Phase Shift Analysis and Phase Identification for Distribution System with 3-Phase Unbalanced Constant Current Loads

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Abstract – Power grids are large complicated networks in use around. An absolute phase value for a particular unknown-phase line at a local site should be identified for the operation and management of a 3-phase distribution network. The phase shift for a specific point in the line, as compared with a phase reference point at a substation, must be within a range of $\pm 60^o$ for correct identification. However, the phase shift at a particular point can fluctuate depending on the line constants, transformer wiring method, line length, and line amperage, etc. Conducted in this study is a theoretical formulation for the determination of phase at a specific point in the line, Simulink modeling, and analysis for a distribution network. In particular, through evaluating the effects of unbalanced current loads, the limitations of the present phase identification methods are described.

Keywords: Simulink, Phase identification, Unbalanced load, Simulation, Distribution lines

1. Introduction

Utilities use power distribution lines to deliver electricity from generating plants to customers. In a typical power distribution, three-phase power is delivered through multiple substations which step voltage down or up for the consumers. Distribution lines branch into multiple circuits to power local pole- or pad-mounted transformers [1]

Moreover, high-voltage power lines are usually transposed to allow for each phase the same physical conditions over the length of the line. In addition to transposition, lines sometimes go underground. Utilities design distribution lines to balance the loads, i.e., the loads at each phase of three-phase lines are equal. However, over time, as customers are added and removed, the loads on each phase change and become unbalanced.

The need is increasing for determining phases in the 3-phase 4-line type distribution lines with multiple grounds. The determination of an absolute phase is difficult when it is needed. When confusion in lines for phases occurs, disproportionate concentrations of loads can easily occur, and this type of disproportionate concentration of loads can cause phase unbalance that can lead to power loss or power failure and, further, equipment failure due to excessive voltage regulation or reduction of useful life, etc. What this would all mean is that it can result in substantial management difficulties such as economic losses, all because of the reduced quality of voltage supplied to the customer. Thus, engineers must become able to determine out there in the field as to which phase of A, B and C

phases the line conductors belong.

Usually in a substation, the A, B, C phase values for electrical signals are made known, however, as one approaches toward the end of the distribution lines, the effort to distinguish an absolute phase value becomes more difficult. As such, most phase distinguishing methods employ methods that distinguish phases based on comparing the known phase value of a substation with the unknown phase value of a local site [2-5].

Power signals exert influences that cause a phase shift between the two points (reference and local) due to the effects from the line length, distribution line characteristics, load current, etc. Traditionally, a 3-phase line was described as a single phase, lumped model by using equal load and balance line conditions, and the analysis that calculates the phase shifts was performed based on the Kirchhoff's voltage law [6].

In this paper, it will be investigated how the phase shift between the two points would change under unbalanced loads. For the phase analysis, mathematical and Simulink model due to unbalance in the loads are developed.

2. Problem definitions

In the first, some explanations need about the way to identify the absolute phase of a three-phase line at local site, farther way off from a substation. The recent phase identification system, newly developed, consists of both a reference phase unit and a field phase identifier, as shown in Fig. 1 [7]. The reference unit installed in a substation serves the absolute three phase information to the phase identifier. The phase identifier at local site measures a phase value for one conductor line of 3-phase lines and requests to send out the absolute phase information to the

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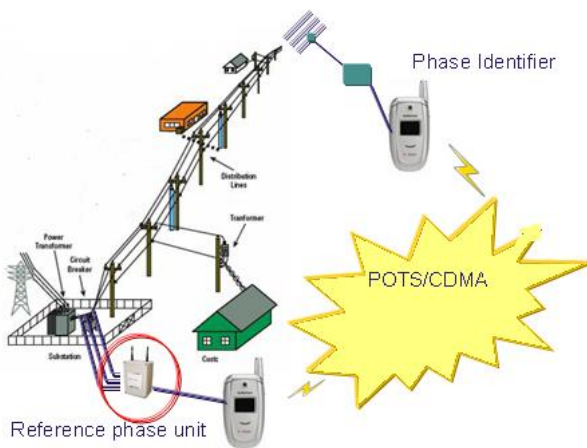
Fig. 1. Phase identification system

reference unit through CDMA or a plain old telephone system. Next, the phase identifier is able to determine the absolute phase for the conductor line based on the phase comparisons between the phase value measured at the phase identifier and the absolute phase values provided from the reference unit. In this phase identification technology, the most important issue is to accomplish the measurement synchronization between phase values used in comparisons.

