Technology Development of a Roof-Delta Connection Transformer

Electrical equipment for Shinkansen line, Traction transformer, Roof-delta connection transformer, Analysis techniques

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Abstract

In the conventional application in Japan, the modified Woodbridge-connected transformer has been used as the traction transformer in a traction substation (more than 187kV of receiving voltage) for Shinkansen lines. Such substations are effectively grounded at 187kV or higher receiving voltage in Japan.

This type of transformer has advantageous points. We could apply existing technologies to the winding arrangement and construction. However, it has the disadvantage that a step-up transformer must be installed to equalize the voltage of two single-phase outputs on the secondary side.

To resolve this problem, we re-evaluated the roof-delta connection transformer, which was not put into service on the Shinkansen lines at the time of the Sanyo Shinkansen line construction because of difficulty in impedance matching. After various engineering discussions, studies, and verification tests, we succeeded in commercial development as a new traction transformer for the Shinkansen line.

1. Preface

In commercializing the roof-delta connection transformer for Shinkansen lines, it was a must to establish the technology to reduce neutral current on the primary side. This phenomenon was not accepted in the 1970s when the Sanyo Shinkansen line was constructed.

To solve this problem, the Working Group (WG) for re-evaluating this technology was primary organized in 2005 by the Railway Technical Research Institute; the Japan Railway Construction, Transport and Technology Agency; and East Japan Railway Company (JR East) as founding members, along with five heavy electrical industry suppliers including our Company as the joint WG. The project research to manufacture and perform the verification test on the core type roof-delta connection transformer prototype was assigned to Meidensha Corporation.

The reason why impedance of the winding for each phase does not match is due to the inherent structural feature of roof-delta connections where the winding configuration for the middle phase is different from ones for other phases. We analyzed the cause and effect relationship between the impedance of delta-connected winding for each phase and the neutral current by simulation and succeeded in finding the formula.

Additionally, once difficult impedance matching was made real by drawing on our engineering resources of the advanced analysis technology and the optimum winding layout design, and manufacturing accuracy improvement, etc., we could achieve a target to reduce the neutral current within 5% of the rated current. The newly 66kV 10MVA prototype underwent the verification test in 2006 at the Kita-Shirakawa Substation on the JR East Tohoku line, and we released this product later.

This paper introduces the analysis results on the unique phenomena observed in various verification tests during our process of commercialization of the roof-delta connection transformer.

2. Configuration and Neutral Current of Roof-Delta Connection Transformer

2.1 Configuration of Roof-Delta Connection Transformer

The roof-delta connection transformer consists of the roof (∧) winding in the A Connection Power Source Circuit (A-CPSC) and the delta (Δ) winding in the B Connection Power Source Circuit (B-CPSC). With the appropriate turn ratio of each winding corresponding to feeding voltage on the secondary side, a 3-phase to 2-phase conversion can be made in a simple configuration. Because a Y-connection is used for the winding on the primary side, it can be used as a 3-phase to 2-phase conversion transformer for extra high voltage where the neutral point is directly grounded. When the same loads are connected to A-CPSC and B-CPSC at the same time, current at the power supply side balances between the three phases.

The current capacity of the U- and W-phases of the delta winding at B-CPSC side is half of the value for the V-phase, and when it is constructed as a 3-phase transformer, the number of turns and size of the winding are different between the U-, W-, and V-phases, but the impedance characteristics of each phase must be the same as much as possible, and sophisticated engineering and manufacturing techniques are required.

2.2 Cause and Magnitude of Neutral Current

A phenomenon unique to the roof-delta connection transformer is the current flowing through the neutral point of the primary side. The cause of the current flowing through the neutral point is the imbalance in the impedance in the Δ winding in B-CPSC. The reason why the neutral current is generated is explained as follows.

Because the Y-connection on the primary side is directly grounded as shown in Fig. 1, the relation Iu = Iw = 1/2 Iv is not satisfied when the impedance of each of the Δ windings in B-CPSC is different, and because distribution of the current is determined based on impedance values, current In flows through the neutral point on the primary side.

