When the tank is involved, this changes the zero-sequence impedance by altering the zero-sequence voltage and current (Fig. A 13.11). If the tank is shielded by means of magnetic shunts, the impedance is increased significantly (1,5 - 2 times).

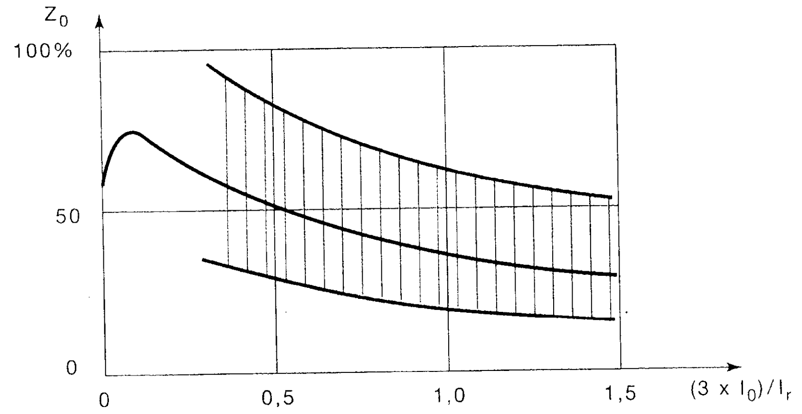

Fig. A 13.11: Variation of three-limb transformer zero-sequence magnetizing impedance with current.

A 13.4 Transformer characteristics with reference to single-phase line-to-neutral loading (2)

The zero-sequence impedance characteristics of power transformers also affect performance in connection with single-phase load ability.

If a single-phase load is connected between two phases, the system of currents on the primary and secondary side contain direct- and inverse-sequence components, but no zero-sequence. On the other hand, if a load is supplied between phase and neutral, there are zero-sequence current components in the windings (see Appendix 12).

Some transformer connections are more suitable than others with regard to single-phase loading. Poor performance is expected for transformers with very high zero-sequence impedance, as in the case with star/star-connected transformers consisting of three single-phase units, three-phase shell-type units, and three-phase core-type units with five-limb cores.

Star/star connection has been relatively unpopular owing to operating difficulties arising from its inherent neutral instability; i.e. due to the fact that the potential of the physical neutral is generally at a point other than the geometrical centre of the voltage triangle, and also because the neutral potential may be greatly affected by the characteristics of the load and other circuit conditions.

Neutral instability is the result of the fact that the currents flowing through the branches of an insulated Y connection are not independent of each other; the currents entering one phase must flow out through the other two. This restriction generally means that the exciting current necessary for proper location of the neutral cannot flow correctly. The consequence is that neutral potential is shifted to an unsymmetrical position.

(2) See Blume et Alii: Transformer Engineering - John Wiley & Sons - New York - London -Sydney.

Star/star-connected transformers, except three-phase three-limb core-type units, are not capable of supplying any appreciable single-phase load from line to neutral without a significant shift in the position of the neutral, owing to the fact that the corresponding primary currents of such loads, flowing through the primaries of the unloaded phases, magnetize them.

Three-limb core-type units, however, may, on account of the magnetic coupling between the three phases and the interlinking of the magnetic fluxes in the three limbs, give tolerably good results under conditions of single-phase loads from line to neutral.

The third-harmonic residual, i.e. the third-harmonic electromotive force induced in each phase because of the suppression of the third-harmonic current necessary for sine wave excitation, is very greatly reduced, and the neutral is also appreciably stabilized.

The third-harmonic flux, which must be present to produce a third-harmonic voltage, flows in the same direction in the three phases and returns from one yoke to the other through the surrounding non-magnetic path (Fig. A13.7 a). Since the return path for the flux is a high-reluctance path, the resulting flux is very much less than in single-phase units or in three-phase shell-type units, in both of which a closed iron path is available for the third-harmonic flux. The effect of the high-reluctance path is to reduce the inherent third-harmonic flux in three-phase core-type transformers approx. from 2% to 5% of the fundamental voltage, depending on magnetic flux density, as against 30% to 70% in single-phase units.

A single-phase load from one line to neutral, equal to 10% of the total three-phase rating can be taken from a three-phase core-type unit without causing any excessive neutral shift.

Referring to Fig. A 13.12 and if unit turn ratio is assumed, a single-phase load current I at the secondary side corresponds to a current at the primary side equal to (2/3) · I in the loaded phase and (1/3) · I in each of the unloaded phases. Hence, each phase carries an un-neutralized (unbalanced) current equal to I/3, which is effective in establishing a zero-sequence flux.

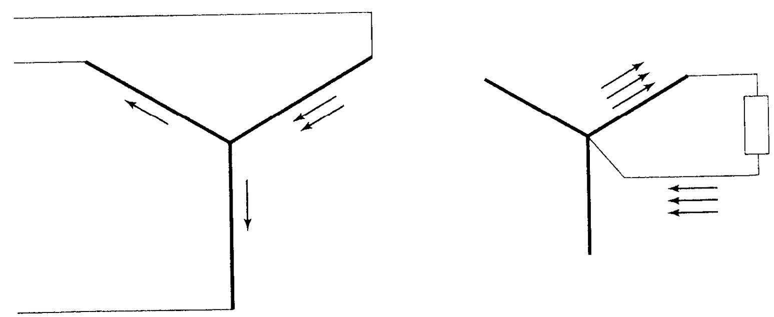

Fig. A 13.12: Distribution of line-to-neutral current in a star/star connected three-phase core-type transformer (the number of arrows indicates the m.m.f. distribution).