However, even if phases are measured at a synchronized time, the two locations cannot be of the same phase value. Fig. 2 shows the instance of the phase values measured at two locations, where the 3 phases at the reference unit are 90°, 330°, 210°, respectively, and the phase at the phase identifier is 100° at a time. In this test, the phase identifier tells that the phase of the conductor line tested is judged as the absolute phase "A". If the phase shift between the two points exceeds 60°, then it can be identified as the other phases.

In order to evaluate correctly the absolute phase, the phase shift between the two points should be less than 60°. However, the phase shift depends on line constants, transformer wiring method, line length, and line amperage, etc. The two points in distribution system are separated by
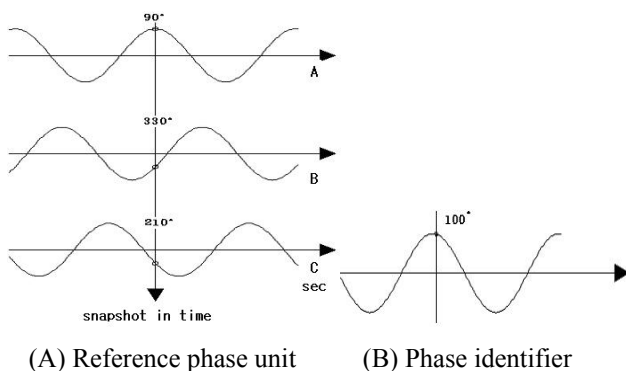

(A) Reference phase unit   (B) Phase identifier

Fig. 2. Example of phases at the two points

a large distance. For a 3-phase balanced distribution line of 50km, the phase shift caused by propagation delay and line constant of impedance, is simulated to be less than 7°. Considering line current with power factor 0.85, the phase shift of about 3° is added to. The total phase shift becomes about 10° [7].

From the field test of phase shift for the 22.9kV distribution line of less than 50km [8, 9], distribution lines with the same phase can be found accurately. Longer than 50km, the accuracy of the phase shift measurement is not guaranteed effectively [10] because it depends on the status or conditions of distribution systems.

In order to apply properly the recent phase identification technology, some analyses about phase shifts should be required for distribution lines. Phase analyses are mostly done based on the single phase line model assuming balanced load conditions [6]. However, real distribution lines are branched and have non-uniformly distributed loads along lines. One of this paper purposes is to investigate about the acceptable conditions for the correct phase identification. Distribution lines under most severe conditions with lumped loads at the end of lines are considered in the analyses of phase shifts. Especially, unbalanced loads will cause additional phase shifts, which may affect the possibility of occurrence of identification errors. The correct phase identification will be possible whenever it is applied under severe conditions considering these kinds of phase shift factors.

This paper proposes a phase shift analysis and method under 3-phase unbalanced constant current loads. In section 3, the phase shift model will be built for 3-phase distribution lines, and in section 4, Simulink model with unbalanced constant current loads will be established. In section 5, phase shifts will be analyzed in accordance with the line length, current load, etc. under balanced and unbalanced loads.

3. Phase Shift Model for 3-Phase Distribution Lines

Distribution network is comprised of 3-phase power sources, circuit breakers, distribution lines, transformers, loads, ground, etc. Distribution network, in particular, can be described with branches going out in radial direction from a substation.

A model that can analyze the phase shift between the two points on a distribution line is designed. Fig. 3 shows a simplified model of distribution lines that have 3-phase, 4-wire multiple conductors.