Although this phenomenon is not limited to the roof-delta connection transformer and is observed in the modified Woodbridge connection transformer, it is more significant in the roof-delta connection transformer because the winding configuration of each phase is not uniform. So it is very important to match the impedance of each phase (impedance matching). With respect to the load in A-CPSC, because the current of the U-phase and W-phase of the ∧ winding is the same, no neutral current is generated on the primary side.

The magnitude of the neutral current in the roof-delta connection can be obtained by solving the difference in the impedance with respect to the electric network. The relationship between the impedance and the neutral current is shown below.

V-phase current when a load is applied on B-CPSC is expressed by Expression (1) and U-phase and W-phase current is expressed by Expression (2).

$$Iv = \frac{(Zu + Zw)}{(Zu + Zw) + Zv} \times Ib \quad \cdots\cdots (1)$$

$$Iu = Iw = \frac{Zv}{(Zu + Zw) + Zv} \times Ib \quad \cdots\cdots (2)$$

When the turn ratio is taken as 1:1, the neutral current on the primary side is expressed by Expression (3).

$$In = Iv - (Iu + Iw) \quad \cdots\cdots (3)$$

Where;

Zu, *Zv*, and *Zw*: Impedance of each phase
Iu, *Iv*, and *Iw*: Winding current of each phase
Ib: Load current in B-phase

From Expression (1), (2), and (3), the neutral current is obtained by Expression (4).

$$In = \frac{(Zu + Zw) - 2 \times Zv}{(Zu + Zw) + Zv} \times Ib \quad \cdots\cdots (4)$$

When impedance *Z* is expressed in the form of *R* + *jX*, the neutral current is expressed as in Expression (5).

$$In = \frac{(Ru + jXu) + (Rw + jXw) - 2 \times (Rv + jXv)}{(Ru + jXu) + (Rw + jXw) + Rv + jXv} \times Ib \quad \cdots (5)$$

2.3 Verification Results of Neutral Current

For the 10MVA prototype, impedance matching was confirmed and winding impedance in each phase was measured inside the tank to verify the relationship between impedance matching and the neutral current. Fig. 2 shows the calculated values and measured values of the neutral current in the prototype. The x-axis represents mismatch of reactance and the y-axis represents the neutral current. Each point in the graph represents the measured values depending on the tap position. The measured values of the neutral current were consistent with the theoretical values, which indicate that the neutral current can be restricted within the

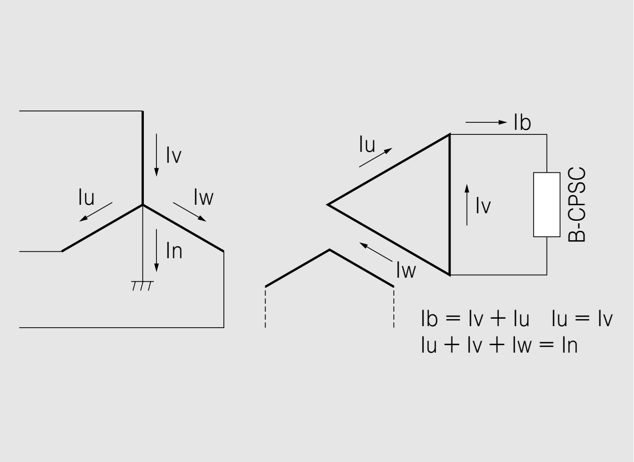


Fig. 1 Distribution of Current in Roof-Delta Connection Transformer with Load Applied on B-CPSC Side
The load current in B-CPSC side is divided in the delta windings and converted in the primary winding.

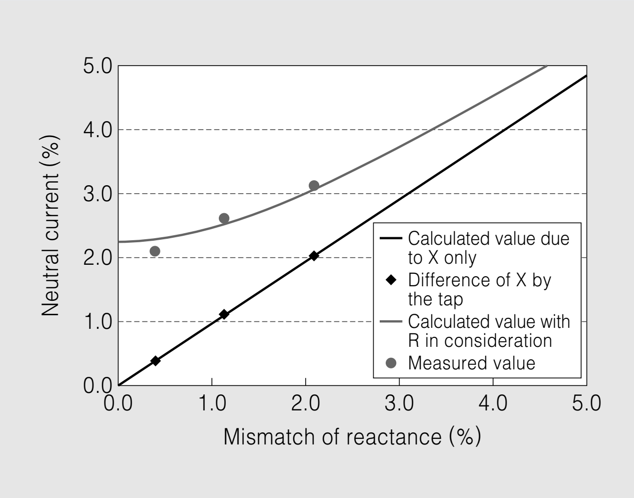


Fig. 2 Mismatch of Impedance and Neutral Current
Degree of mismatch of reactance differs depending on position of taps. Phase of the effect due to mismatch of resistance component is 90° different from the effect due to mismatch of reactance.

tolerance owing to impedance matching.

