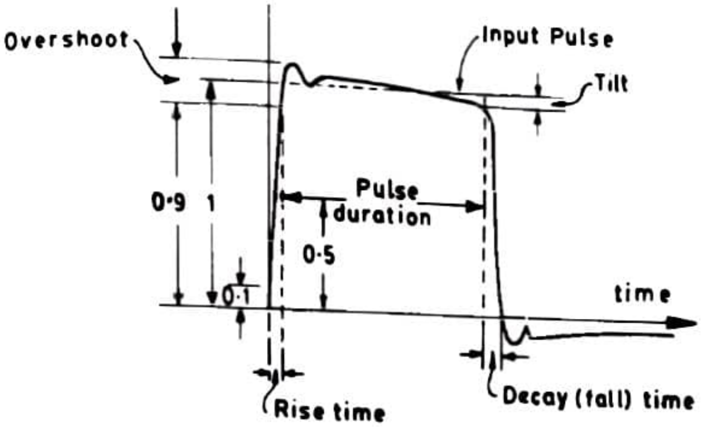


Fig. 1.74. Waveform of output voltage pulses for a pulse transformer.

of its final value. The distortions present in the output pulse can be determined through the transient analysis of its equivalent circuit.

The transformer analysis is usually carried out by dividing its solution into three parts. The first part gives the response near the front edge of the pulse, the second part gives the response during the flat-top and the third part gives the response after the termination of the pulse.

For leading edge of the input pulse analysis of the equivalent circuit is done by including stray capacitance. In order to keep the rise time within limits, the leakage inductance of the transformer should be kept to a minimum.

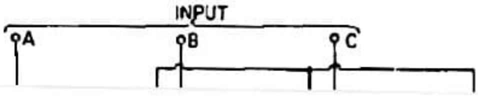
The transformer response to the flat-top portion of the input pulse is carried out by using the low-frequency equivalent circuit of Fig. 1.70 (*b*). The output voltage is seen to have downward tilt, or drop-off, during its pulse duration time. The output voltage cannot remain flat as this would mean dc passing through a transformer which is not possible. The drop-off of the pulse can be kept as small as possible by having high magnetizing inductance for the transformer.

When the input pulse is zero, the output pulse does not reduce to zero instantaneously because of the magnetic energy stored in the transformer inductance. The fall, or decay, time for the output pulse is shown in Fig. 1.74. There is a backswing of the output voltage and because of transformer inductance and stray capacitance, damped oscillations and a long-duration negative overshoot are observed after the decay time of the pulse.

Pulse transformers are quite small in size. Both primary and secondary windings have comparatively few turns so that leakage inductance is minimum. In order that transformer has maximum magnetizing inductance, its core is made of ferrites or from high permeability alloys such as permalloy. As the off-period (time interval between successive pulses) is usually quite large as compared with on-period, the transformer can handle high pulse-power levels.

1.19. Three-phase Transformers

Generation, transmission and distribution of electric energy is invariably done through the use of three-phase systems because of its several advantages over single-phase systems. As such, a large number of three-phase transformers are inducted in a 3-phase energy system for stepping-up or stepping-down the voltage as required. For 3-phase up or down transformation, three units of 1-phase transformers or one unit of 3-phase transformer may be used. When three identical units of 1-phase transformers are used, Fig. 1.75 (*a*), the arrangement is usually called a bank of three transformers or a **3-phase transformer bank**. A single 3-phase trans-



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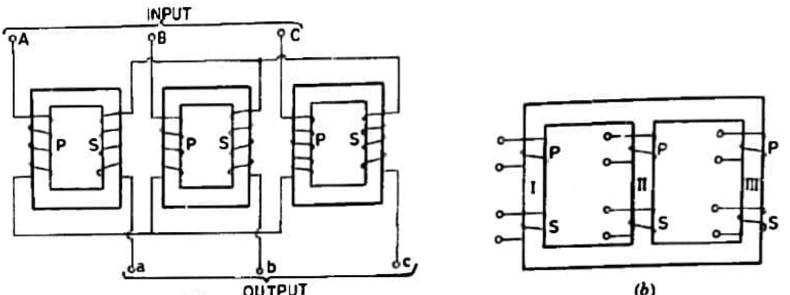

