the curve, the value of $X_{2(LL)}$ corresponding to negative-sequence current equal to rated current is the rated-current value.

b) The defined negative-sequence reactance for sinusoidal negative-sequence current is obtained from the value obtained during a line-to-line short circuit using Equation (102). To make this correction, the direct-axis subtransient reactance, X''_d, in per unit, should be known for approximately the same conditions. To correct the per unit rated-current value of $X_{2(LL)}$, the rated current value of X''_d may be used. To correct the rated-voltage value of $X_{2(LL)}$, the value of X''_d determined at rated voltage by a sudden short circuit should be used (see 11.5.3.1.4). The results give the per unit rated-current and rated-voltage values of the negative-sequence reactance, respectively.

$$X_2 = \frac{\left(X_{2(LL)}\right)^2 + \left(X''_d\right)^2}{2X''_d} \tag{102}$$

where

X''_d is the direct-axis subtransient reactance, in per unit

c) The presence of harmonics may influence the results from this test. In tests of machines without connected amortisseur windings using Method 3, it is advisable to take waveforms in addition to meter readings and use the waveforms to obtain the rms values of the fundamental and third-harmonic components of voltage and current. If both the voltage and current contain significant third-harmonic components, the per unit value of the wattmeter reading should be corrected in accordance with Equation (103).

$$P'_{v-a} = P_{v-a} - \sqrt{3}E_3 I_3 \tag{103}$$

where

P'_{v-a} is the adjusted value of the measured power, compensated for third-harmonics contents
P_{v-a} is the measured power, in per unit of *base single-phase power*
E_3 is the rms third-harmonic voltage, in per unit of base line-to-line voltage (see 9.2.3)
I_3 is the rms third-harmonic current, in per unit of base line current (see 9.2.3)

10.5.1.6 Method 4. Applied single-phase line-to-line sudden short circuit

See 11.5.3.5.3 for Method 6 of determining X_2 from a sudden short circuit.

10.5.1.7 Method 5. Applied single-phase voltage

This method is described more fully in Clause 11 since, even though the particular tests are sustained or steady state, they are a complementary procedure to the sudden short-circuit tests for determining the parameters X''_d and X''_q. These tests are detailed in 11.5.3.5.3 (for X''_d) and 11.5.3.5.3 (for X''_q).

A few notes and precautions are given below for general information. If the test is made at rated frequency, the frequency of the rotor current will be one-half that of the negative-sequence current under normal operating conditions. If the effects of rotor-current frequency on negative-sequence reactance are appreciable, this method should not be used.

In terms of the quantities defined in 11.5.3.5.3, negative-sequence reactance can be calculated using Equation (104).

$$X_2 = \frac{K}{2} \tag{104}$$

where

X_2 is the negative-sequence reactance calculated by Method 5, in per unit
K is defined in Equation (144)

The negative-sequence current in each test is the per unit value of the fundamental component of the test current divided by $\sqrt{3}$. However, the level of magnetic saturation is associated with the sum of the negative-sequence and positive-sequence components. The test reactance may be plotted as a function of the sum of the positive-sequence and negative-sequence currents, which may be obtained by multiplying the test current by $2/\sqrt{3}$. The rated-current value of negative-sequence reactance is the value at rated current on the curve.

10.5.2 Determining negative-sequence resistance, R_2

For the definition of *negative-sequence resistance*, see Clause 3.

If negative-sequence resistance varies appreciably with current, the value for rated-current may be determined by plotting the resistance as a function of negative-sequence current and selecting the value corresponding to rated current.

Negative-sequence resistance can be determined by the following methods:

- Method 1. Applied negative-sequence current (see 10.5.2.1)
- Method 2. Single-phase line-to-line sustained short circuit (see 10.5.2.2)

10.5.2.1 Method 1. Applied negative-sequence current

An applied sinusoidal negative-sequence current test is made in accordance with 10.5.1.3. The negative-sequence resistance is obtained by Equation (97). No correction for temperature is included because of the uncertain nature of the correction. The connections, precautions, etc., are identical to Method 1 for determining negative-sequence reactance.

If the test current is not substantially sinusoidal, an appreciable error in the negative-sequence resistance may result.