Because, in the prototype, the size of the Δ winding for the B-CPSC side in each phase is designed to correspond to the magnitude of the current that flows through the winding, about 2% of the neutral current due to the mismatch in resistance is present even without the mismatch in reactance. In the case of the target unit with a larger capacity, %IX becomes larger and %IR becomes smaller than those of the prototype, so the effect of the resistance portion on the neutral current is small.

3. Potential Oscillation

In the roof-delta connection transformer, there are connecting points that are not taken out to outside both in A- and B-CPSC. At this connecting point, voltage may become higher than the voltage at the external terminals because lightning surges penetrated from outside may be amplified due to potential oscillation within the winding. So accurate insulation design is required to estimate the voltage generated by the potential oscillation.

For the potential oscillation, voltage at various points of the winding was calculated by a computer for the equivalent circuit consisting of the mutual inductance and capacitance of the windings (Fig. 3). Values of the actual unit were measured by the analyzer test during the manufacturing process. While analysis and measurement data are available for the Scott connection transformer etc., the potential oscillation was evaluated in the manufacturing process of the 10MVA prototype because the roof-delta connection transformer is a new type of transformer.

The prototype was manufactured with the identical winding arrangement and type with respect to the 275kV and 150MVA class target unit as the scaled-down model, and a comparison was made by conducting an analysis of the potential oscillation and the analyzer test. Fig. 4 shows the values obtained by the analysis and the measured values of the potential oscillation calculation. Peak values and the oscillation cycle are both in good agreement. It was found that the same computation program used so far can be used for the roof-delta connection transformer, and insulation design of the target unit against lightning impulses is possible.

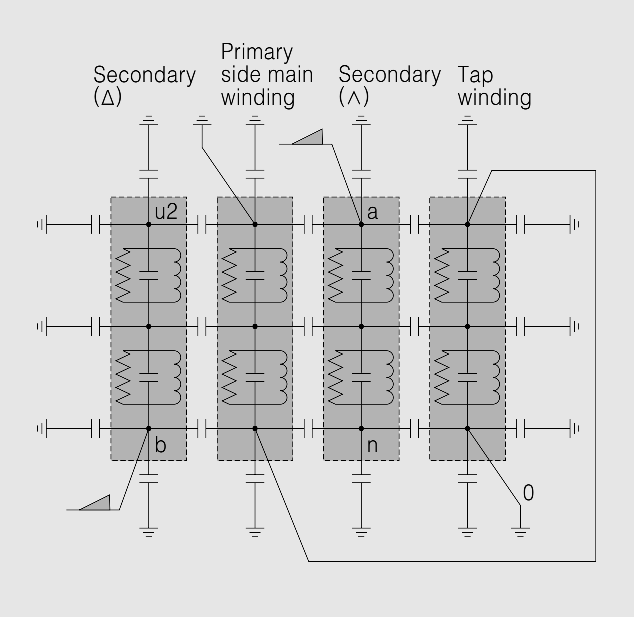
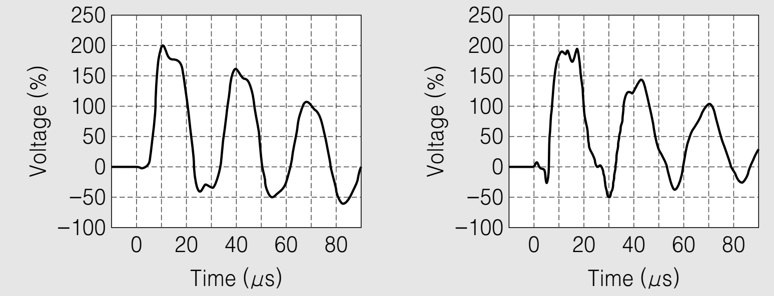


Fig. 3 Equivalent Circuit for Potential Oscillation Calculation
The equivalent circuit of the transformer windings is simulated with the circuit combining inductance and capacitance.