Fig. 1.75. (*a*) Three-phase transformer bank, both windings in star (*b*) three-phase core-type transformer.

former unit may employ 3-phase core-type construction, Fig. 1.75 (*b*) or 3-phase shell-type construction (not shown). A single-unit 3-phase core-type transformer uses a three-limbed core, one limb for each phase winding as shown in Fig. 1.75 (*b*). Actually, each limb has the l.v. winding placed adjacent to the laminated steel core and then h.v. winding is placed over the l.v. winding. Appropriate insulation is placed in between the core and l.v. winding and also in between the two windings.

A 3-phase core-type transformer costs about 15% less than a bank of three 1-phase transformers. Also, a single unit occupies less space than a bank.

1.19.1. Three-phase transformer connections

Three-phase transformers may have the following four standard connections :

(*a*) star-delta ($Y-\Delta$) (*b*) delta-star ($\Delta - Y$)
(*c*) delta-delta ($\Delta - \Delta$) (*d*) star-star ($Y - Y$)

These connections are shown in Figs. 1.76 and 1.77, where V and I are taken as input line voltage and line current respectively. Primary and secondary windings of one phase are drawn parallel to each other. With phase turns ratio from primary to secondary as $N_1/N_2 = a$, the voltages and currents in the windings and lines are shown in Figs. 1.76 and 1.77. The various connections are now described briefly.

(*a*) **Star-delta (*Yd*) connection.** This connection is commonly used for stepping down the voltage from a high level to a medium or low level. The insulation on the h.v. side of the transformer is stressed only to 57.74% $\left(= \frac{1}{\sqrt{3}} \times 100\right)$ of line to line voltage.

For per-phase m.m.f. balance, $I_2 N_2 = I_1 N_1$

Here primary phase current, I_1 = primary line current I

∴ Secondary phase current, $I_2 = \frac{N_1}{N_2} I_1 = aI$

Secondary line current $= \sqrt{3}\, I_2 = \sqrt{3} \cdot aI$

Also, voltage per turn on primary = voltage per turn on secondary

$$\frac{V}{\sqrt{3}} \cdot \frac{1}{N_1} = \frac{V_2}{N_2}$$

* For more details of 3-phase transformers, see chapter 8 of the book, "Generalized Theory of Electrical Machines" by the same author.

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Secondary phase voltage, $V_2 = \frac{N_2}{N_1} \cdot \frac{V}{\sqrt{3}} = \frac{V}{a \cdot \sqrt{3}}$

Secondary line voltage = secondary phase voltage $= \frac{V}{a \cdot \sqrt{3}}$

Input $VA = 3 \frac{V}{\sqrt{3}} I$ = output $VA = 3 \cdot \frac{V}{a\sqrt{3}} \cdot \sqrt{3}\, aI = \sqrt{3}\, VI$

Phase and line values for voltages and currents on both primary and secondary sides of star-delta transformer are shown in Fig. 1.76 (*a*).

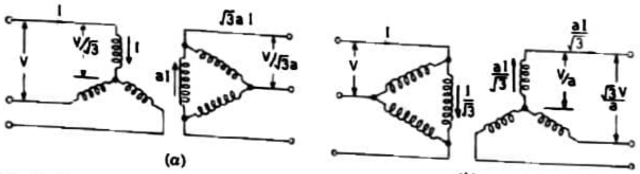

Fig. 1.76. (*a*) Star-delta connection and (*b*) delta-star connection of 3-phase transformers.

(*b*) Delta-star (*Dy*) connection. This type of connection is used for stepping up the voltage to a high level. For example, these are used in the beginning of h.v. transmission lines so that insulation is stressed to about 57.74% of line voltage.