10.5.2.2 Method 2. Single-phase line-to-line sustained short circuit

A sustained single-phase short-circuit test is made in accordance with 10.5.1.5. From this test, values of impedance, Z_2, and reactance, X_2, are obtained (see 10.5.1.5). From these two values, the negative-sequence resistance is determined using Equation (105).

$$R_2 = \sqrt{(Z_2)^2 - (X_2)^2} \tag{105}$$

where

R_2 is the negative-sequence resistance determined by Method 2, in per unit
Z_2 is the negative-sequence impedance from Equation (100), in per unit
X_2 is the negative-sequence reactance from Equation (101), in per unit

If the rated-current value is determined by plotting resistance from test as a function of negative-sequence current, it should be noted that negative-sequence current for this test equals test current divided by $\sqrt{3}$.

No correction for temperature is included because of the uncertain nature of the correction and the approximate nature of the test value of the resistance.

NOTE—The corrections, precautions, etc., are identical to those associated with Method 3 for determining negative-sequence reactance (see 10.5.1.5).

10.6 Zero-sequence quantities

10.6.1 Determining zero-sequence reactance, X_0

For the definition of *zero-sequence reactance*, see Clause 3. The zero-sequence reactance has significance only for a wye-connected machine with accessible neutral.

10.6.1.1 Values of zero-sequence reactance

For currents equal to or less than rated current, zero-sequence reactance usually varies only slightly with current. However, if the value of zero-sequence reactance varies appreciably with test current, it may be plotted as a function of the zero-sequence current and the value for rated current determined from the curve. No rated-voltage value of zero-sequence reactance is recognized.

Zero-sequence reactance can be determined by the following methods:

- Method 1. Parallel circuit (see 10.6.1.2)
- Method 2. Series circuit (see 10.6.1.3)
- Method 3. Sustained short circuit (see 10.6.1.4)

10.6.1.2 Method 1. Parallel circuit

With the neutral terminals of the windings connected together as for a normal operation, the three line terminals are also connected together so that the three phases are in parallel. A single-phase alternating voltage is applied between the line terminals and the neutral terminals (see Figure 35).

It is preferable that the machine be driven at normal speed, with the field short-circuited and with normal cooling. However, nearly the same values will be obtained with the rotor at standstill, and the test may, therefore, be conducted under this condition providing heating is not excessive. The conditions of the test should be stated.

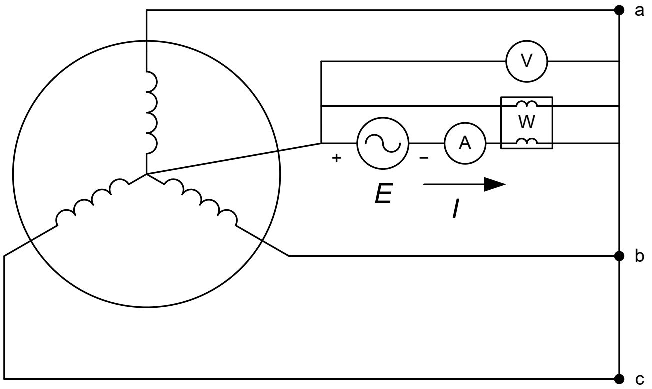

Figure 35—Test setup for Z_0 measurement using Method 1

For several values of applied voltage, producing, if possible, total test current up to three times rated current or higher, readings should be taken of voltage and current. Experience had shown that it is possible to measure a good value of X_0, at least for large salient-pole machines, at standstill with current as small as 0.002 p.u. rated current (Karmaker et al. [B30]).

It is highly recommended to use the short-circuit bar, generally supplied by the alternator manufacturer, instead of cables to connect together the three line terminals. Therefore, the best time to conduct this test is right after the short-circuit saturation curve test (see 5.1.3).

If the zero-sequence resistance is to be determined or if a resistance correction is to be applied, readings of power input should also be taken. If the zero-sequence resistance is to be corrected for temperature, the temperature of the armature winding, by resistance (see 7.7.5) or detector, should be determined for two or three of the higher currents as promptly as possible after these readings are taken and extrapolated back to the instant of reading.