(a) Analytic value (b) Measured value

Fig. 4 Calculated Value and Measured Value of Potential Oscillation Waveform
Measurement of the potential oscillation is in good agreement with the analytic value both in oscillation cycle and in magnitude.

4. Grounding Potential when the AT is Open

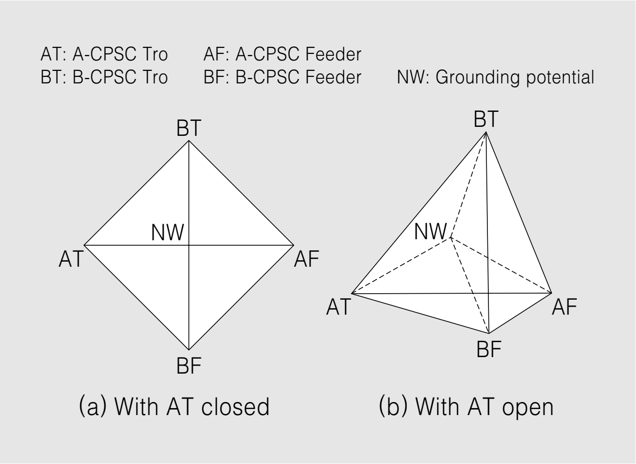
4.1 Vector Diagram of Grounding Potential

In the roof-delta connection transformer, A-CPSC and B-CPSC are not connected, which is different from the modified Woodbridge connection transformer. Because of this, short circuit current does not flow in the case of inter-phase mixture when the AT is open. On the other hand when the AT is open, grounding voltage at each terminal is different as shown in the vector diagram in Fig. 5 (b), which will affect the set points of the 64B (bus line earth fault relay) and 84AB (inter-phase short circuit relay).

4.2 Relation with Transformer Configuration

Voltage at each terminal when the AT is open is dependent on capacitance between the windings and the grounding capacitance. Characteristics peculiar to the roof-delta connection transformer are as follows.

As A-CPSC side consists of U- and W-phase windings only, the neutral potential of the roof winding is affected by the capacitance between the windings with high voltage winding. Fig. 6 shows the arrangement of the A-CPSC winding. In the case of our roof-



(a) With AT closed (b) With AT open

Fig. 5 Vector Diagram of Secondary Side Grounding Voltage of the Roof-Delta Connection Transformer

Grounding voltage at each terminal is the same when the AT is closed, but when it is open, the neutral point will move and different grounding voltage will result between terminals.

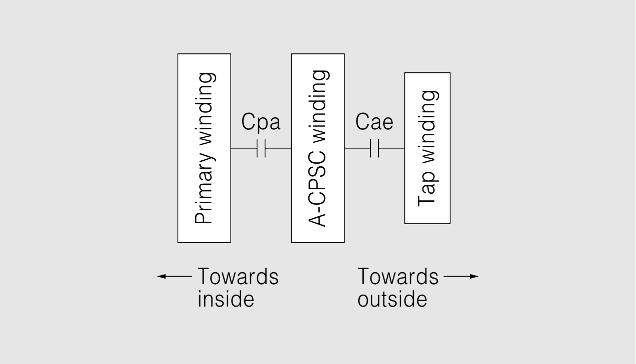


Fig. 6 Arrangement of A-CPSC Winding

Because capacitance between A-CPSC winding and tap winding Cae is included in the grounding capacitance, the grounding voltage of A-phase winding does not fluctuate significantly.

delta connection transformer, a tap winding is provided that is close to the grounding potential at the outside of the A-CPSC winding to prevent an excessive increase in the neutral voltage due to capacitance between the windings. At the B-CPSC side, 3-phase windings are provided, and the neutral potential of the delta windings is close to the midpoint of the triangle.

