Transformer Connections: Types and Their Impact on System Performance

by **Ed Khan**

Photo: Doble Engineering

Transformers are connected in various configurations, some of which are delta/wye, wye/wye and wye/delta. Transformer connections have an impact on a number of criteria of system performance, including the following:

1. Phase shifts impact relay protection and system operability

2. Neutral grounding of wye connected winding impacts ground relaying and overall system performance

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3. Flow of ground fault current impacts relay protection and system performance

4. Passage of third harmonic current is needed to produce sinusoidal transformer output voltage

5. Connections enabling twelve pulse rectification

Impact on differential protection

One of the impacts is related to transformer differential protection. To understand this impact, we must review the phase angle shifts that result from various connections.

Figure 1 shows the wye-wye connection. In this connection the primary and secondary currents, in all phases, are in phase and hence there is no need for compensation.

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Figure 2 shows the delta-wye connection (which can also be wye-delta). In this connection the primary and secondary currents in all phases are not in phase. There is a 30-degree phase shift and hence, a compensation is needed. This compensation is performed through current transformer connections, or, internally, in a microprocessor differential relay.

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Figure 3 shows common transformer connections that are in use. The phase shifts are designated in terms of hour positions on a clock. For example, Dd0 means that the primary and the secondary current are in phase with A phase of windings at 12 o'clock or zero hours.

Similarly, DY1 connection means that the primary winding is connected in delta with A phase pointing at 12 o'clock and the secondary winding is connected in wye with A phase pointing towards 1 o'clock, resulting in a phase shift with wye winding lagging delta winding by 30°.

If we look at a three-winding transformer, a connection designated as YNy0d1 means that the primary is wye grounded at 12 o'clock and the secondary winding is wye ungrounded also set at 12 o'clock or zero hours. The delta tertiary is shifted towards 1 o'clock resulting in a phase shift of thirty degree from the wye windings. The letter N or n stands for grounded neutral.

