiment, which may be combined with other embodiments, the power transmission line length may be separately directly measured, to provide an approximate length of the power transmission line. As explained, the estimate $\hat{d}(t)$ does not give an absolute length. For example, a direct delay measurement may be used. After performing this direct delay measurement for obtaining a rough estimate of the length of the powerline, the carrier phase measurement method described above is then employed to deliver relative length measurements of higher accuracy and resolution. The delay measurement method relies on "two-way measurements" of message delay between first network node 110 and the second network node 120.

At time T1 (as measured by the clock on node 1), node 1 sends a message to node 2. Node 2 measures its arrival time as T2 (measured by the clock on node 2). Then at time T3 (measured by the clock on node 2), node 2 in turns sends a message to node 1, which measures its arrival time as T4 (measured by the clock in node 1). Assuming that the message delay τ is the same in both directions,

$$d = \frac{\tau}{c} = \frac{1}{c}\frac{(T4 - T1) - (T3 - T2)}{2}. \quad (19)$$

This is a variant of the round trip delay measurement (T4 – T1), corrected by the processing time (T3 – T2) in node 2. Due to processing time jitter and to the lower frequency content of the data signal carrying the messages, such message delay measurements are considerably less accurate and have much lower resolution than the carrier phase method described above. For example, a (low) message delay measurement jitter of 10 μs translates to a length error of 2 km, to be compared with a 1° resolution of phase measurements corresponding to length resolution of about 5 m.

Fig. 6 shows an embodiment of a method that may be used for performing a measurement of a length quantity of a power transmission line between a first location and a second location. In a first step a first signal having a first carrier frequency at a first network node. In a further step the first signal is transmitted from the first locatoin to the second location via the power transmission line. In a further step a second signal is provided having a second frequency at the second network node. In another step, a first phase difference between the first signal and the second signal is measured at the second network node. Finally, the length quantity from the measured phase difference is calculated.

The written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to make and use the invention. While the invention has been described in terms of various specific embodiments, those skilled in the art will recognize that the invention can be practiced with modifications within the spirit and scope of the claims. Especially, mutually non-exclusive features of the embodiments described above may be combined with each other. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims.

Claims

1. A method for determining a length quantity of a power transmission line, wherein the power transmission line connects a first location with a second location, wherein the method comprises:
providing a first signal having a first carrier frequency (f_1) at the first location;
transmitting the first signal from the first location to a second location via the power transmission line;
providing a second signal having a second frequency (f_1') at the second location;
measuring a first phase difference between the first signal and the second signal at the second location;
calculating the length quantity from the measured phase difference.

2. The method according to claim 1 or 2, wherein
the first signal is a power line communication signal, wherein in particular modulated user data.is compensated or eliminated.

3. The method according to one of the claims 1 or 2, wherein
the second frequency (f_1') is equal to the first carrier frequency (f_1), wherein frequency generators for generating the first carrier frequency at the first location and the second frequency at the second location are synchronized.

4. The method according to one of the claims 1 or 2, wherein
the second frequency (f_1') is equal to the first carrier frequency (f_1), wherein the phase and the frequency of the frequency generators for generating the first carrier frequency at the first location and the second frequency at the second location are synchronized.

5. The method according to one of the claims 1 or 2, further comprising:
providing a third signal with a third carrier frequency (f_2');
transmitting the third signal from the second location to the first location;
providing a forth signal having a forth frequency (f_2) at the second location;
measuring a second phase difference between the third signal and the forth signal at the second location.

6. The method according to claim 5, wherein the first carrier frequency and the forth frequency at the first location are generated from the same local frequency source having a first base frequency (f_0), and wherein the third carrier frequency and the

second frequency are generated from the same local frequency source having a second base frequency (f_0').

7. The method according to claim 6, wherein the first carrier frequency and/or the forth frequency is a multiple or a fraction of the first base frequency, respectively, and/or the third carrier frequency and/or the second frequency is a multiple or a division of the second base frequency, respectively.

8. The method of one of the claims 1 to 7, wherein the first carrier frequency and/or the third carrier frequency is/are in the range of 10 kHz to 2000kHz, in particular in the range of 20kHz to 1000kHz, in particular in the range of 40kHz to 500kHz.