10.6.1.2.1 Parameter determination using Method 1

The zero-sequence impedance is obtained by Equation (106).

$$Z_0 = \frac{3E}{I} \tag{106}$$

where

Z_0 is the zero-sequence impedance determined by Method 1, in per unit
E is the test voltage, in per unit of base *line-to-neutral* voltage (see 9.2.3)
I is the total test current, in per unit of base line current (see 9.2.3)

In most cases, the zero-sequence reactance may be taken as equal to the zero-sequence impedance. However, for small machines, or where the armature resistance is relatively large and the zero-sequence reactance relatively small, as for example in machines having a winding of two-thirds pitch, correction for resistance may be needed. For such cases, Equation (107) can be used.

$$X_0 = Z_0\sqrt{1-\left(\frac{P}{EI}\right)^2} \tag{107}$$

where

X_0 is the zero-sequence reactance determined by Method 1, in per unit
P is the test power (wattmeter reading), in per unit of base *single-phase* power (see 9.2.2)

10.6.1.3 Method 2. Series circuit

In this method, the windings of the three phases are connected in series, as shown in Figure 36. This method can be used only when both terminals of each phase are accessible for external connection. In other respects, this method is similar to Method 1 (see 10.6.1.2.1). A single-phase alternating voltage is applied across the windings of the three phases in series, and readings of voltage and current are taken, if possible, for several values of current up to rated current or higher. If the zero-sequence resistance is to be determined or if the resistance correction is to be applied, readings of power input should also be taken. If the zero-sequence resistance is to be corrected for temperature, the temperature of armature winding, by resistance (see 7.7.5) or detector, should be determined for two or three of the higher currents as promptly as possible after the readings are taken and extrapolated back to the instant of reading.

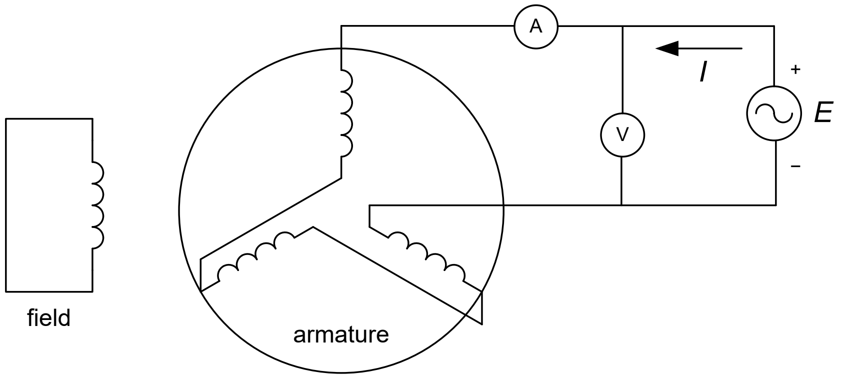

Figure 36—Connection diagram for determining zero-sequence reactance using Method 2

10.6.1.3.1 Parameter determination using Method 2

The zero-sequence impedance for the series circuit connection is obtained by Equation (108).

$$Z_0 = \frac{E}{3I} \tag{108}$$

where

Z_0 is the zero-sequence impedance determined by Method 2, in per unit
E is the test voltage, in per unit of base *line-to-neutral* voltage (see 9.2.3)
I is the total test current, in per unit of base line current (see 9.2.3)

The correction for resistance, if needed, is made using Equation (107). For this test, the zero-sequence current is equal to the test current.

10.6.1.4 Method 3. Sustained short circuit

The machine is driven at rated speed with a sustained short circuit from two lines to neutral, as shown in Figure 37. Light lines are shown for metering circuits. Readings are taken of the voltage from the open terminal to neutral and of the current in the connection of the two short-circuited terminals to neutral. If the zero-sequence resistance is to be determined or if a resistance correction is to be applied, readings of the power represented by the test voltage and test current should also be taken. The field excitation is adjusted to give a series of readings for values of the normal current, if possible, up to three times rated current or higher.

CAUTION

This test should be terminated as promptly as possible. Serious overheating may result if the currents are carried too high or sustained for too long a time, particularly for cylindrical-rotor machines.

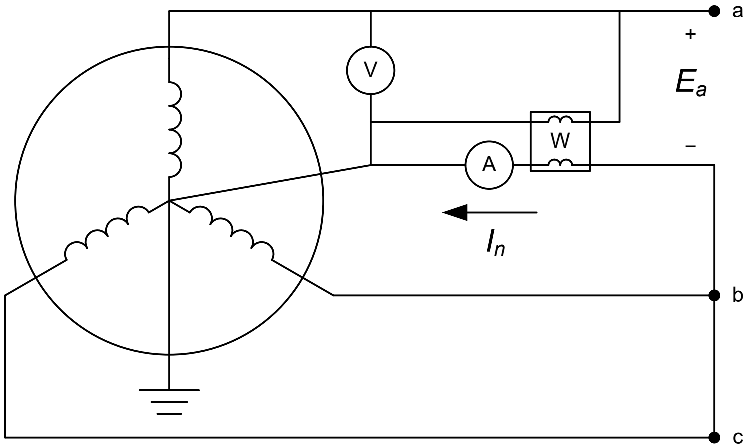

Figure 37—Diagram for determining zero-sequence parameters using Method 3

10.6.1.4.1 Parameter determination using Method 3

The zero-sequence impedance is obtained by Equation (109).

