Design optimisation for distance between additional and tap winding in high-voltage transformers

Kamran Dawood1*, Ahmet Kerem Köseoğlu2, Güven Kömürgöz1

1Department of Electrical Engineering, Istanbul Technical University, Istanbul, Turkey
2Best Transformers, Balıkesir, Turkey
*E-mail: kamransdaud@yahoo.com

Abstract: The transformer is one of the main components in the power network and transformer windings are one of the most expensive elements in the power transformer. Optimisation of winding distances is one of the most important parameters during the manufacturing of transformer. The distance between the windings in the two winding transformers is well known to transformer designers and manufacturers. However, insulation of the high voltage transformer with additional winding and tap winding is still a major problem for transformer designers. In this study, the additional winding to tap winding distance optimisation is made for a high voltage power transformer. Optimisation of the transformer's windings just not minimises the cost of the transformer but also increases the lifetime of the transformer. With additional winding and tap winding in high-voltage transformers, insulation distance is a major concern for minimising the cost and size of the high voltage transformer. In this study, an approach is made to balance the cost, size, and safety of high voltage transformers. The optimised distance and position between tap winding and additional winding are determined by using the finite element analysis. The finite element method results were also verified by making a prototype transformer.

1 Introduction

Power transformers are the key element for power networks. Transformers work a day continuously, and the service of the power network mainly depends on the working of the power transformer. Copper and aluminium are used for the active parts of the power transformers. Apart from aluminium and copper, several ferrous, nonferrous, cold rolled grain oriented silicon steel, and insulating materials are used for the manufacturing of the transformer. For the compact size of the transformer and less losses in the transformer optimal utilisation of all the materials according to the mechanical, electrical, physical, chemical and thermal characteristics is one of the main steps for the manufacturing of the transformer. Aluminium can be used in low power transformers. However, for >4 MVA rated power transformers, copper is the optimal solution. The copper as a metal is more expensive than aluminium. The main aim of the transformer designers is to use less copper without compromising on the performance and quality of the transformer.

The optimal design of the transformer is one of the most important aspects of transformer manufacturers and designers. It can decrease the cost and size of the transformer and also increase profit due to less copper and no-load losses. For that purpose, several analyses and experiments are performed to find the optimal design of the transformer. Optimal design can be defined as where usage of the copper will be minimised and safety factors must be high and fulfil all the international standards. Reducing safety factors due to the cost can be risky because transformers must withstand not only the rated current but also overvoltages and short-circuit conditions. Many different types of protection elements are being used in transformers to protect the transformer from the negative effect of the power system. However, transformers are always designed for the worst-case situation and the transformer must be able to withstand short-circuit situations and excessive voltage of network.

The most important overvoltage situation in service is lightning impulses into transformer lines and the transformer may suffer the effect of thousands of lightning impulses [1]. To withstand these impulses, transformer winding to winding and winding to ground distances and insulation paper thicknesses must be determined accordingly and optimally.

Power transformers have been in the electricity business since the 1870s and there are many companies and transformer designers with their own design distances and protection experiences. If the distance between windings is insufficient, discharge in oil will occur and it will degrade the transformer oil and can result in further damage in the transformer. On the other hand, if the distance is more than required, then more copper will be required and will result in a bigger and heavier transformer. So finding optimum insulation distance in design is crucial for the transformer designers.

Several studies have been conducted on the applications of non-destructive dielectric measurement techniques and time-domain insulation response for insulation condition assessment [2, 3]. Few types of research are also conducted on the superimposed voltage conditions for transformer insulation [4–6]. During the manufacturing and designing of the transformer, understanding the potential and electric field distribution in the insulation system is one of the important factors.

The majority of the transformer failures are mainly reported due to the insulation problem in the transformer windings. Impulse overvoltages of different wave shapes are one of the main sources of failures [7]. A standard lightning impulse test is one of the main criteria for the manufacturing of a high voltage power transformer.

During the standard lightning impulse test, the insulation strength of the transformer is predicted by making comparisons between reduced and rated levels for chopped and full impulses. To determine the insulation strength of the distribution and power transformers, lightning impulse test is performed. In this test, impulsive overvoltages caused by lightning discharges are applied to the transformers. In the high voltage transformers, insulation is one of the most important parts and the transformer's working and performance mainly depends on its insulation system. The lifetime of a transformer is also governed by the lifetime of the insulation system [8, 9]. As the voltage level of the transformer increases, the insulation strength of the transformer gets more and more importance and attention. Lightning strikes, switching transient overvoltages or short circuits are some of the most common reasons for insulation failure in the transformers [10, 11]. However,
few of these adverse incidents originate due to the weakness in the transformer insulation system which could be made during the designing and manufacturing process of the transformer [12, 13].

In this study, to reduce the use of the copper in a high power transformer, a different winding arrangement is used and multiple analyses are made to determine the optimum distance between tap winding and additional winding.