The distribution lines can be modeled as a distributed parameter circuit through the application of, instead of a static model based on the circuit theory of Kirchhoff, the transmitted wave theory. Power signal that goes through a power line moves in accordance with the electromagnetic
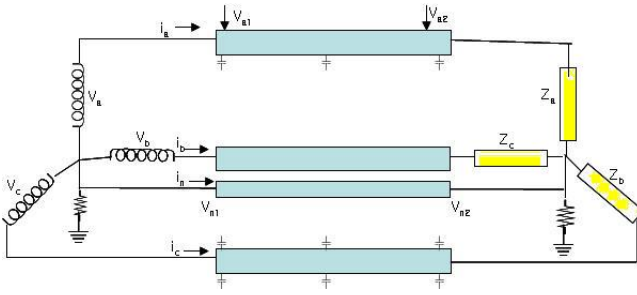
Fig. 3. 3-phase 4-wire grounded wye line segment model

transmission theory. The transmission equation for a power signal is applied to a distribution line as shown in Eq. (1). The magnitude and phase of voltage and current on the distribution line change in accordance with the time and location. In addition, the voltage in the distribution line equations changes depending on the influence of the reflection coefficient that follows the load impedance Z_L at the end of line.

$$\frac{\partial v(z,t)}{\partial t} = -Ri(z,t) - L\frac{\partial i(z,t)}{\partial t}$$
$$\frac{\partial v(z,t)}{\partial t} = -Gv(z,t) - C\frac{\partial v(z,t)}{\partial t} \tag{1}$$

where *R, L, G* and *C* are the per-unit-length resistance (Ω/m), impedance (H/m), conductance (S/m) and parallel capacity (F/m), respectively.

Concerning a circuit with balanced 3-phase supply voltages (v_a, v_b, v_c) and *Y*-load impedance (Z_a, Z_b, Z_c), an assumption that currents (i_a, i_b, i_c) flow on the lines is made. In addition, the power waveform applied to the lines is assumed to be a sinusoidal waveform. The individual phase of a three-phase voltage signal is a 120° apart and it is of a 60Hz frequency. In order to distinguish individual 3 phases, the symbols *A, B* and *C* are used.

Consider a distribution line with a multigrounded neutral as shown in Fig. 3. Applying Kirchhoff's voltage law to the 4-wire grounded neutral line circuit, phase impedance matrix is obtained by Eq. (2).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_n \end{bmatrix}_1 = \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_n \end{bmatrix}_2 + \begin{bmatrix} Z'_{aa} & Z'_{ab} & Z'_{ac} & Z'_{an} \\ Z'_{ba} & Z'_{bb} & Z'_{bc} & Z'_{bn} \\ Z'_{ca} & Z'_{cb} & Z'_{cc} & Z'_{cn} \\ Z'_{na} & Z'_{nb} & Z'_{nc} & Z'_{nn} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_n \end{bmatrix} \tag{2}$$

Eq. (2) can be reduced 3 x 3 phase matrix consisting of the self and mutual equivalent impedances for the three phases. "Kron" reduction method is applied in usual. The voltage equation in matrix form for the line is given by Eq. (3) [6]:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}_1 = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}_2 + \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{3}$$

Many times the analysis of the line can be formulated with sequence impedance components such as the positive, negative, and zero sequence impedances for the line. The definition for line-to-ground phase voltages as a function of the line-to-ground sequence voltages is given by Eq. (4):

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \tag{4}$$

where a $=1.0 \angle 120^0$

Eq. (3) can be transformed to the sequence domain by multiplying both sides by Eq. (5)

$$\begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}^{-1} \tag{5}$$

and also substituting in the definition of the phase currents. Finally, Eq. (6) for converting line-to-ground phase voltages to sequence voltages is obtained by:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}_1 = \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}_2 + \begin{bmatrix} Z_{00} & Z_{01} & Z_{02} \\ Z_{10} & Z_{11} & Z_{12} \\ Z_{20} & Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \tag{6}$$

where the diagonal terms of the matrix are the sequence impedances of the line such that:

Z_{00} = zero sequence impedance
Z_{11} = positive sequence impedance
Z_{22} = negative sequence impedance

The off-diagonal terms represent the mutual coupling between sequences. In the idealized state, these off-diagonal terms would be zero as in Eq. (7). In order for this happens, it must be assumed that the line has been transposed. For high voltage distribution lines, this will generally be the case. When the lines are transposed, the mutual coupling between phases (off-diagonal terms) is equal and consequently the off-diagonal terms of the sequence impedance matrix become zero [6].