$$Z_0 = \frac{E_a}{I_n} \tag{109}$$

where

Z_0 is the zero-sequence impedance determined by Method 3, in per unit
E_a is the line-to-neutral voltage of the open phase, in per unit of base *line-to-neutral* voltage
I_n is the neutral current, in per unit of base line current

In most cases, the zero-sequence reactance may be taken as equal to the zero-sequence impedance. However, for small machines, or where the armature resistance is relatively large and the zero-sequence reactance is relatively small, as for example in machines having a winding of two-thirds pitch, correction for resistance may be needed. When a correction is made, the zero-sequence reactance is obtained from Equation (110).

$$X_0 = Z_0 \sqrt{1 - \left(\frac{P_{an}}{E_a I_n} \right)^2} \tag{110}$$

where

X_0 is the zero-sequence reactance determined by Method 3, in per unit
P_{an} is the test power (wattmeter reading), in per unit of base *single-phase* power (see 9.2.2)

For this test, the zero-sequence current is one-third of the neutral current.

10.6.1.4.2 Additional comments on parameter determination using Method 3

a) If the speed of the machine is not equal to rated speed at the moment the readings are taken, correction for small speed deviations may be made by multiplying the value of zero-sequence reactance by the ratio of the rated speed to actual speed.

b) Since any impedance in the neutral circuit of Figure 36 will be measured as part of the machine's zero-sequence reactance and since the latter can be very small, it is important to select the current transformer, ammeter, and leads to help minimize the impedance.

c) For large machines, having a small value of X_0, Equation (109) and Equation (110) may lead to unacceptable error on X_0. In this case, the metering scheme of Figure 38 should be considered, and Equation (111) should be applied to mitigate the effect of cable impedances.

$$X_0 = \frac{Q_{an} + (2+k)Q_{pn}}{I_n^2} \frac{60}{f} \tag{111}$$

where

Q_{an} is the reactive power measured with voltage E_a and current I_n, in per unit of base single-phase power.
Q_{pn} is the reactive power measured with voltage V_{pn} and current I_n, in per unit of base single-phase power. The voltage V_{pn} would be close to zero if the cable impedances are negligible; Q_{pn} would approach zero in that case.
k is the ratio between the cable lengths l_{bp} (between points *b* and *p* in Figure 38) and l_{pn}
f is the electrical frequency associated with the machine speed when the measurements were taken, in hertz.

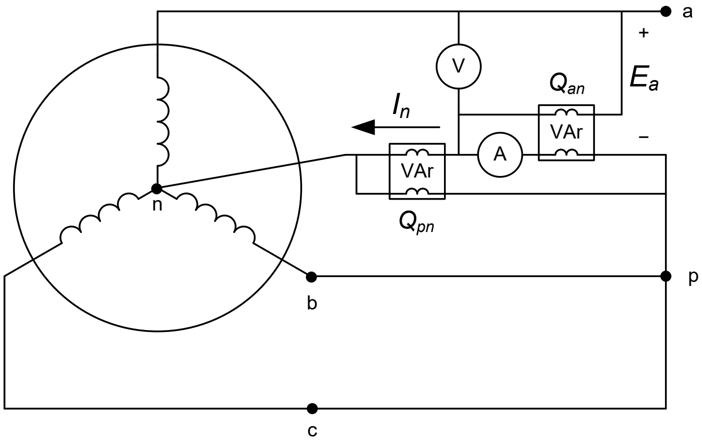

Figure 38—Additional measurements to mitigate effects from cable impedances

d) The instrumentation should be set to fundamental measurements or harmonic analysis conducted to get rid of the third harmonic present in measured voltages and currents.

10.6.2 Determining zero-sequence resistance, R_0

For the definition of *zero-sequence resistance*, see Clause 3. The zero-sequence resistance has significance only for a wye-connected machine with accessible neutral.

Ordinarily, zero-sequence resistance does not vary appreciably with current. If it does vary, the value for rated current may be determined by plotting the resistance as a function of zero-sequence current and selecting the value corresponding to rated current.