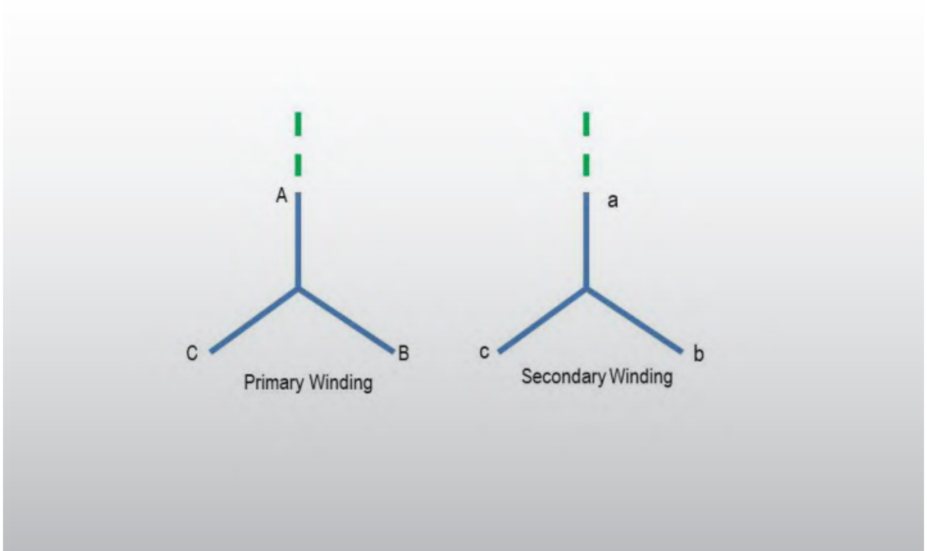

Figure 1. Wye-wye connection

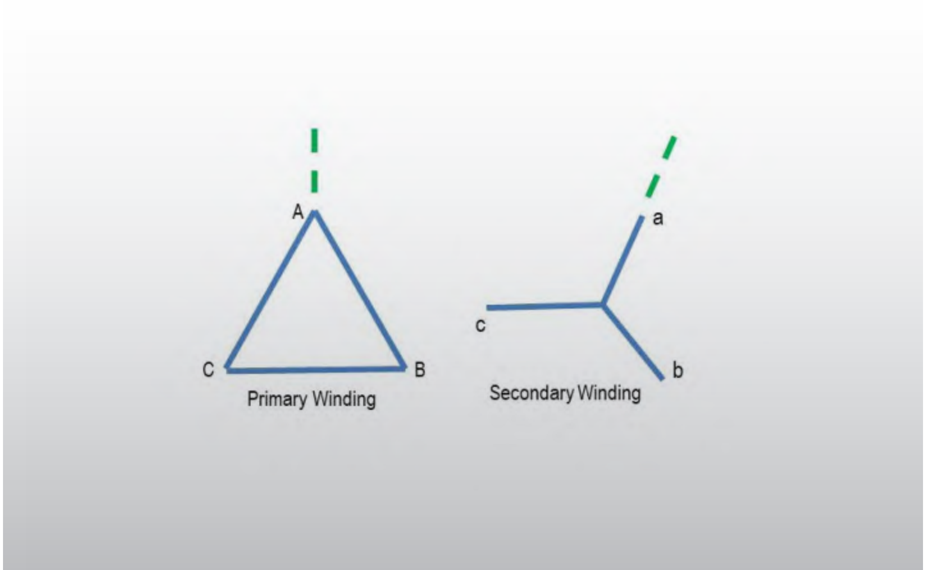

Figure 2. Delta-wye connection

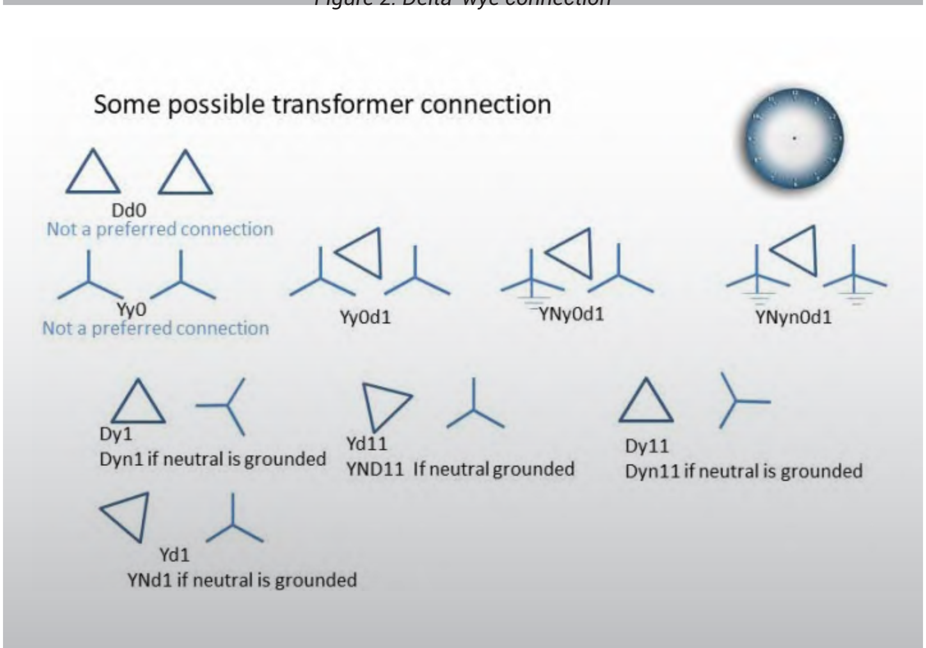

Figure 3. Common transformer connections

Photo: Doble Engineering

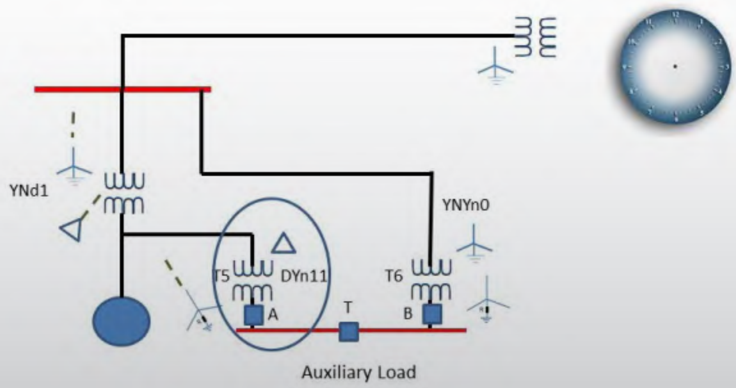

Figure 4. A typical powerplant layout

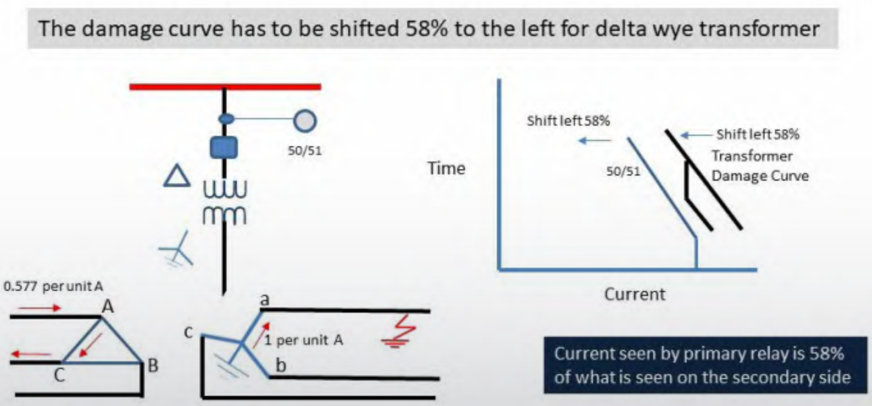

Figure 5. A delta-wye transformer with neutral grounded

Phasing issues

Transformer connections can lead to phasing issues which can be solved by using appropriate winding connections.