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}_1 = \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}_2 + \begin{bmatrix} Z_{00} & & \\ & Z_{11} & \\ & & Z_{22} \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \tag{7}$$

In cases where the electric energy flows out in a radiation pattern from the substation side along the distribution line to the customer side, a phase shift between the two points can occur depending on the flow of current.

In order to represent different two points on the distribution line, the subscript symbols 1 and 2 are used. The voltages at point 1 of the distribution line are given by Eq. (8) in the time domain.

$$
\begin{aligned}
v_{a1} &= v_{a1m}\sin(wt - \theta_{a1}) \\
v_{b1} &= v_{b1m}\sin(wt - 120^\circ - \theta_{c1}) \\
v_{c1} &= v_{c1m}\sin(wt + 120^\circ - \theta_{c1})
\end{aligned}
\tag{8}
$$

The voltages at another point 2 are given by Eq. (9).

$$
\begin{aligned}
v_{a2} &= v_{a2m}\sin(wt - \theta_{a2}) \\
v_{b2} &= v_{b2m}\sin(wt - 120^\circ - \theta_{b2}) \\
v_{c2} &= v_{c2m}\sin(wt + 120^\circ - \theta_{c2})
\end{aligned}
\tag{9}
$$

To determine the phases for the point 1 and 2, the voltage waveform of the time axis needs to be converted into signals of the frequency domain. Under an assumption that only 60 Hz frequency components are included, voltage signals can be expressed in amplitude and phase components. Phasor is expressed as a vector that has a magnitude and a phase. Using the Euler's formula, voltage signal waveforms are converted to phasors as shown in Eq. (10).

$$
\begin{aligned}
v_{a1} &= v_{a1m}\sin(wt - \theta_{a1}) \\
&= v_{a1m}Re\left\{e^{j(wt - \theta_{a1})}\right\} \\
&= v_{a1m}Re\left\{e^{jwt}e^{-j\theta_{a1}}\right\} \\
v_{a2} &= v_{a2m}\sin(wt - \theta_{a2}) \\
&= v_{a2m}Re\left\{e^{j(wt - \theta_{a2})}\right\} \\
&= v_{a2m}Re\left\{e^{jwt}e^{-j\theta_{a2}}\right\}
\end{aligned}
\tag{10}
$$

The phase values of individual points continue to fluctuate over time. Thus, in order to determine the phase shift between the two points, synchronization in time
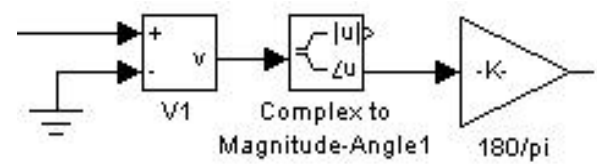

Fig. 4. Phase calculation model by Simulink

should be made. When the phases of the points 1 and 2 are obtained under synchronization conditions and their phase shift is calculated, it becomes Eq. (11).

$$
\theta = \theta_{a1} - \theta_{a2}
\tag{11}
$$

Digital computers can be used to accommodate various methods in calculating phases at the two points. Flow calculations, fault current calculations, EMTP analysis, etc. can be considered. In this paper MATLAB Simulink software is used [11]. Compared to other software programs, Simulink software offers the advantage of not requiring a compilation process for the source code.

The Simulink model to calculate the phase value at a certain point is shown in Fig. 4. Voltage signal that has gone through a measurement block (V1) is generated as complex numbers, and it is converted again into phasor for magnitude and phase [12]. Afterwards, the radian phase output is converted to a 360° format.

4. Simulink Modeling for 3-phase Distribution System

Phase shift between the two points depends on a lot of parameters such as line configuration, power apparatus, system operation conditions, etc. More details for the Simulink model such as power sources, lines, unbalanced loads, transformers, grounding resister and phase measurement system for phase simulation are explained below.