No correction for temperature is included because of the complex nature of the correction and the approximate nature of the test value of the resistance.

Zero-sequence resistance can be measured by the following methods:

- Method 1. Parallel circuit (see 10.6.2.1)
- Method 2. Series circuit (see 10.6.2.2)
- Method 3. Sustained short circuit (see 10.6.2.3)

10.6.2.1 Method 1. Parallel circuit

When making a test for zero-sequence reactance in accordance with 10.6.1.2.1, the power input, P, is measured by a single-phase wattmeter. The zero-sequence resistance is determined by Equation (112).

$$R_0 = \frac{3P}{I^2} \tag{112}$$

where

R_0 is the zero-sequence resistance determined by Method 1, in per unit
P is the measured power (from the wattmeter), in per unit of base *single-phase* power

I is the total test current, in per unit of base line current

For this test, the zero-sequence current is one-third of the total test current.

10.6.2.2 Method 2. Series circuit

When making a test for zero-sequence reactance in accordance with 10.6.1.3, the power input, P, is measured be a single-phase wattmeter. The zero-sequence resistance is determined by Equation (113).

$$R_0 = \frac{P}{3I^2} \tag{113}$$

where

R_0 is the zero-sequence resistance determined by Method 1, in per unit
P is the measured power (from the wattmeter), in per unit of base *single-phase* power
I is the total test current, in per unit of base line current

For this test, the zero-sequence current is equal to the total test current.

10.6.2.3 Method 3. Sustained short circuit

When making a test for zero-sequence reactance in accordance with 10.6.1.4, the power, P_{an}, represented by the test voltage and test current is measured by a single-phase wattmeter. The zero-sequence resistance is determined as shown in Equation (114).

$$R_0 = \frac{P_{an}}{I_n^2} \tag{114}$$

where

R_0 is the zero-sequence resistance determined by Method 3, in per unit
P_{an} is the measured power (from the wattmeter), in per unit of base *single-phase* power
I_n is the neutral current, in per unit of base line current

10.7 Testing procedures and parameter determination for positive-sequence resistance for a synchronous machine

10.7.1 General

Positive-sequence resistance, R_1, may be used on occasion for a complete simulation of unbalances at or near the stator terminals of a machine. If the total stator losses are of interest under running conditions, the positive-sequence resistance should be used in calculations.

The issue of using R_a, the dc armature resistance, rather than R_1, arises also in Clause 12 when discussing the determination of operational quantities as viewed from the machine stator terminals.

For the definition of *positive-sequence resistance*, see Clause 3.

10.7.2 Determination from test

First, the dc armature resistance, R_a, is determined by test and corrected to a specified temperature (see 4.3).

The stray-load loss, W_{LO}, is determined according to 5.3.2.5. No correction for temperature is included. The positive-sequence resistance is determined by Equation (115)

$$R_1 = R_a + \frac{W_{LO} \times 10^3}{3I_N^2} \tag{115}$$

where

R_1 is the positive-sequence resistance, in ohms. The positive-sequence resistance, in per unit, is obtained by dividing the value, in ohms, by the base armature impedance (see 9.2.4).
R_a is the armature resistance per phase corrected to specified temperature, in ohms
W_{LO} is the stray-load loss at base line current, in kW
I_N is the base line current, in amperes (see 9.2.3)

The temperature, t_s, for which the positive sequence resistance is determined should be stated.

10.8 Additional miscellaneous steady-state tests for synchronous machines

10.8.1 Determination of short-circuit ratio (SCR)

10.8.1.1 General

The test procedures required for determining the SCR are similar to the procedures described in 10.3 for calculating the direct-axis synchronous reactance. These procedures are detailed in 5.3.2.4 and 5.3.2.5.

Although the SCR is not used in stability calculations (as is the direct-axis synchronous reactance, X_{du} or X_{ds}), it has been a practice to use this value to give some idea of the machine’s steady-state characteristics, and it is also used as an approximate guide to size and relative synchronous machine costing.

For the definition of *short-circuit ratio* (SCR), see the *IEEE Standards Dictionary Online.*

10.8.1.2 Calculation

The field currents from the open-circuit saturation curve and from the synchronous impedance test, at rated frequency in each case, are used in determining the SCR, in accordance with Equation (116) (See Figure 16 in 6.2.2.1.)

$$SCR = \frac{I_{FNL}}{I_{FSI}} \tag{116}$$