9. The method according to one of the claims 1 to 8, comprising
calculating the length of the power transmission line based on the measured first and/or second phase difference(s).

10. The method according to claims 1 to 9, wherein the length quantity is the total length or a relative change in length.

11. A system for determining the length of a power transmission line (130) between a first location (110) and a second location (120), wherein a second receiver at the second location is adapted to receive a first signal having a first carrier frequency (f_1) from the first location, wherein the system comprises an frequency generator (122) for creating a second signal having a second frequency (f_1') at the second location; wherein the receiver further comprises a phase detection device (126) adapted for detecting a first phase difference between the second frequency and the first carrier frequency at the second location.

12. The system according to claim 11, wherein the system further comprises a second transmitter at the second location having a frequency generator (122, k_2) for creating a third carrier frequency (f_2') of a third signal, wherein the second transmitter is adapted to send the third signal via the power transmission line to the first location.

13. The system according to claim 12, wherein the second receiver and the second transmitter at the second location are adapted to use a common frequency source (122) for creating the third carrier frequency for the third signal and for creating the second signal, wherein the common frequency source (122) have a second base frequency

(f_0'), wherein in particular the third carrier frequency of the third signal is a multiple or a fraction of the second base frequency, and/or the second frequency is a multiple or a fraction of the second base frequency.

14. The system according to one of the claims 12 or 13, wherein the system wherein the system comprises at the first location a first receiver adapted to receive the third signal from the second location, wherein the system comprises a frequency generator (112, k_2) at the first location for creating a forth signal having a forth frequency (f_2); wherein the system further comprises a phase detection device adapted for detecting a second phase difference between the forth frequency and the third carrier frequency.

15. The system according to claim 14, wherein the system further comprises a first transmitter at the first location having a frequency generator (112, k_1) for creating the first carrier frequency of a first signal, wherein the first receiver and the first transmitter at the first location are adapted to use a common frequency source (112) for creating the first carrier frequency for the first signal and for creating the forth signal, wherein the common frequency source (112) have a first base frequency (f_0), wherein in particular the first carrier frequency of the first signal is a multiple or a fraction of the first base frequency, and/or the forth frequency is a multiple or a fraction of the first base frequency.