In the first, the input source is expressed in terms of power with an internal resistance and inductance as shown in Fig. 5. Power capacity that can sufficiently provide power used in the load is arranged. Power is wired as a 3-
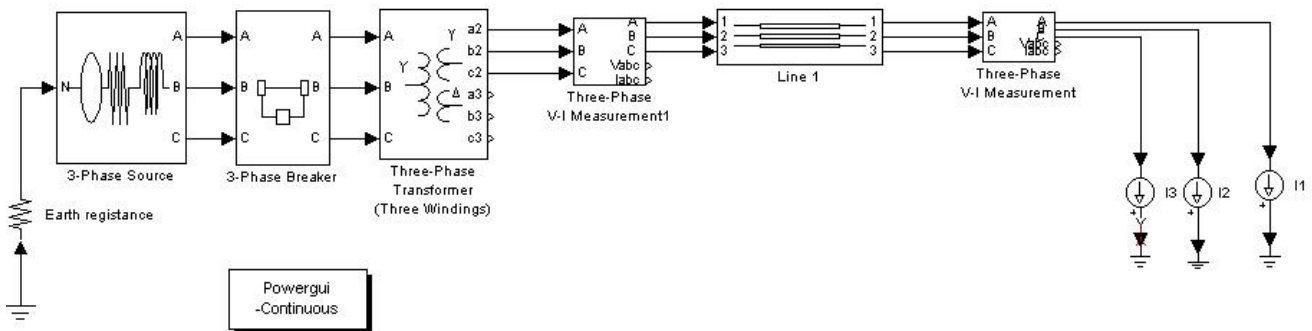

Fig. 5. Sample of Simulink distribution system model

phase and a supply voltage is sinusoidal. A neutral point is connected to a grounding resistance. The power output is provided to distribution lines through a transformer wired as a wye(*Y*) or delta (*Δ*).

Fig. 6 shows the Simulink output for *A*, *B* and *C* phase voltage waveforms provided to the distribution system. Phase voltages of 13.8 kV are shown.

For the Simulink model of loads, various forms such as a constant impedance, a constant current load, or a constant capacity, etc. can be used. A constant impedance model is that linear load that has a series resistance, inductance and capacitance value in a prescribed frequency. The effective and reactive power dissipated in the load has the characteristics of being proportional to square of the applied voltage. Simulink model of a constant current load is useful for allotting any current by lines and is used in this paper.

In modeling a transformer, the voltage ratio of primary and secondary voltages and wiring method can set. Transformer specifications used in simulation comprise 3-phase transformer with 3 single-phase transformers, and *Y* and *Delta* wiring is possible in the primary and secondary. In this paper, the transformer model that takes into consideration internal loss that is dependent on internal resistance and inductance is used. Recent transformers have very low resistance and voltage drop, therefore, usually the voltage phase shift across a transformer is calculated as less than ±5°.
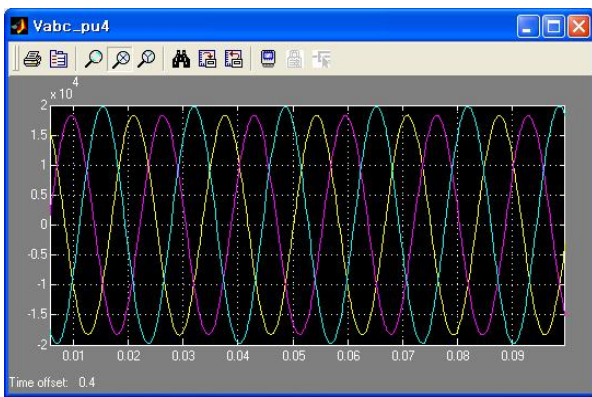

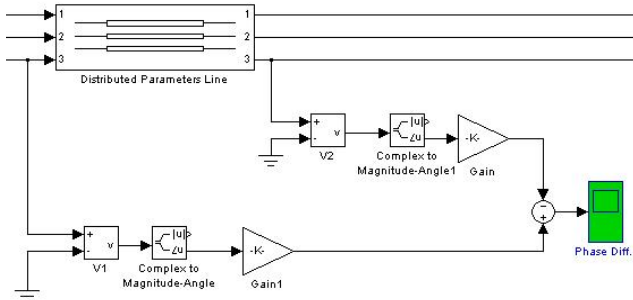**Fig. 6.** 3 Phase voltage waveform by Simulink

Fig. 7. Phase shift measurement system

Ground is modeled as having only a resistive component. Ground resistance is assumed to be 5Ω, which is a standard value for a 22.9 kV multiple-grounding system [13].