Figure 4 shows a layout at a typical powerplant. Transformer T5, which has been circled in the diagram, feeds the auxiliary load. When the generator is started and brought online, the power to the auxiliary bus is fed by transformer T6. Breakers B and T are in close position and breaker A is open. The auxiliary bus feeds motors and other loads that are necessary to support the generator. Once the generator is synchronized, breaker A is closed followed by opening of breaker B. Hence, the two sources fed by breakers A and B are paralleled for a short duration. Hence, the output of transformer T5 and T6 should be in phase. To achieve this, the transformer T5 has to be of certain connection, as shown in Figure 4. If the generator step up is connected as YNd1, T5 will have to be connected as DYn11.

Shifting of transformer damage curve

Figure 5 shows a delta-wye transformer with neutral grounded. In the event of a line to ground fault on the wye side of the transformer, the ground relays on the delta side will not see this ground fault. This is due to infinite zero sequence impedance between the two windings. However, the phase relays will see this as a phase-to-phase fault with magnitude diminished to 58% of what it would see if there were a three-phase fault on the wye side. The transformer damage curve, which represents the capability of the transformer to withstand a through fault is plotted for a three-phase fault. In effect, the phase relays on the delta side are seeing only 58% of the current and hence will not trip in time to protect the transformer. Hence, the solution is to shift both the damage curve and the characteristics of the phase relay by 58% towards the left. In effect, the setting for the phase overcurrent relay needs modification.

Managing the flow of third harmonic

Excitation current required by transformers is between 1-5% of the rated current of the transformers. The excitation current contains 60 Hz along with few harmonics. Most prominent harmonics are the 3rd, 5th, 7th, 9th, and 11th. The 3rd harmonic, which is most prominent, requires special attention. To understand the issue, we must understand the characteristics of this harmonic.

Figure 6 shows the sequence of the 1st through 3rd harmonic. The first, second and third harmonics exhibit positive, negative and zero sequence characteristics, respectively. Using the first harmonic phase angles as reference, we obtain the sequence angles for 2nd and 3rd harmonics by multiplying the 60Hz angles by two and three, respectively. As shown Figures 6 and 7, the 2nd and 3rd harmonics exhibit characteristics of negative and zero sequence, respectively.

Similarly, the 4th, 5th and 6th harmonics are positive, negative and zero sequence and likewise 7th, 8th and 9th harmonics are also positive, negative and zero sequence.

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In Figure 7 we observe that the vector addition of IA, IB, and IC for both positive and negative sequences result in a sum of 0 because of 120° separation. Hence, there is no current at the neutral to flow back to another available neutral. This is not the case with the 3rd, 6th, and 9th harmonics. These are zero sequence harmonics and the summation at the neutral is three times the current in each phase. The 3rd, 6th and 9th harmonic will flow if there is either a delta winding or a close path through ground. In short, the zero sequence harmonics need a closed path. This is explained in Figure 8.

Furthermore, in the case of wye-delta connection as shown in Figure 8, the 3rd harmonic line-neutral emf will force a third harmonic current in the delta which forms a close loop.

