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Application of All-pass Filters for Protective Relaying of Power Systems

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ABSTRACT: This paper presents a relatively inexpensive method of determining the positive, negative and zero sequence components of a three-phase circuit. A one-pole all-pass filter circuit is used to obtain a phase shift of 120° by adjusting the RC time constant of the filter. By cascading two stages of the filter network, a phase shift of 240° can be obtained and summer circuits are used to obtain the sequence voltages, which formed the basis for relay protection of power systems. The method proves very convenient and inexpensive compared to most other protective approaches for three-phase machines

KEYWORDS: All-pass Filter, Protective Relaying, Symmetrical Components, Power Protection Systems, Fault Detection

I. INTRODUCTION

Most faults in power systems are unsymmetrical with the consequence of finite fault impedance. And symmetrical components have over the years presented itself as one of the most convenient method of obtaining information regarding unbalanced three-phase circuits.The sequence components of currents and voltages are used for several purposes. Voltage regulators often use the positive sequence component of the voltage, the negative sequence component of current can be used in protective relays of three-phase machines and power systems, while the zero sequence component can be used for the detection of earth faults [1].

Digital filtering methods using passive, active and microprocessors have been commonly used for extracting of positive, negative and zero sequence components [2]. The digital filter approach has two major drawbacks for real time application. These drawbacks are:

i) They require analogue-to-digital and digital-to-analogue converters, which introduce a time delay in realizing the sequence components. This delay affects the effective operation of the protective devices that may be used for machines and power systems.

ii) The circuit is usually complex and involves many components, which makes the approach rather expensive.

A number of techniques have been proposed to estimate the symmetrical components of a three-phase voltage and current. In particular, techniques such as the Kalman filter [1], [2], the fast Fourier transform (FFT) [4]; adaptive line combiner [5], stochastic estimation theory [6], and the concept of state observer [7],[8] have been employed to estimate the instantaneous symmetrical components. Furthermore, phase-locked loop (PLL) based algorithms [9]–[12] have been introduced to extract the symmetrical components in order to handle the unbalance phenomenon.

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This paper seeks to overcome these disadvantages by using a relatively cheaper circuit devoid of the complexity in microprocessor based protective circuits. The paper made use of the basic principle of an all-pass active filter to obtain a phase shift without changing the magnitude of the components due to changes in frequency.

II. SYMMETRICAL COMPONENTS

The method of symmetrical components can be applied to any poly-phase systems containing any number of phases, but the three-phase is the one commonly used. In the subsequent analysis, it will be applied to a set of unbalanced three-phase currents or voltages. The symmetrical components of a line current may be said to be fictitious, since metering the line current directly gives the current, which may be unbalanced i.e. unequal in magnitude to the other two line currents and or not at 120° with respect to each of them [3].

The theory of symmetrical components states that, by the superposition principle in a linear network, any set of symmetrical three-phase phasors of sequence abc, e.g. currents I_a, I_b and $I_c$can be replaced by the sum of three sets of current:

$$I_a = I_{a1} + I_{a2} + I_{a0}$$

$$I_b = I_{b1} + I_{b2} + I_{b0} \qquad (1)$$

$$I_c = I_{c1} + I_{c2} + I_{c0}$$

Here,I_a, I_b, I_c are the phase currents where $I_{a1}, I_{a2}, I_{a0}, I_{b1,}, \ldots, I_{c0}$ are sequence components of current.