For the distribution lines, parameters are represented as symmetric (zero, positive, negative) components [12, 14, 15].

Fig. 7 shows the measurement system that calculates the phase shift between the two points on the same line.

5. Simulation Results and Analysis

Using the sample distribution model shown in Fig. 5, the phase shift is analyzed. There are several factors such as propagation delay, the length of line, the distributed parameters, and load current, etc to affect the phase shift.

With the assumption that electrical signals move at the speed of light is made, propagation time would be required for electrical signals to move a certain distance. This implies that the phases at the two points are not identical at the same time. A line length of 14 km corresponds to 1° of phase shift. The phase shift between the two points increases proportionally with the line distance. Table 1 shows the increases in phase shifts that correspond to line distances of 10 km, 50 km and 100 km. When the line distance is 100 km, the phase shift due to propagation delay is 7.140°.

Next, the phase shift resulting from voltage drop depending on the line parameters is described. Voltage and phase shifts occur at the same time. The component values used in the simulation of Eq. (6) are as follows [16].

Zero Phase R_o = 0.23 Ω/km, L_o = 5.478 mH/km,
C_o = 0.008 µF/km
Positive Phase R_1 = 0.17 Ω/km, L_1 = 1.21 mH/km,
C_1 = 0.00969 µF/km

The shifts are caused by the distributed parameters and the line distance as shown in Fig. 8. The balanced load of 200A with a power factor of 1.0 is used. As the distribution line increases, it increases proportionally.

Table 1. Phase shift by signal propagation

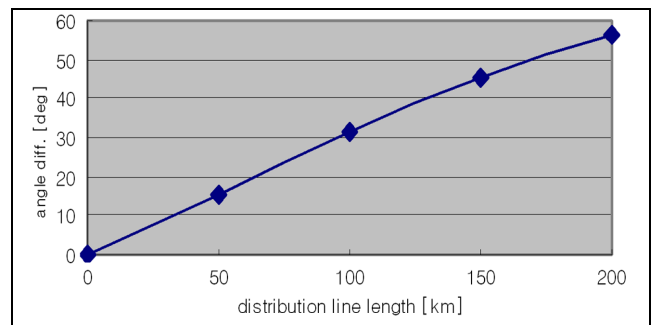| Line distance	10km	50km	100km	200km
Phase difference(deg)	0.710	3.570	7.140	14.280

Fig. 8. Phase shift vs line length (with current load of 200A)
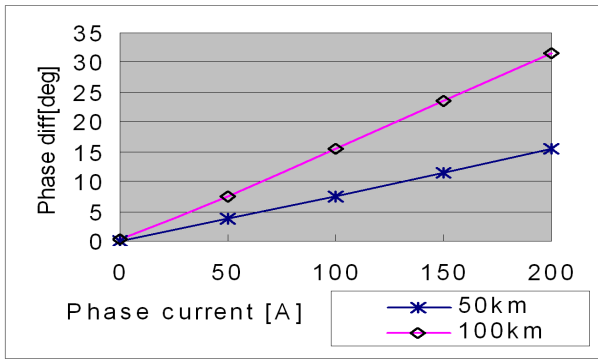
Fig. 9. Phase shift vs current load and line length

Fig. 9 shows the analysis results of phase shift depending on current load (I). For each of line distances of 50km and 100km, phase shift according to the current load is calculated. For the analysis, the constant current load with a factor of 1.0 is used. Under the same current condition of 100A, phase shift of 7.5° is observed for the line length of 50km and 15.6° is observed for 100km.

For the analysis of the phase shift that depends on the internal impedance of transformer, a transformer with a resistance of 0.015 p.u and an internal inductance of 0.035 p.u is used. A primary voltage of 345kV and secondary voltage of 22.9kV in *Y-Y* wiring is used. It is assumed that 200A 3-phase balanced current loads flow for a 10MVA transformer capacity. The phase shift of 0.33° is observed for the voltage across the primary and secondary ends of the transformer.