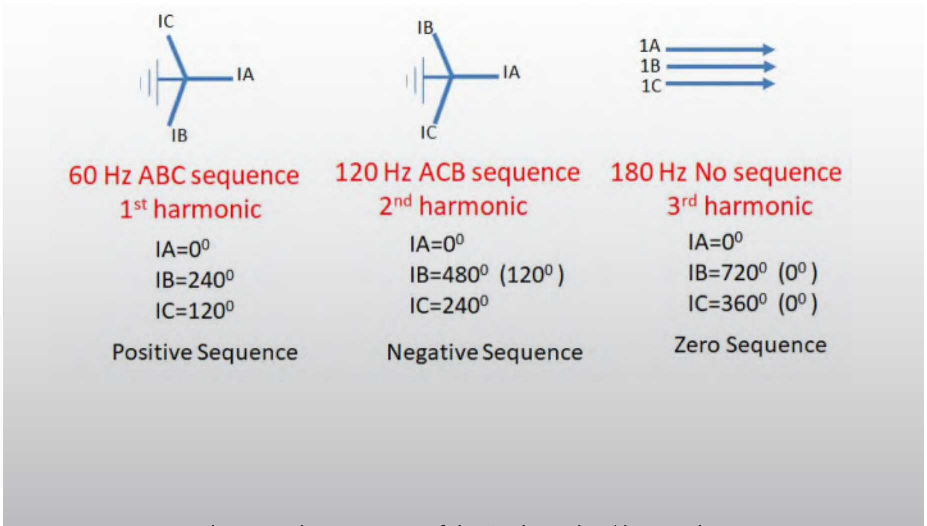

Figure 6. The sequence of the 1st through 3rd harmonic

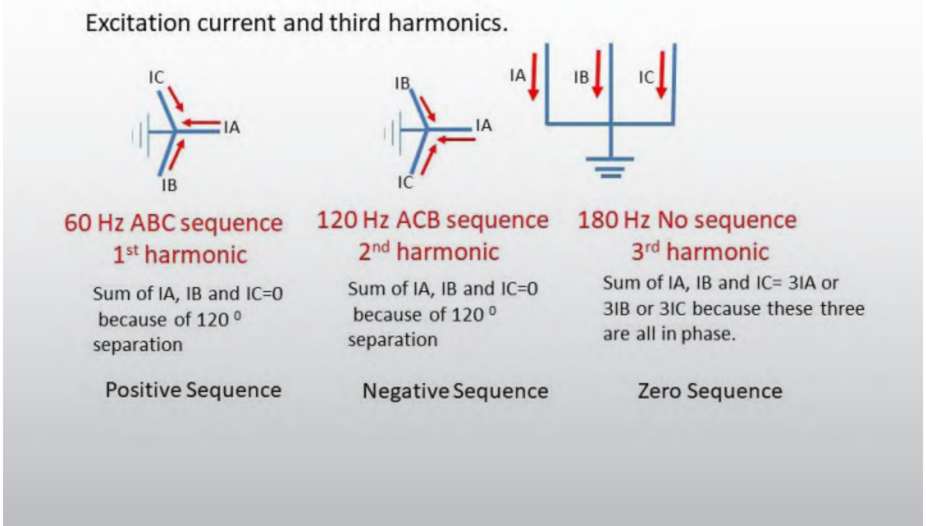

Figure 7.