Using the equation (1), the relationship between the phase quantities and sequence components can be defined as

$$\begin{bmatrix} G_a \\ G_b \\ G_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & h^2 & h \\ 1 & h & h^2 \end{bmatrix} \begin{bmatrix} G_0 \\ G_1 \\ G_2 \end{bmatrix} \qquad (2)$$

$$\begin{bmatrix} G_0 \\ G_1 \\ G_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & h & h^2 \\ 1 & h^2 & h \end{bmatrix} \begin{bmatrix} G_a \\ G_b \\ G_c \end{bmatrix} \qquad (3)$$

Equation (2) and (3) are the mathematical expressions of the phase rotating vector, h of the components. The vector h is defined as

$$h = 1\angle 120^0 = exp\left(\frac{-j4\pi}{3}\right) = exp\left(\frac{j2\pi}{3}\right)$$

$$h^2 = 1\angle 240^0 = exp\left(\frac{j4\pi}{3}\right) = exp\left(\frac{-j2\pi}{3}\right)$$

Thus, h is the operator that multiplies the phasor to rotate it 120^0 in the positive (anticlockwise) direction, without any change in magnitude. Also h^2 implies the rotation of the phasor 240^0 again in the positive direction.

In this paper, advantage is taken of the ability of operational Amplifier (Op-Amp) circuit to do summation, shift phase and multiplication by a constant to realize the sequence components from the phase values.

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III. USE OF ALL-PASS FILTER FOR PHASE SHIFTING

An all-pass filter network has a magnitude H(s) = 1 at all frequencies but the overall filter response normally also specifies the phase characteristic of the filter [4]. Our interest is to control phase response by dividing the all-pass section into two stages, since the phase response of each stage varies with frequency.

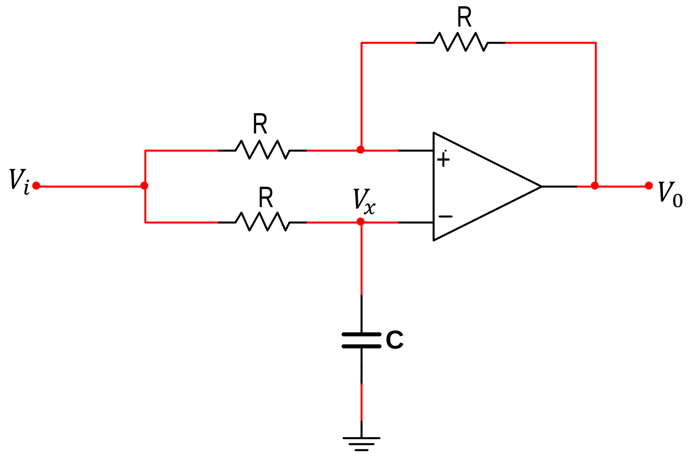

Fig. 1 A one-pole All-pass Active Filter

Using Fig. 1,

$$V_1 - 2V_x = -V_0 \tag{4}$$

and

$$V_x = \frac{V_1}{\omega CR + 1} \tag{5}$$

The transfer function of the one-pole all-pass active filter can be developed from equations (4) and (5) and given as

$$H(w) = \frac{V_0}{V_1} = \frac{1-wRC}{1+wRC}; \; H(j\omega) = \frac{1-j\omega RC}{1+j\omega RC} \tag{6}$$

The magnitude of the pole and zero (frequencies) in equation 6.0 are equal. This gives the circuit its characteristic all-pass filtering ability. Therefore, the circuit in Fig. 1 can be used to realize a specified phase shift at one frequency without changing the magnitude of H(w) even if the frequency changes.

Let β be the phase of the signal V_1 fed into input of the circuit and $\Delta\beta$ be the phase shift of the signal V_0 at the output such that

$$\Delta\beta = \beta - \phi \tag{7}$$

and

$$\beta + \phi = 180 \tag{8}$$

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Substituting equation 7.0 into equation 8.0

$$\beta = \frac{\Delta\beta + 180}{2} \quad (9)$$

Using equation 6.0 and 7.0, the phase shift of the signal seen at the output of the filter will be

$$\Delta\beta = \tan^{-1}(-\omega RC) - \tan^{-1}(\omega RC) \quad (10)$$

Substituting equation 10.0 in equation 9.0, the value of the phase of the input V_1 is

$$\beta = \tan^{-1}(\omega RC) = -\tan^{-1}\left(\frac{\omega}{\omega_0}\right) \quad (11)$$

The relation shows that by adjusting the RC time constant of the circuit; a phase shift between 0^0 and 180^0 can be added over an approximate frequency range of

$\frac{1}{10RC} \langle \omega \langle \frac{10}{RC}$ to the filter characteristic.