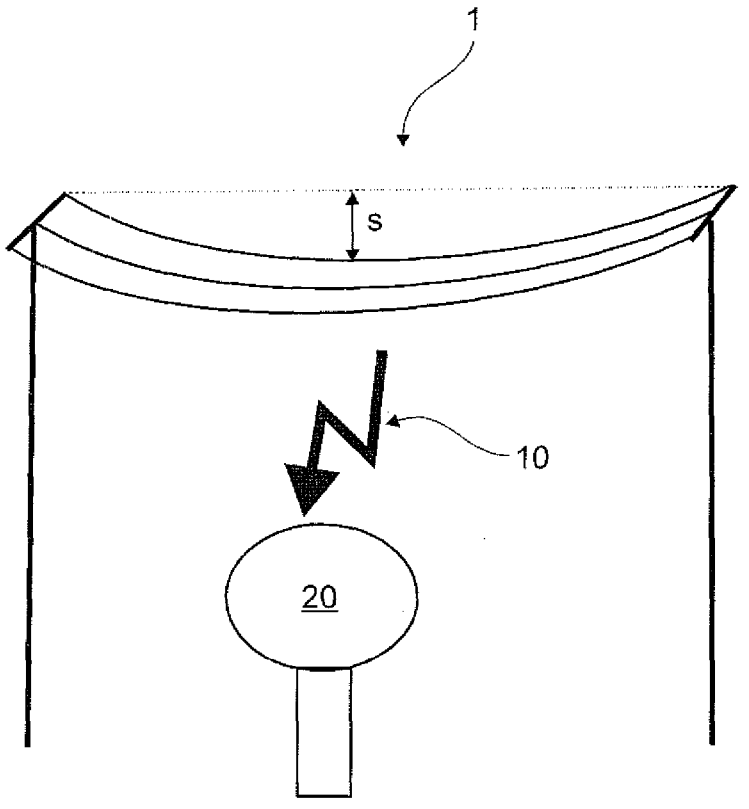


Fig. 1

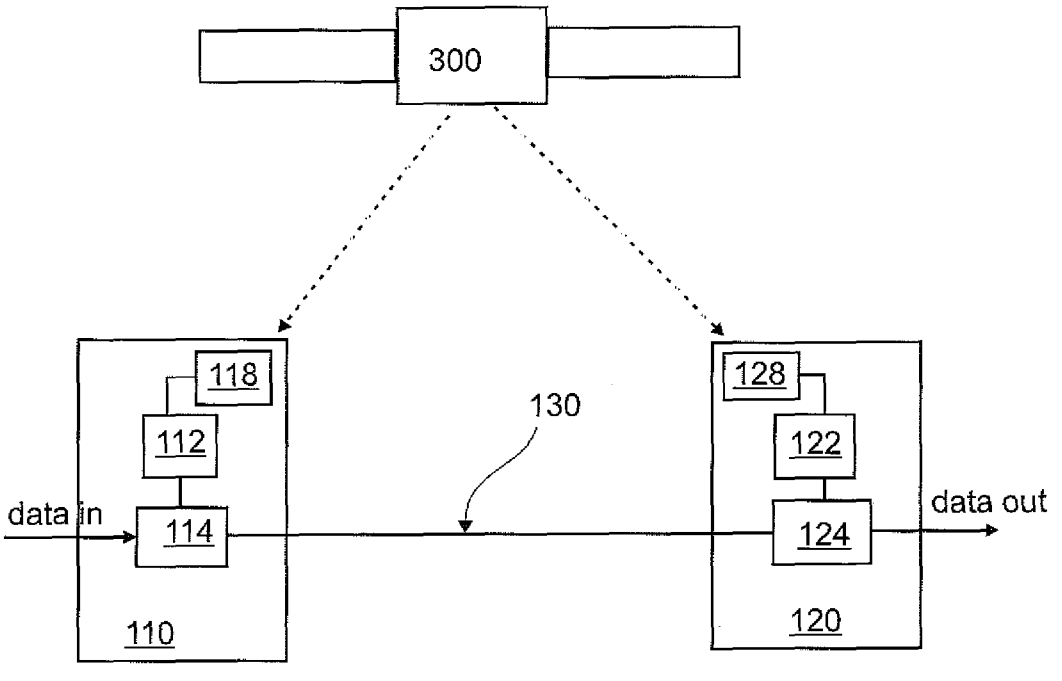


Fig. 2

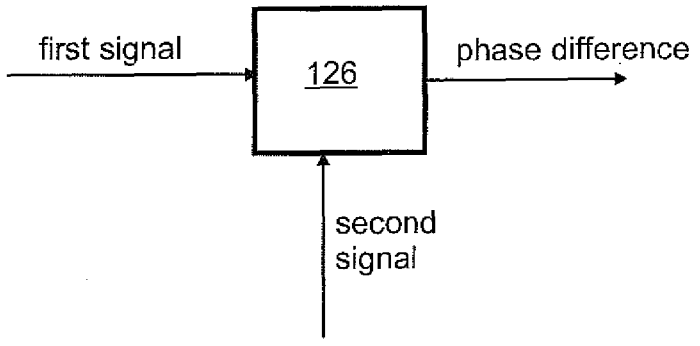

first signal
126
phase difference
second signal

Fig. 3