The total phase shifts between the two points in accordance with all the factors mentioned are: in the case of 100A current load and 50km distribution line, 3.57° + 7.5° = 11.1°; and in the case of 200A current load and 100km line, 7.14° + 32° = 39°.

Described next are the effects on the phase shift by unbalance current loads. Even if distribution lines and power supply voltages maintain to be balanced, unbalances for phase shifts are induced among phases, because of the unbalance of the current loads. Referring to the calculation method of the voltage unbalance factor index used by IEEE [17], the definition for the current unbalance factor (CUF) is induced similarly as in Eqs. (12) or (13).

If real-time current is used, then it is defined as follows:

$$\%CUF = \frac{max.current.deviation.from.the.avg}{avg.phase.current} \times 100$$
$$= \frac{(max(ia+ib+ic)-(ia+ib+ic)/3)}{(ia+ib+ic)/3} \times 100 \quad (12)$$

or by using the concept of phasors

$$\%CUF = \frac{max.current.deviation.from.the.avg}{avg.phase.current} \times 100$$
$$= \frac{(max(Ia+Ib+Ic)-(Ia+Ib+Ic)/3)}{(Ia+Ib+Ic)/3} \times 100 \quad (13)$$

For example, when a 3-phase unbalanced current load with power factor of 1.0 is Ia = 100A, Ib = 200A, Ic = 300A, the current unbalance factor would become 50%.

Fig. 10 shows the current values of each phase in accordance with the current unbalance factors (CUF). The current of B-phase is to be maintained constant, and when A-phase current is increased, current in C-phase is reduced the same amount, whereby the total amount of current is made to remain constant.

For a line of 100km, individual phases near the source are shown in accordance with the current unbalance factors as in Fig. 11. Changes in the individual phases of voltage signals are very small, and this implies that the effects exerted by unbalanced current loads are quite small. However, for the load side, the individual phases for voltage signals change much than the source side as shown in Fig. 12. Changes in the individual phases for voltage signals increase proportionally with the current load unbalance factors.

And the phase shifts between the two points are shown as in Fig. 13. On the A-phase line as the current unbalance factors decrease, the shifts decrease, and on the B-phase or C-phase lines the phase shifts increasing up to 56° or 49°. Especially, when the unbalance factor is 30% or more, the C-phase shift of increases up to 43.7° in comparison with
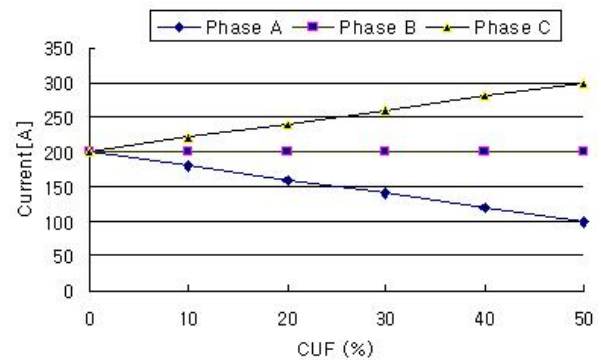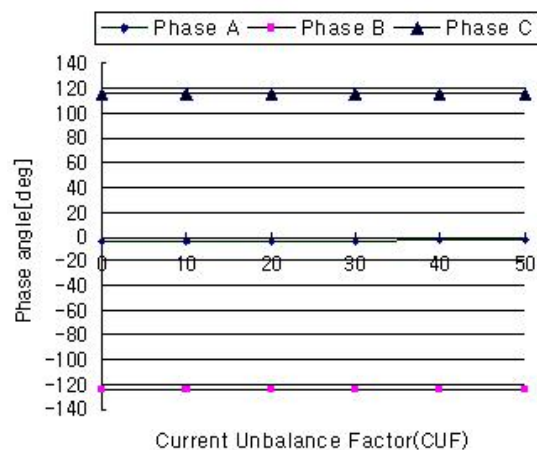