For a signal of phase shift of $120^0 (\Delta\beta = 150^0)$ and supply frequency of 50 Hz, the values of the components can be computed from

$$RC = 0.0018387 \quad (12)$$

For C equal to 0.05 μF, the value of R is 38 kΩ.

The single stage circuit in Fig 1.0 is cascaded as shown in Fig 2.0 to give a phase shift of 240^0.

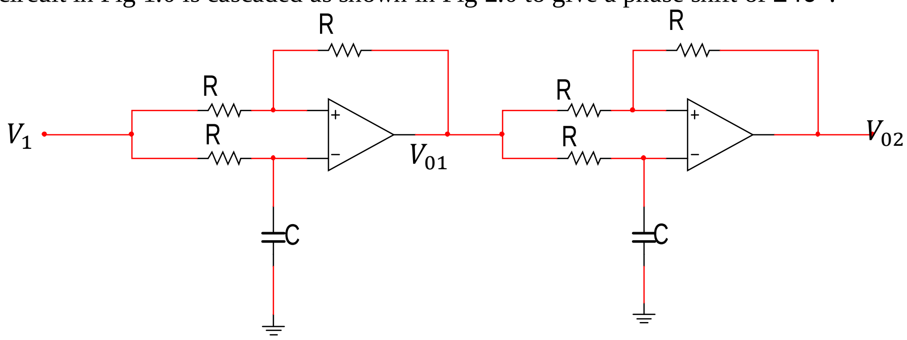

Fig. 2 Cascaded All-pass Filter Circuit to rotate the Phase Voltage

From equation (6)

$$V_{01} = V_1\left[\frac{1-\omega RC}{1+\omega RC}\right] \quad (13)$$

and

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$$V_{02} = V_1 \left[\frac{1-\omega RC}{1+\omega RC} \right]^2 \quad (14)$$

Equations (13) and (14) can be generalized as

$$V_{01} = hV_1 \quad (15)$$

$$V_{02} = h^2 V_1 \quad (16)$$

where $h = \frac{1-\omega RC}{1+\omega RC}$, is the phase shift operator

IV. SUMMATION OF THE PHASE VOLTAGES

In order to sum the phase voltages and relate them to equation 2.0, the adder network in Fig.3is used.

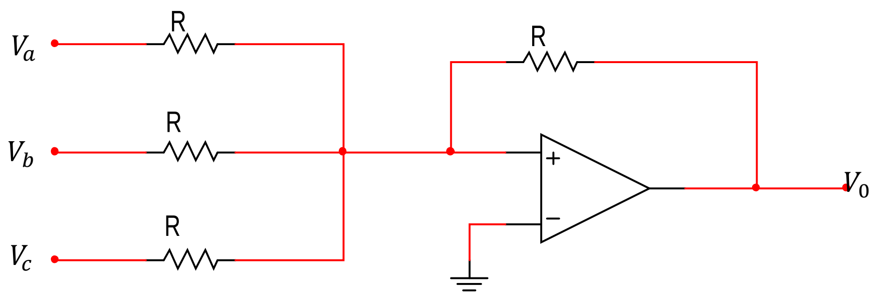

Fig.3 Adder Network to achieve the Symmetrical Components

The output voltage from the adder circuit is

$$V_0 = \frac{V_a + V_b + V_c}{3} \quad (17)$$

$$V_1 = \frac{V_a + hV_b + h^2 V_c}{3} \quad (18)$$

$$V_2 = \frac{V_a + h^2 V_b + hV_c}{3} \quad (19)$$

The matrix of the symmetrical components is

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$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & h & h^2 \\ 1 & h^2 & h \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (20)$$

Fig.4 is the complete circuit diagram that can be used to determine negative, positive and zero sequence components.