Delta-star transformers are also generally used as distribution transformers for providing mixed line to line voltage to high-power equipment and line to neutral voltage to 1-phase low-power equipment. For example, 11 kV/400V, delta-star distribution transformer is used to distribute power to consumers by 3-phase four-wire system. Three-phase high-power equipment is connected to 400 V, three line wires, whereas 1-phase low-power equipment is energised from 231 V line to neutral circuits.

For per-phase m.m.f. balance, $I_2 N_2 = I_1 N_1$

Here primary phase current, $I_1 = \frac{1}{\sqrt{3}}$ (primary line current I)

Secondary phase current, $I_2 = \frac{N_1}{N_2} I_1 = a \frac{I}{\sqrt{3}}$

Also, $\frac{V_2}{N_2} = \frac{V_1}{N_1}$

Secondary phase voltage, $V_2 = \frac{N_2}{N_1} \cdot V_1 = \frac{V}{a}$

Secondary line voltage $= \sqrt{3} \cdot \frac{V}{a}$

Input $VA = 3 \cdot V \cdot \frac{I}{\sqrt{3}} = \sqrt{3}\, VI$ = Output $VA = 3 \cdot \frac{V}{a}\, a \frac{I}{\sqrt{3}} = \sqrt{3} \cdot VI$

Phase and line values for voltages and currents on primary as well as secondary sides of a 3-phase delta-star transformer are shown in Fig. 1.76 (*b*).

(*c*) Delta-delta (*Dd*) connection. This scheme of connections is used for large l.v. transformers. It is because a delta-connected winding handles line voltage, so it requires more turns per phase but of smaller cross-sectional area. The absence of star point may be a disadvantage in some applications.

In case a bank of three transformers is used, then one transformer can be removed for maintenance purposes while the remaining two transformers (called an *open*-delta or *V-connection*) can still deliver 58% of the power delivered by the original 3-phase transformer bank.

For per-phase m.m.f. balance, $I_2 N_2 = I_1 N_1$

Primary phase current, $I_1 = \frac{1}{\sqrt{3}}$ (primary line current I)

Secondary phase current, $I_2 = \frac{N_1}{N_2} I_1 = \frac{aI}{\sqrt{3}}$

Secondary line current

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Also

$V_2 = \frac{N_2}{N_1} V_1 = \frac{V}{a}$ (Here $V_1 = V$)

In case a bank of three transformers is used, then one transformer can be removed for maintenance purposes while the remaining two transformers (called an *open*-delta or *V-connection*) can still deliver 58% of the power delivered by the original 3-phase transformer bank.

For per-phase m.m.f. balance, $I_2 N_2 = I_1 N_1$

Primary phase current, $I_1 = \frac{1}{\sqrt{3}}$ (primary line current I)

Secondary phase current, $I_2 = \frac{N_1}{N_2} I_1 = \frac{aI}{\sqrt{3}}$

Secondary line current $= \sqrt{3}\left(\frac{aI}{\sqrt{3}}\right) = aI$

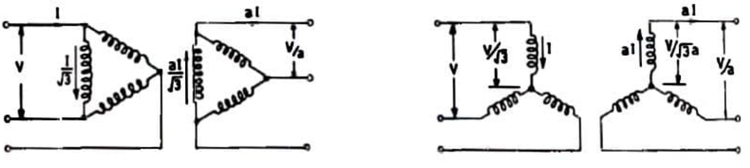
Also $\frac{V_2}{N_2} = \frac{V_1}{N_1}$

Secondary phase voltage, $V_2 = \frac{N_2}{N_1} V_1 = \frac{V}{a}$ (Here $V_1 = V$)

Secondary line voltage, $= V_2 = \frac{V}{a}$

Input $VA = 3\,V \cdot \frac{I}{\sqrt{3}}$ = output $VA = 3 \cdot \frac{V}{a} \cdot \frac{aI}{\sqrt{3}} = \sqrt{3}\,VI$

Phase and line values for voltages and currents on both primary and secondary sides of a 3-phase delta-delta transformer are shown in Fig. 1.77 (*a*).