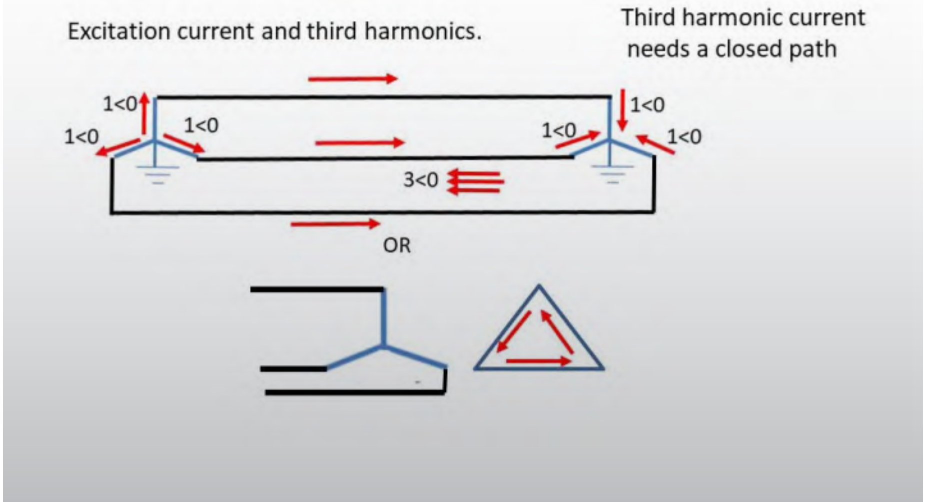

Figure 8. The 3rd harmonic in the wye-delta connection

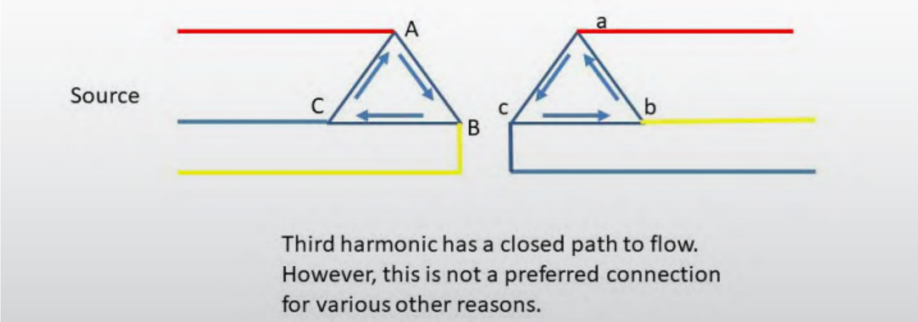

Figure 9. A delta-delta connection

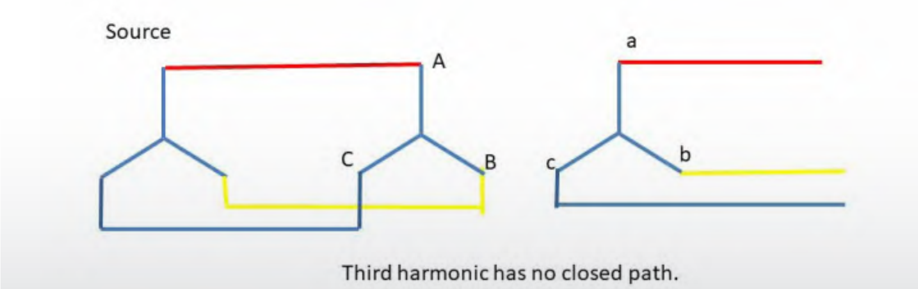

Figure 10. A wye-wye configuration

Photo: Shutterstock

There is no need for 3rd harmonic current to flow in the wye winding. Additionally, there is no line-to-line 3rd harmonic emf present because the 3rd harmonic currents are all in phase.

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Figure 9 shows a delta-delta connection. This connection is not a preferred option for various reasons. However, this connection does provide a closed path for the third harmonic to flow.

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Figure 10 shows a wye-wye configuration for a transformer. The source supplies the excitation voltage, which contains 3rd harmonic line-neutral voltage. This voltage is impressed on primary winding of the transformer. However, there is no closed path for the third harmonic to flow. Third harmonic current must be allowed to flow to eliminate any third harmonic voltage in the transformer output voltage.

If the transformer is core type, third harmonic current will flow since in a core type transformer the winding layout creates a fictitious delta tertiary. If it is a shell type, a delta tertiary will be required unless the neutral of the source and the neutral of the transformer primary are grounded. However, the grounding of these two neutrals is not preferred since the flow of 3rd harmonic between the two neutrals will cause interference with communication circuits.

One exception related to zero sequence harmonic (3rd, 6th, 9th) as opposed to 60 Hz zero sequence is that the flow of these triplen harmonic currents do not follow the balancing ampere turn rule. This means that a current flow in one winding does not require a flow of current in the other winding. In other words, balancing the ampere turns is not required.

The wye-wye connections with neutrals ungrounded as connection shown in Figure 10 has other issues such as neutral instability, overvoltage, etc. and hence is not preferred unless the transformer has a core type winding.

In the case of a shell type transformer, a tertiary winding is definitely used. Figure 11 shows a shell type transformer and this connection will allow third harmonic current to flow and suppress the 3rd harmonic voltage in the transformer output voltage. If this was a core type transformer, the third harmonic will flow without the delta tertiary since the core type winding creates a fictitious delta tertiary.

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Figure 12 shows a case where the transformer is connected in wye-wye with system neutral grounded and the primary of the transformer grounded. In this case 3rd harmonic will flow in the wye primary winding. However, the flow of harmonic between the system neutral and the transformer primary neutral will result in interference with communication system.

In this case if there is a delta tertiary in addition to the grounding of neutrals as shown in Figure 12, the 3rd harmonic will split between the primary winding and the delta winding and this split is of no concern.

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Figure 13 shown below is the best connection for allowing the flow of 3rd harmonic. The 3rd harmonic emf is impressed on the delta winding and resultant 3rd harmonic flows in the delta winding.

There is no need for corresponding 3rd harmonic to flow in the secondary winding since balancing ampere turns is not required as far as 3rd, 6th, 9th harmonics are concerned.

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Figure 14 shows the same configuration as Figure 13 except the primary winding is connected in wye and the secondary winding is connected in delta. In this case also the 3rd harmonic current has a closed path to flow within the delta.