Grounding potential when the AT is open is affected by the grounding capacitance of the external circuit of the AT in addition to that of the roof-delta connection transformer. While grounding capacitance of the external circuit has an effect on making the neutral potential close to the potential when the AT is closed, such capacitance is not large enough compared with the capacitance of the roof-delta connection transformer in the substations of Shinkansen lines in general. The equipment that will have the largest ground capacitance when the external circuit is the OT (inverse Scott connection transformer).

Grounding potential when the AT is open (a vector in Fig. 5(b)) can be determined by obtaining precise

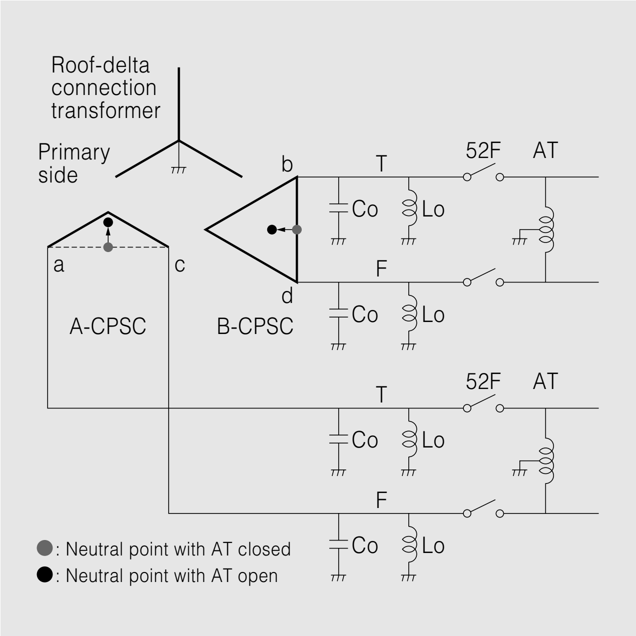


Fig. 7 Mechanism of Ferroresonance

A neutral point of the circuit is at the point in blue when the AT is closed but it moves to the red point when the AT is open. Decaying oscillation due to grounding capacitance C_o and excitation inductance L_o is induced as a transient phenomenon.

values for the capacitance between windings and grounding capacitance.

5. Transient Phenomenon when AT is Open

5.1 Ferroresonance Phenomenon with Grounding Potential Transformer (GPT) in Roof-Delta Connection Transformer

In case of the roof-delta connection transformer, grounding voltage when the winding potential is settled with the AT connected is different from the voltage when the AT is not connected. Because of this, the neutral potential of the winding moves as shown in Fig. 7 when the AT is open, and the transient phenomenon of the grounding potential is induced.

If the exciting inductance of the GPT L_O is linear, oscillation at the resonance frequency of the exciting inductance of the GPT with the grounding capacitance of the circuit C_O will decay gradually. However, because the actual L_O is not linear, transient abnormal voltage may be induced or resonance may continue due to resonance with the line frequency or its fractional order caused by magnetic saturation of the core, depending on circuit conditions. Such a phenomenon is called as ferroresonance.

5.2 Cause of Ferroresonance and its Simulation

The following factors are relevant for ferroresonance to occur.

(1) Grounding potential of the winding when ungrounded

Transient phenomena when the AT is open become significant when the difference in the potential of the winding from the grounding potential is large.

The grounding potential of the winding is determined by the winding arrangement, capacitance between windings and between the wiring and the ground, and the grounding capacitance of the external circuit.

(2) Grounding capacitance of the winding and the circuit and excitation inductance of the GPT

Because ferroresonance is a resonant phenomenon, it is affected by the grounding capacitance of the circuit and the excitation capacitance of the GPT. As the GPT has nonlinear excitation inductance, the range where resonance with grounding capacitance of the circuit occurs is wide. According to measurement results of the units installed for actual service at present (one substation each for 60Hz and 50Hz areas), circuit constants are within the range where ferroresonance can occur.

(3) Grounding circuit losses

The transient phenomenon affects the decay rate and continuation of ferroresonance through circuit losses. The grounding circuit losses are dielectric loss of the capacitance (tanδ), core loss of the GPT, and loss due to load resistance. The magnitude of dielectric loss is small, and the load of the GPT is small due to use of digital type protective devices and instruments, which makes ferroresonance occur easily.