The per-unit neutral shift - which is the impedance drop in the unloaded phases - for any single-phase load I is in quadrature with the load current, and its value expressed as a percentage of the normal limb voltage is equal to:

$$\text{neutral shift [\%]} = \frac{I \cdot z_0}{3}$$

where:

I = single-phase load current, in per-unit of full load current;

z_0 = percentage zero-sequence impedance (percentage of normal phase-voltage, obtained by means of connection shown in Fig. A13.2, with rated current in each of the excited coils).

The percentage impedance drop in the loaded phase due to normal primary-to-secondary impedance is equal to:

$$\frac{2 \cdot I}{3} \cdot z$$

where: z = primary-to-secondary percentage impedance at rated current.

The vector sum of these two expressions gives the total voltage drop in the loaded phase (Fig. A 13.13).

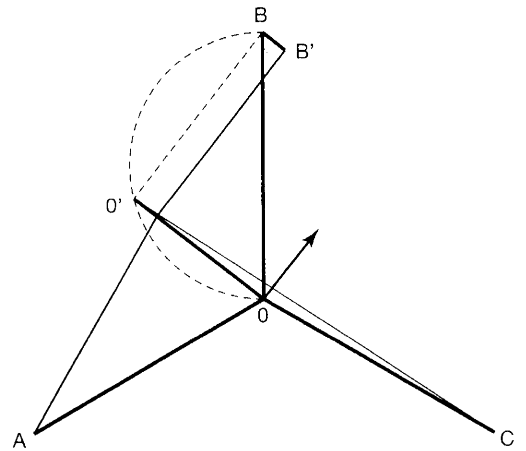

Fig. A 13.13: Voltage distortion in a star/star connected three-phase core-type transformer due to single-phase line-to-neutral load.

The voltage phasor graph shows the effect of the primary-to-secondary impedance and the one caused by yoke-to-yoke flux, on the voltages. In this OO' is the neutral shift caused by yoke-to-yoke flux, and BB' the one caused by primary-to-secondary short-circuit impedance. The yoke-to-yoke flux averages the equivalent of 0,85 p.u. impedance.

The performance of star/star-connected transformers in relation to single-phase loads from line to neutral or under unbalanced conditions on a four-wire, three-phase system can be improved by adding a delta-connected tertiary winding, whose purpose is to stabilize the neutral. There are two distinct cases:

(3) This is the reason why the tertiary winding is often designed for 1/3 of the rated power of the main windings.

a) If the tertiary winding is intended to stabilize the neutral in the presence of unsymmetrical loading conditions, the load in each phase of the tertiary is equal to one third of a single-phase or unbalanced load [3], and at this load the voltage drop between primary and tertiary should not be excessive (Fig. A 13.14).

b) If the tertiary winding is intended to hold a stable grounded neutral on an otherwise insulated system, then:

   b.1) The reactance should be as low as possible, and the tertiary winding should be capable of withstanding the short-circuit current - which will only be limited by the impedance of the generation system - if it is desired to limit the shifting of the neutral to a minimum. This requires that the tertiary as well as the main windings of the step-down transformer have the same short-circuit capacity as the step-up transformer.

   b.2) If, however, the tertiary winding is required to draw only a sufficient short-circuit current to operate the circuit breakers when one of the lines becomes earthed, higher short-circuit impedance and a relatively smaller-capacity tertiary winding may then be used; here, however, there will be considerable neutral shift and also considerable voltage rise on the lines in relation to earth.

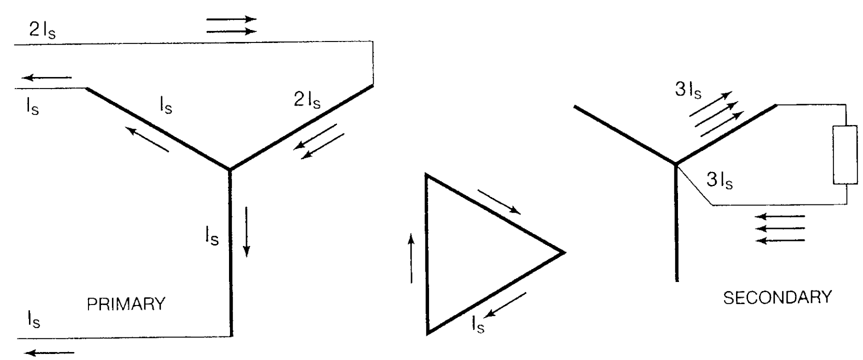

Fig. A 13.14: Current distribution in a star/star connected three-phase transformer provided with a tertiary delta-connected winding to stabilize neutral, for single-phase line-to-neutral loading.

If earth and short circuit are on the secondary transformer side, the short-circuit current in the tertiary is equal to (refer to Appendix 12):

$$I_s = \frac{I \cdot 100}{2 \cdot z_{PS} + z_{TS}}$$

Subscript TS means between tertiary and secondary. The current in the short circuit is $3 \cdot I_s$ (Fig. A 13.14), that in one phase of the primary is $2 \cdot I_s$, and that in the other phases of the primary is I_s. The value of I_s in the different coils must take into account the turn ratio, since all diagrams in Figs. A 13.12 and A 13.14 assume unit turn ratio.

If earth and short circuit are on the excited side, short-circuit currents only flow through the primary and tertiary windings, and the analysis under star-delta connection applies.