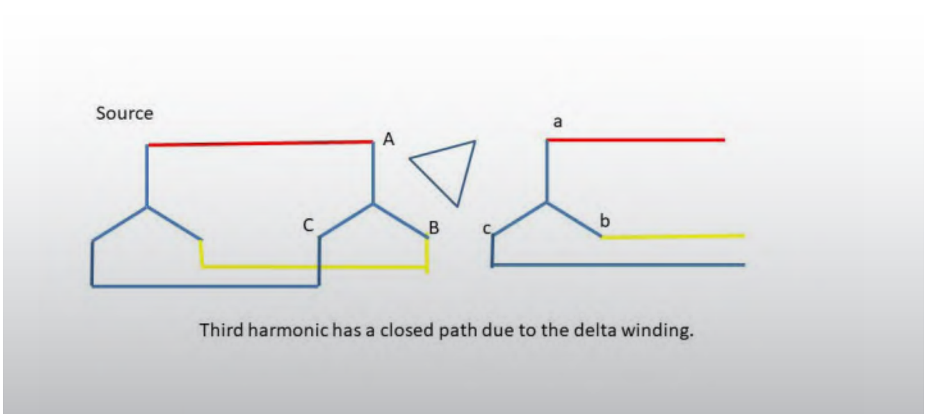

Figure 11. A shell type transformer

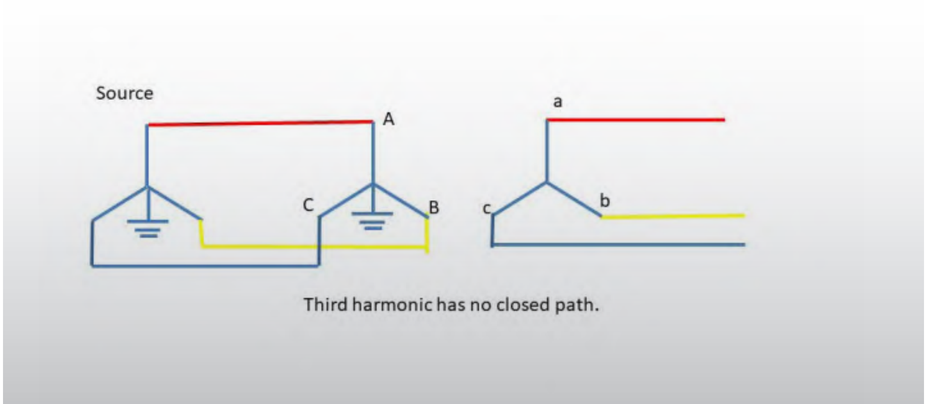

Figure 12. A wye-wye connected transformer with system neutral grounded and the primary of the transformer grounded.

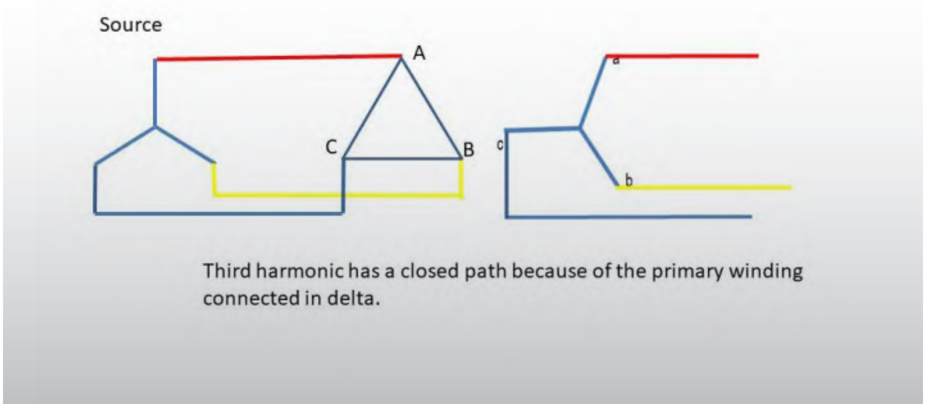

Figure 13. Best connection for allowing the flow of 3rd harmonic.

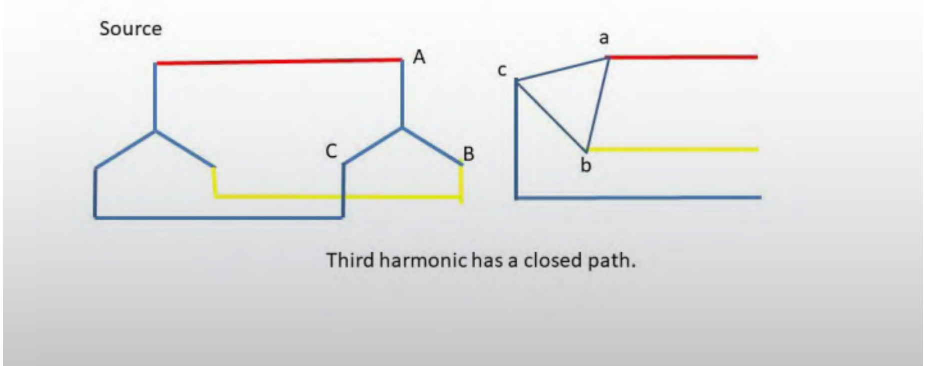

Figure 14. Same as Fig. 13 but here the primary winding is connected in wye and the secondary winding is connected in delta.