(*a*) (*b*)

Fig. 1.77. (*a*) Delta-delta connection and (*b*) Star-star connection of three-phase transformers.

(*d*) **Star-star (*Yy*) connection.** This connection is used for small h.v. transformers. As stated before, with star connection, turns per phase are minimum and the winding insulation is stressed to 57.74% of line voltage. Star-star connection is rarely used in practice because of oscillatory neutral problems.*

For per-phase m.m.f. balance, $I_2 N_2 = I_1 N_1$

Primary phase current, $I_1 =$ primary line current, I

Secondary phase current, $I_2 = \frac{N_1}{N_2} I_1 = aI$

= secondary line current

Secondary phase voltage, $V_2 = \frac{N_2}{N_1} V_1 = \frac{V}{\sqrt{3}\,a}$

Secondary line voltage $= \sqrt{3}\,V_2 = \sqrt{3} \cdot \frac{V}{\sqrt{3} \cdot a} = \frac{V}{a}$

Input $VA = 3 \cdot \frac{V}{\sqrt{3}} \cdot I$ = output $VA = 3 \cdot \frac{V}{\sqrt{3} \cdot a} \cdot aI = \sqrt{3}\,VI$

* For more details, see Chapter 8 of the book, "Generalized theory of Electrical Machines" by the same author.

As before, phase and line values of voltages and currents on both the sides of a star-star transformer are shown in Fig. 1.77 (*b*).

Example 1.66. *A 3-phase transformer is used to step-down the voltage of a 3-phase, 11 kV feeder line. Per-phase turns ratio is 12. For a primary line current of 20 A, calculate the secondary line voltage, line current and output kVA for the following connections :*

(a) star-delta (b) delta-star (c) delta-delta (d) star-star. Neglect losses.

Solution. (*a*) Three-phase transformer with star-delta connection is shown in Fig. 1.78 (*a*).

As before, phase and line values of voltages and currents on both the sides of a star-star transformer are shown in Fig. 1.77 (*b*).

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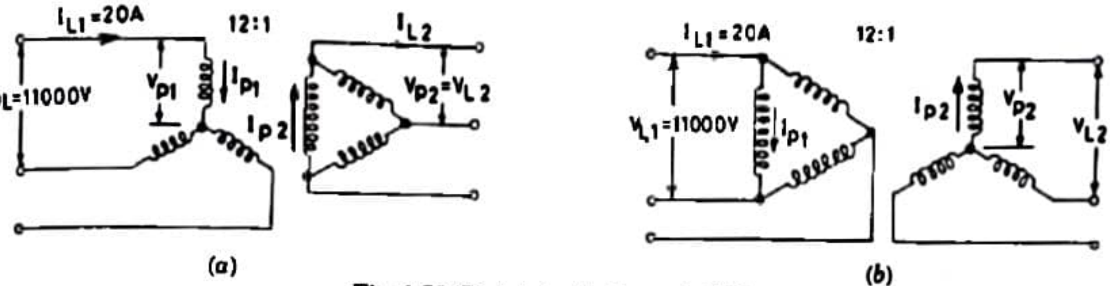

Fig. 1.78. Pertaining to Example 1.66.

Phase voltage on primary, $V_{p1} = \frac{V_{L1}}{\sqrt{3}} = \frac{11000}{\sqrt{3}}$ V

Phase current on primary, $I_{p1} = I_{L1} = 20$ A

Here $\frac{V_{p1}}{12} = \frac{V_{p2}}{1}$ and $I_{p1} \times 12 = I_{p2} \times 1$

∴ Phase voltage on secondary, $V_{p2} = \frac{11000}{\sqrt{3} \times 12} = 529.25$ V

Line voltage on secondary, $V_{L2} = V_{p2} = 529.25$ V

Phase current on secondary, $I_{p2} = 12\, I_{p1} = 12 \times 20 = 240$ A

Line current on secondary, $I_{L2} = \sqrt{3}\, I_{p2} = \sqrt{3} \times 240 = 415.68$ A

$$\text{Output kVA} = \frac{3\, V_{p2} \cdot I_{p2}}{1000} = 3 \cdot \frac{11000}{\sqrt{3} \times 12} \times 240 \times \frac{1}{1000} = 381.04 \text{ kVA.}$$

(*b*) Delta-star connection of 3-phase transformer is shown in Fig. 1.78 (*b*).