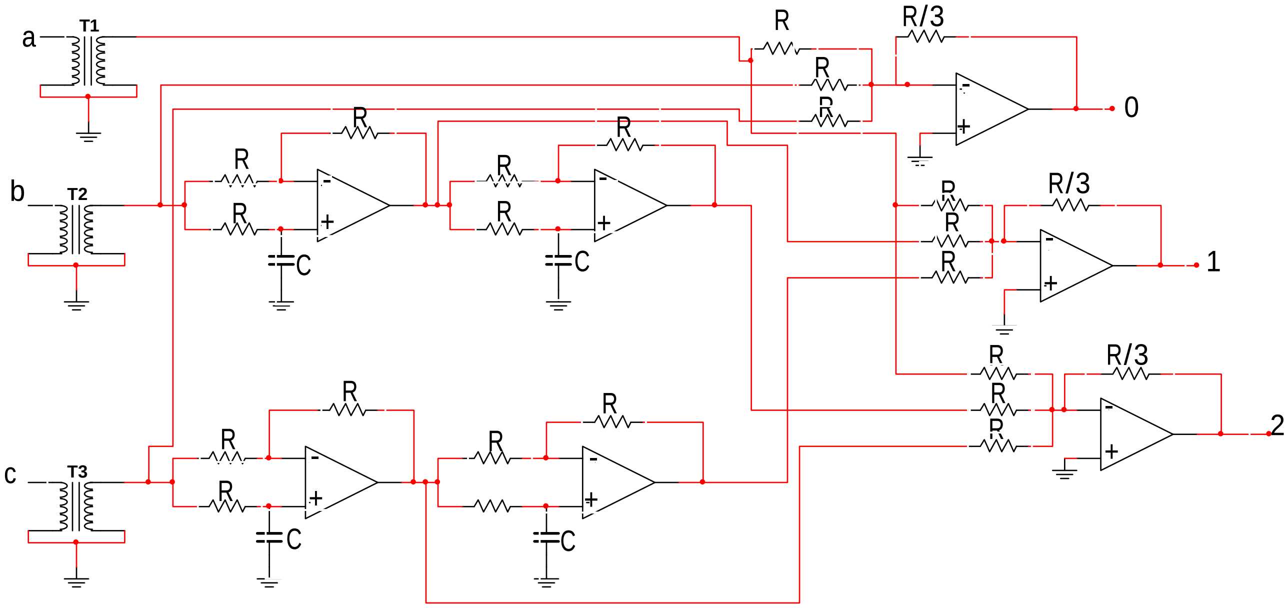

Fig. 4 Complete Circuit Diagram of the Symmetrical Component Extraction Network

V. RESULTS

A current transformer is used to supply 12 volts (AC) to each of the sub-circuits. The proportional relationship of the voltages to the phase currents in the current transformer is used as the basis for this application. The four common faults if simulated will give the filter response readings in Table 1. The faults are the common unsymmetrical faults through impedances and open conductors.

Table 1: Filter Response to Unsymmetrical Fault

S/N	Types of Faults	Readings of the Sequence Voltages		
		V_0	V_1	V_2
1	Double line-to-ground	V	V	V
2	Balanced three phase fault	0.0	0.0	0.0
3	Single line-to-ground	V_2	$-2V_0$	V_0
4	Line-to-line fault	0.0	V_2	V_1

The zero sequence voltage can be used to polarize directional earth-fault relays, while a positive sequence voltage shown in table 1 can be used to operate the automatic voltage regulator controlling the excitation of an alternator.

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VI. CONCLUSION

The circuit designed is able to determine the negative, positive and zero sequence of three phase voltages and currents. The outputs of the three operational amplifiers used as summers (adders) can be configured for relay control.Though the circuit is quite cheap, it proved to be a reliable source of phase shifting since the filter responded to all types of asymmetrical faults. For real application, the value of the resistor R or capacitor need to be trimmed to obtain a phase shift of 120^0and240^0.

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