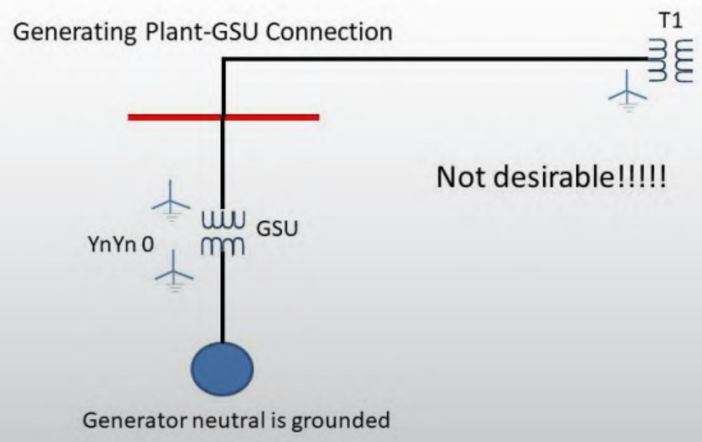

Figure 15. A GSU connected grounded-wye/grounded-wye

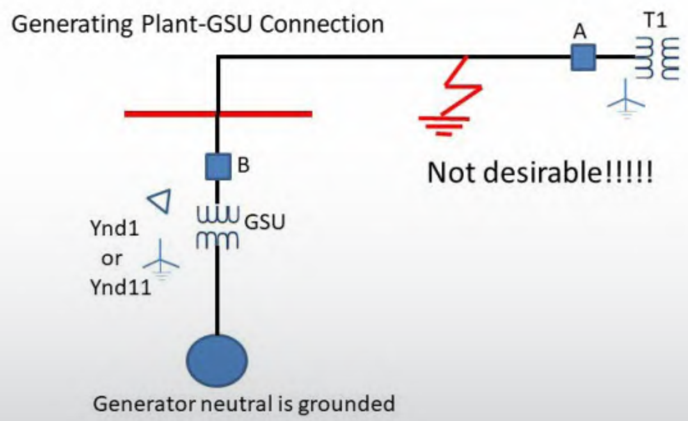

Figure 16. A GSU connected in delta on the high side and wye grounded on the generator side

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Connections for Generator Step up Transformers (GSU)

One of the factors that influence the selection of transformer connection is the flow of ground fault current though the transformer. Connections can either allow or block the flow of ground fault currents between two parts of the system connected via transformer. One critical area requiring careful attention is the selection of transformer connection for GSUs.

Figure 15 shows the GSU connected grounded-wye/grounded-wye. This connection is not desirable because the magnitude of ground fault flowing in each winding is indeterminant during a ground fault on either side of the GSU. This connection makes it difficult to determine proper settings for ground protection relays.

If this GSU is of shell type design, it will contain a tertiary winding. Presence of tertiary winding will complicate ground fault relay protection even further. In short, determination of current distribution between the two grounded system is difficult.

If the GSU is core type design, a physical tertiary is not required. A core type transformer by design creates a fictitious delta tertiary. With the connection as shown in Figure 15, ground relaying becomes complicated whether it is shell or core type design.

Figure 16 shows the GSU connected in delta on the high side and wye grounded on the generator side. This is not a desirable connection for the GSU.

A ground fault between on the line connecting GSU and transformer T1 will be cleared by breaker A. However, the wye side of the transformer will not see this fault and hence breaker B will not trip. The grounded conductor will remain connected to the generator and hence will be live. It is a safety issue and furthermore if there is distribution circuit tapped off the line, the generator will supply an ungrounded system. This is an unacceptable situation.

One solution is to install a grounding bank on the high side of GSU as shown in Figure 17. This will provide a path for the ground fault current to flow through the grounding transformer. This will enable tripping of breaker B via relay applied in the neutral of the grounding bank.

Figure 18 shows a desirable connection. Ground faults in the transmission line will be cleared by brakers A and B. Ground faults on the generator side will be cleared by tripping breaker B via ground relays applied at the generator. The generator neutral is grounded.