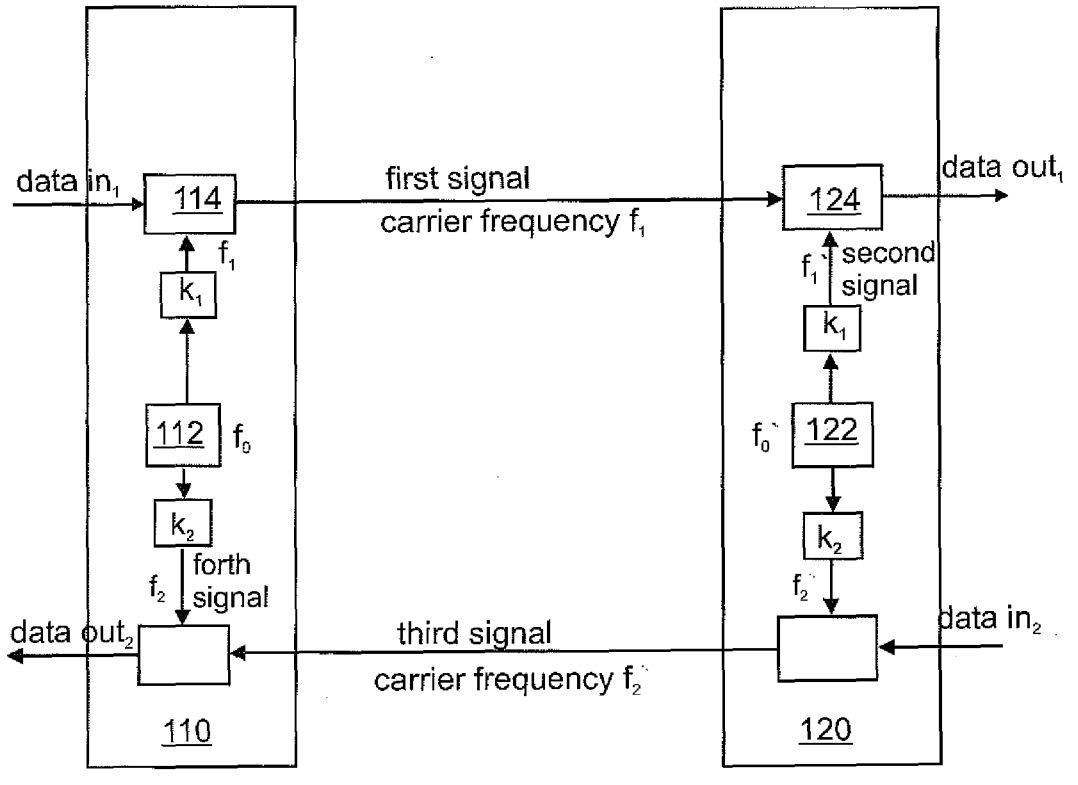

data in1
114
f1
k1
112
f0
k2
f2
forth signal
data out2
110
first signal
carrier frequency f1
third signal
carrier frequency f2
124
data out1
f1
second signal
k1
f0
122
k2
f2
data in2
120