Phase voltage on secondary, $V_{p_2} = \frac{V_{p1}}{12} = \frac{V_{L1}}{12} = \frac{11000}{12}$ V = 916.67 V

Line voltage on secondary, $V_{L2} = \sqrt{3}\, V_{p2} = \sqrt{3} \times \frac{11000}{12} = 1587.67$ V

Phase current on primary, $I_{p1} = I_{L1}/\sqrt{3} = \frac{20}{\sqrt{3}}$ A

Phase current on secondary, $I_{p2} = 12\, I_{p1} = 12 \times \frac{20}{\sqrt{3}} = 138.568$ A

Line current on secondary, $I_{L2} = I_{p2} = 138.568$ A

$$\text{Output kVA} = 3 \times \frac{11000}{12} \times \frac{12 \times 20}{1000 \times \sqrt{3}} = 381.04 \text{ kVA.}$$

(c) Delta-delta connection of 3-phase transformer is shown in Fig. 1.78 (c).

Phase voltage on secondary, $V_{p2} = \frac{V_{p1}}{12} = \frac{V_{L1}}{12} = \frac{11000}{12}$ V = 6351 V

Line voltage on secondary, $V_{L2} = V_{p2} = 6351$ V

Phase current on primary, $I_{p1} = \frac{20}{\sqrt{3}}$ A

Phase current on secondary, $I_{p2} = 12\, I_{p1} = 12 \times \frac{20}{\sqrt{3}}$ A

Line current on secondary, $I_{L2} = \sqrt{3}\, I_{p2} = \sqrt{3} \cdot \frac{12 \times 20}{\sqrt{3}} = 240$ A

$$\text{Output kVA} = 3 \times \frac{11000}{12} \times \frac{2400}{1000} = 381.04 \text{ kVA.}$$

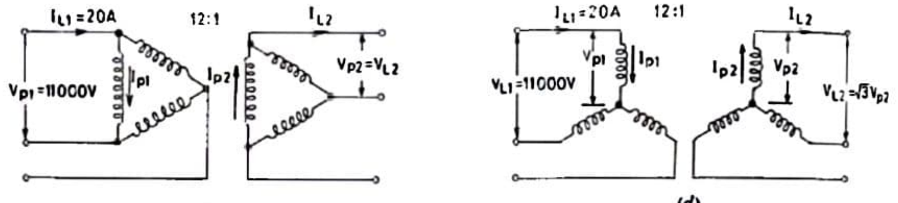

Fig. 1.78. Pertaining to Example 1.66.

(d) 3-phase transformer with star-star connection is shown in Fig. 1.78 (d).

Phase voltage on secondary, $V_{p2} = \frac{V_{p1}}{12} = \frac{11000}{\sqrt{3} \times 12}$ V

Line voltage on secondary, $V_{L2} = \sqrt{3}\, V_{p2} = \sqrt{3}\, \frac{11000}{\sqrt{3} \times 12} = \frac{11000}{12}$ V

Phase current on primary, $I_{p1} = I_{L1} = 20$ A

Phase current on secondary, $I_{p2} = 12\, I_{p1} = 12 \times 20 = 240$ A

Line current on secondary, $I_{L2} = I_{p2} = 240$ A

$$\text{Output kVA} = \frac{3 \times 11000}{\sqrt{3} \times 12} \times \frac{240}{1000} = 381.04 \text{ kVA.}$$