Fig. 10. Current loads vs CUF

Fig. 11. Phase shifts vs CUF (source side)
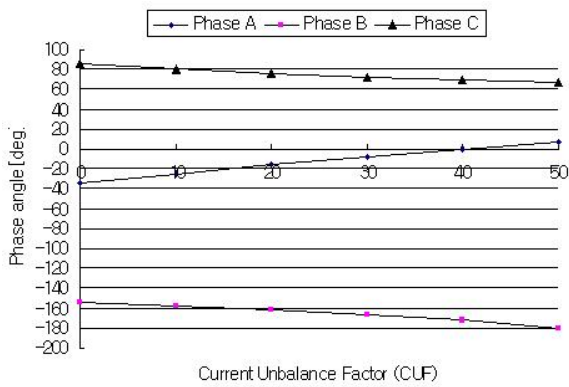
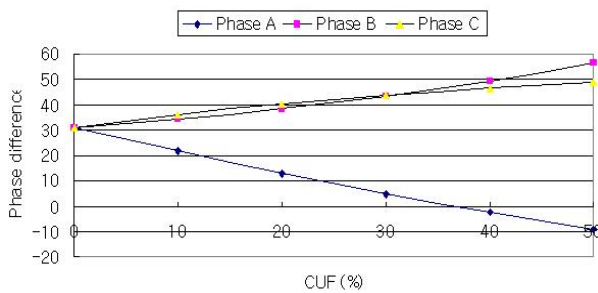**Fig. 12.** Phase shifts vs CUF (load side)

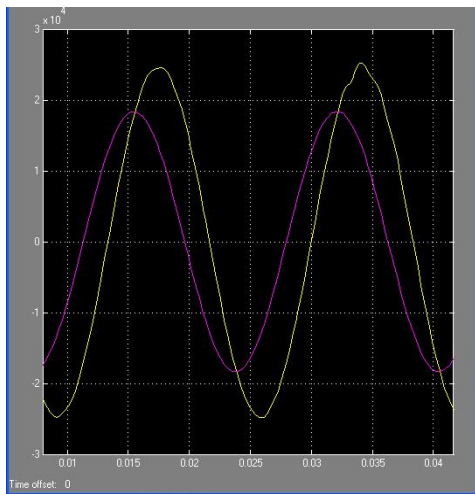**Fig. 13.** Phase shifts between two end points

Fig. 14. Voltage waveform of phase C at both ends (100 km, 30% of CUF)

the phase shift of 32° under the balance condition.

In addition, the voltage waveform of the two ends on the C-phase line is shown in Fig. 14. The increased phase shifts due to unbalanced current loads cause to increase the possibility of error in identifying phases at field.

6. Conclusion

In order to identify the absolute phase at a local site, the recently developed method that compares the phases at the reference point and the local site is utilized. On 3-phase lines the comparative phase shift should be within 60°, in order that the determination of the absolute phases can be achieved without error.

For the proper application of the phase identification technology, phase shifts are analyzed under the severe conditions with lumped loads at the end of lines. Simulink models and theoretical methods are presented for the analyses of the phase shifts between the two points.

Attributable to effects such as propagation delays, delays due to the line distributed parameters, delays due to the magnitude of load current, etc., a phase difference of 11° ~ 39° was approximately calculated for balanced currents. Here, additional phase shift occurred due to the unbalanced current loads. Under CUF of 30%, phase shifts between the two points away 100km was simulated to be increasing to the phase shift of 56.6°, rather than 30.8° under balanced conditions. Considering the propagation shift of 7.14, the total phase shift becomes 63.74° (56.6° + 7.14°), which fall outside the certain boundary of 60°. When phase variations due to transformer winding, power factor, more increased current, imperfect transpose, etc, is considered, it get worse.

The study results suggest that, in distribution systems, reference units should be installed and operated in appropriate scales so that the phase shift between a reference point and local site would fall within a certain range.

For extreme load unbalances such as changes in transormer wiring fluctuations, changes in the line distributed parameters or failures occurrence, the possibility of errors in phase identification will increase.

For the further research topics, more complex unbalanced system is considered.

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