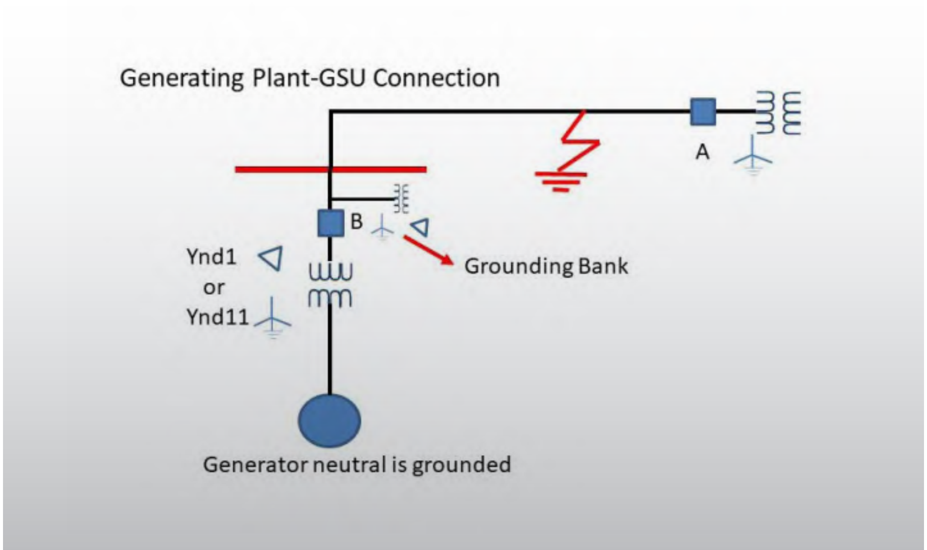

Figure 17. A grounding bank on the high side of GSU

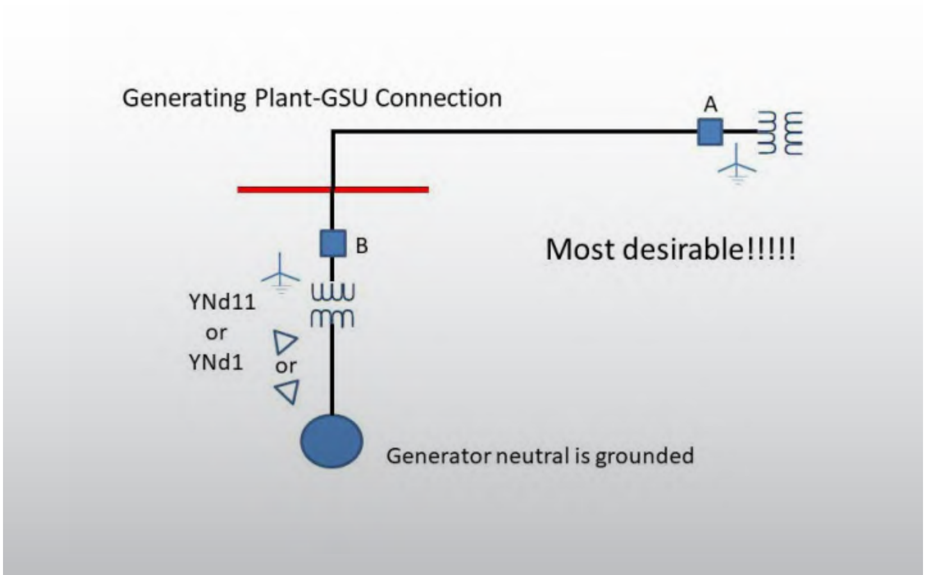

Figure 18. A desirable connection for a GSU transformer

The role of transformer connection in rectification

Figure 19 shows an adjustable speed drive system utilized in industrial plants to power adjustable speed motors. There is rectification followed by inversion of DC current into adjustable 60 Hz power to the motor.

Commonly used schemes are 6 pulse and 12 pulse. Figure 14 shows a 12-pulse rectification using twelve diodes/thyristors. The disadvantage of cheaper option 6 pulse scheme is two-fold. The DC output is not smooth, and the rectification creates significant harmonics that are injected into the incoming AC power supply. The two main harmonics that create voltage and current distortions are the 5^{th} and the 7^{th} harmonics.

The issue of DC current quality is solved by using a more expensive option of 12-pulse rectifier, which uses 12 diodes/thyristors scheme. The issue of harmonic distortion is solved by introducing a 30-degree phase shift between the two secondary windings as shown in Figure 19. Due to proper selection of transformer connection, a 30-degree phase shift is achieved resulting in significant reduction in harmonics injected into the incoming AC power supply.

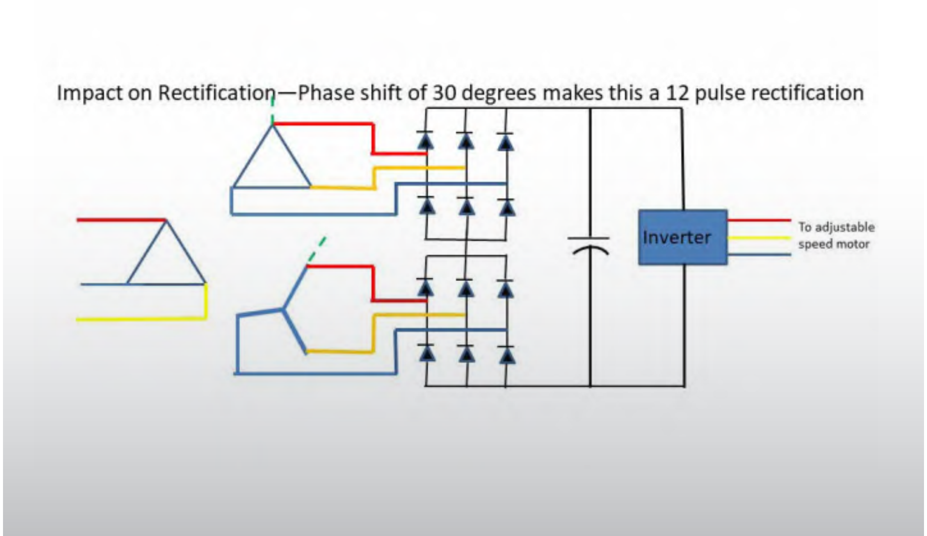

Figure 19. An adjustable speed drive system