Example 1.67. *A 11000/415 V, delta-star transformer feeds power to a 30 kW, 415 V, 3-phase induction motor having an efficiency of 90% and full-load pf 0.833. Calculate the transformer rating and phase and line currents on both high and low voltage sides.*

Solution. Transformer kVA rating $= \frac{30}{0.9 \times 0.833} = 40$ kVA

Line current on l.v. side of transformer $= \frac{\text{Total load in VA}}{\sqrt{3} \times \text{line voltage}} = \frac{40{,}000}{\sqrt{3} \times 415} = 55.65$ A

For star-connected l.v. winding, phase current in l.v. winding = line current on l.v. side = 55.65 A

Line current on h.v. side of transformer $= \frac{40{,}000}{\sqrt{3} \times 11000} = 2.1$ A

For delta-connected h.v. winding,

phase current in h.v. winding, $= \frac{1}{\sqrt{3}}$ (line current on h.v. side)

= 55.65 A

Line current on h.v. side of transformer $= \frac{40,000}{\sqrt{3} \times 11000} = 2.1$ A

For delta-connected h.v. winding,

phase current in h.v. winding, $= \frac{1}{\sqrt{3}}$ (line current on h.v. side)

$$= \frac{1}{\sqrt{3}} \times 2.1 = 1.212 \text{ A.}$$

Example 1.68. *An industrial load takes 100 A at 0.8 pf lag from a 3-phase 11000/400 V, 50 Hz, star-delta transformer. Calculate (a) power consumed by load (b) kVA rating of transformer (c) phase and line currents on both h.v. and l.v. sides.*

Solution. (*a*) Power consumed by load $= \sqrt{3}\, V_l I_l \cos \theta_2$

$$= \sqrt{3} \times 400 \times 100 \times 0.8 \times \frac{1}{1000} = 55.424 \text{ kW.}$$

(*b*) kVA rating of transformer $= \sqrt{3} \times 400 \times 100 \times \frac{1}{1000} = 69.28$ kVA.

(*c*) Phase current or line current on star-connected h.v. side

$$= \frac{69.28}{\sqrt{3} \times 11} = 3.636 \text{ A}$$

Line current on l.v. secondary side $I_l = 100$ A

Phase current on delta-connected secondary side $= \frac{I_l}{\sqrt{3}} = \frac{100}{\sqrt{3}} = 57.73$ A.

1.20. Transformer Noise

The readers must have observed that the transformers using ferromagnetic core produce noise. In case transformers are located in a residential area, then the noise emanating from transformers may be annoying to the nearby houses. The hum, leading to noise, originates in the ferromagnetic core of a transformer.

The major cause of noise in transformers is the magnetostriction. When ferromagnetic transformer core is magnetized, the core length along the alternating flux decreases and increases alternatively, with a corresponding increase and decrease of its cross-section. This phenomenon involving very small changes in dimensions of the magnetized core is called *magnetostriction*. As the steel laminations change their dimensions* alternately, the ferromagnetic core vibrates and humming is produced. This humming traverses from the core to the transformer oil, to tank and then to the surroundings in the form of noise. The degree of humming level depends on the flux density in the core. Greater the core flux density, greater is the tendency for humming in transformers.

In brief, the factors producing the noise in transformers are the following :

(*i*) The first cause of hum, and therefore the noise, is the magnetostriction.

(*ii*) The details of core construction, size and gauge of laminations and the degree of tightness of clamping the core by nuts and bolts do influence the frequency of mechanical vibrations and therefore the noise in transformers.

(*iii*) Joints in the core are also responsible for noise production though to a lesser degree.

Most of the noise emission from a transformer may be reduced

(*a*) by using low value of flux density in the core,

(*b*) by proper tightening of the core by clamps, bolts etc.

(*c*) by sound-insulating the transformer core from the tank wall in case of large transformers or by sound-insulating the transformer core from where it is installed in case of small transformers.

* Dimensions change by 1.2×10^{-4} percent for a flux density of 1T.