Fig. 4

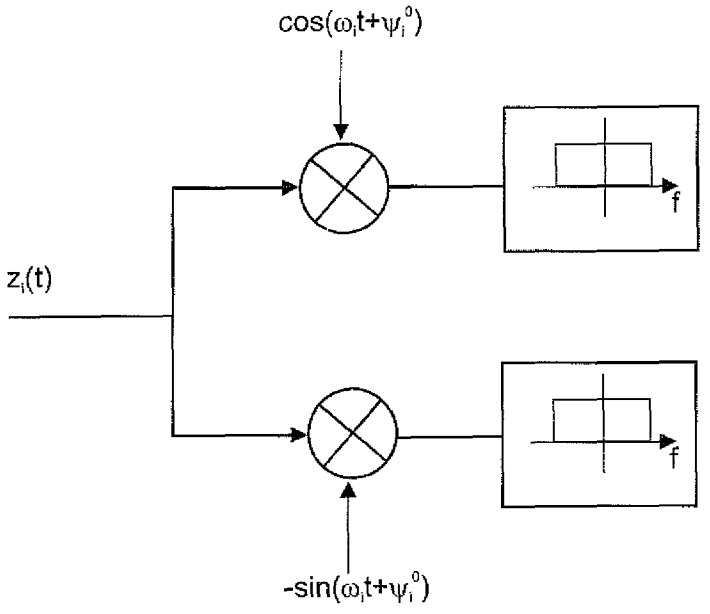


Fig. 5

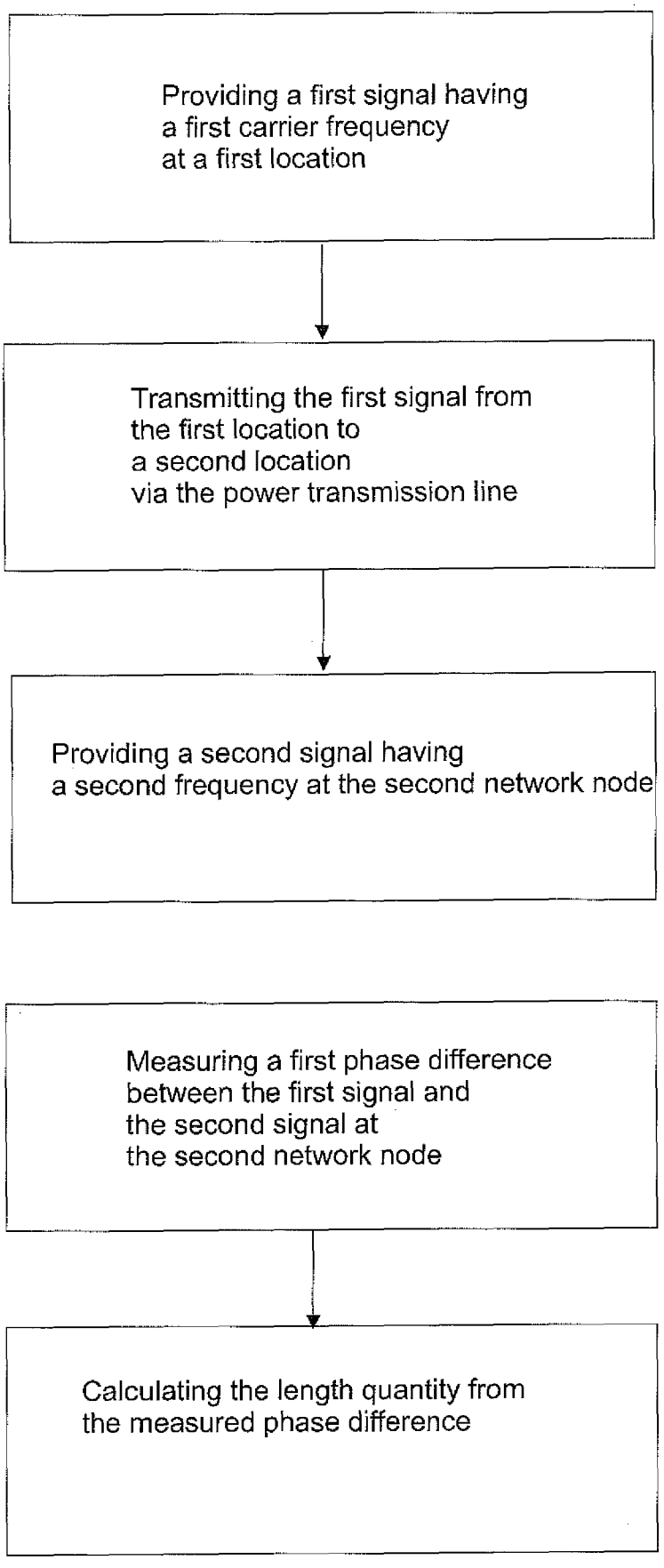

Providing a first signal having a first carrier frequency at a first location
Transmitting the first signal from the first location to a second location via the power transmission line
Providing a second signal having a second frequency at the second network node
Measuring a first phase difference between the first signal and the second signal at the second network node
Calculating the length quantity from the measured phase difference

Fig. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2009/065375

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01B7/02 G01R31/02 H04B3/46

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01B G01R H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 60 138401 A (KOKUSAI DENSHIN DENWA CO LTD) 23 July 1985 (1985-07-23) abstract; figure	1-15
A	US 5 714 876 A (BAKER DANIEL G [US]) 3 February 1998 (1998-02-03) column 1, line 66 - column 3, line 29 abstract; figures 1,2	1-15
A	EP 1 684 184 A (BELKIN CORP [US]) 26 July 2006 (2006-07-26) abstract; figure 1	1-15

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
4 December 2009	15/12/2009

Name and mailing address of the ISA/	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2009/065375

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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