(4) Phase of breaking current when the AT is Open

In the case of a single-phase circuit in general, the DC component reduces in the transient phenomenon after the current is broken when the power factor is one. In the case of a roof-delta connection transformer, as there is a phase difference of 90° between the direction of shift of neutral potential and the voltage between terminals, the transient DC component decreases when the current is broken at a lower power factor than when it is broken at a power factor of one. Accordingly, ferroresonance seldom occurs when the load power factor is low at the time the AT is open. Because the load power factor of the feeder line for the Shinkansen system when the AT is open is small due to the grounding capacitance of the feeder line, ferroresonance will seldom take place except when voltage is applied in the rail yard.

(5) Simulation of ferroresonance

Analysis of the transient phenomenon when the AT is open is made using the model of the circuit shown in Fig. 7 by the EMTP. Grounding capacitance calculated to obtain the grounding potential when the AT is open in Section **5** was used in the analysis. In order to determine the ferroresonance precisely, the excitation properties, winding resistance, and load of the GPT should be accurately incorporated into the model. It is also critical to accurately reflect power factor of the load circuit.

Fig. 8 shows the waveform obtained by the simulation when ferroresonance takes place. The condition represented in Fig. 8 is that the voltage is applied in the rail yard, the load of the GPT is a few VA, and ferroresonance takes place when the AT is open where remnant magnetic fluxes are present in the GPT after repeated closing tests.

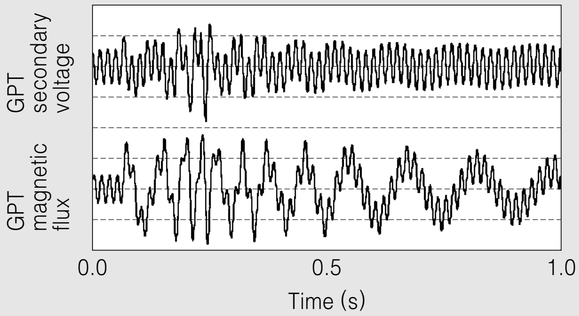


Fig. 8 Typical Simulated Waveform when Ferroresonance Takes Place

Abnormal oscillation is observed due to ferroresonance induced when the AT is open.

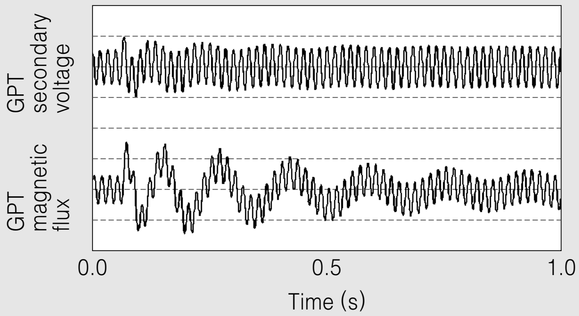


Fig. 9 Simulation Result when the Resister is Connected to GPT Secondary Side

Because of the resister connected to the GPT secondary side, oscillation due to grounding capacitance and GPT excitation inductance decays stably.

5.3 Reduction of Ferroresonance

When ferroresonance takes place, the core of the GPT is saturated and excessive current rushes into the primary winding. As the GPT is designed to withstand the excitation in-rush current when the circuit is closed, such excessive current will not be a problem for a short period of time, but if ferroresonance persists, excessive increases in the winding temperature of the GPT will cause a problem.

A countermeasure is to connect a resister to the secondary circuit of the GPT. When this method is used, effect of DC component in the GPT can be quickly reduced and occurrence of ferroresonance is effectively controlled. The simulation result when resister of 120Ω (equal to the load of 100VA) is connected to the secondary circuit of the GPT in the condition of Fig. 8 is shown in Fig. 9. It is shown that occurrence of ferroresonance is controlled by connection of such resister.

6. Postscript

The analysis techniques explained above were used for practical application of the roof-delta connection transformers, which were supplied and successfully operating on the Kyushu and Tohoku Shinkansen lines. We would like to express special thanks to the East Japan Railway Company; the Japan Railway Construction, Transport and Technology Agency; and the Railway Technical Research Institute for giving us the chance to perform the demonstrative test on the 10MVA prototype unit prior to our commercial release of the roof-delta connection transformer.