The main aim of this study is to minimise the size of the high voltage transformer and to reduce the stresses, by using two different materials for the insulation. During the design of the transformer, the tap winding was split into two and additional winding was split into three. After designing the transformer by using the finite element method (FEM), a prototype transformer was manufactured and all the required tests were performed and verified. After an experimental verification; it is proven that optimum solution suggestion is successfully applied for the designing of the high voltage transformer.

2 Impulse distribution in power transformers

Impulse distribution in power transformers is a key factor in the design and test stages of the transformers. Transformer insulation must withstand all the excessive voltages which occur during the operational life of a transformer. Before connecting a transformer to a power system and electrical grid, different tests are performed in the factory to ensure the reliability and stability of a transformer.

It is expected from the transformer to deliver continuous power to the network, any mistake in the design stage can cause significant financial loss to the electric providers and affect the working and stability of the power system. During the design of the transformer, different dielectric tests are performed such as switching impulse (SI), basic lightning impulse (BIL), long and short-duration power-frequency test with partial discharge measurement. The insulation’s overvoltage withstand capability can be checked by SI, short-duration power-frequency test and lightning impulse. The insulation behaviour under the working voltage stress can be checked by performing the long duration test. The design of insulation between various electrodes is decided by one or more of these test levels [14].

During the actual operation of the power system, the transformer may be subjected to lightning impulse and superimposed AC voltages [14]. Bellaschi and Teague [15] report the dielectric strength under lightning stress levels and superimposed AC voltages. The breakdown voltage under the lightning impulse alone can be significantly higher than the corresponding value for the superimposed stress condition. Lightning distribution mainly depends on the physical specifications of the conductor, the distance between the conductors and dielectrics around the conductor.

A transformer receives voltage pulses under impulse conditions. These voltage pulses contain high-frequency components that produce capacitive effects, which cannot be found in the normal operating frequencies. The transformer windings respond to lightning distribution mainly as a system of capacitance network. There are two capacitances of windings, which effect the lightning distribution, namely, series capacitances \((C_s)\) and capacitances to earth \((C_e)\). The voltage distribution on the winding depends on the series capacitances, capacitances to earth, and the winding inductance \((L)\). Equation (1) shows the stress distribution on the winding

\[
\frac{C_e}{L} \frac{d^2 v}{dx^2} + \frac{14}{L} \frac{dv}{dx} - \frac{C_s}{L} \frac{dv}{dx} = 0
\]

The voltage at any point of the winding can be calculated by using (2) [1]

\[
v(x) = U \left( \frac{\sinh \left( \frac{\alpha x}{L} \right)}{\sinh \alpha} \right)
\]

where \(U\) is the amplitude of the applied voltage at the winding terminal and \(L\) is the length of the winding. The concentration of the voltage distribution in a winding is governed by the factor \(\alpha\). Factor \(\alpha\) can be represented by (3) [16]

\[
\alpha = \sqrt{\frac{C_s}{C_e}}
\]

The transformer’s insulation structure under power frequency can be expressed as a static electric field [17] which is given by the following equation:

\[
E = - \nabla \phi
\]

where \(E\) is the electric field intensity, and \(\phi\) is the applied potential. Space charges are not normally present in most of the high-voltage applications, and hence the potential distribution is governed by the Laplace’s equation, as shown in the following:

\[
\nabla^2 \phi = 0
\]

Equations (7) and (8) show the boundary conditions between the two different dielectrics

\[
\phi_1 = \phi_2,
\]

\[
\varepsilon_1 \frac{\partial \phi}{\partial n} = \varepsilon_2 \frac{\partial \phi}{\partial n}
\]

where \(\varepsilon_1\) and \(\varepsilon_2\) is the permittivity of the first and second dielectric, respectively. In recent years, several numerical methods have been developed to solve the partial differential equations, including Laplace’s equations. There are inherent difficulties in finding solutions in 2D or 3D for complex boundary conditions or for systems of different insulation materials. The proper design of high voltage transformers and other systems requires complete knowledge of the distribution of the electric field. It is possible to solve the simple physical systems with an analytical solution. However, when the physical system becomes complex, numerical methods are more appropriate to calculate the electric fields as compared to the analytical solution [18].

Oil has the minimum dielectric stress level of all components in the transformer. Kappeler proved that the breakdown strength of an oil gap, expressed in kV/mm decreases exponentially when the gap width is increased, as shown in Fig. 1 [19]. The ability of the oil to withstand electric discharges is reduced with distance, i.e. when the distance of winding to another winding increases, the dielectric strength of oil reduces. Due to this property of the oil, insulation is one of the most important concerns for the transformer designers for the modelling of the high voltage transformer. Therefore, just oil cannot be used as an insulation material between the two conductors in the high voltage transformers. Insulation material like pressboards must be placed accordingly to minimise insulation problems.

The breakdown of electric stress in transformer oil is decreased with the increase in the moisture, cellulose fibres particles, and dissolved gases in the oil. It is difficult to give a perfect mathematical expression for the calculation of breakdown electric strength. Electric stress can be predicted by analytic equations developed according to the experimental studies. Most studies are focused on experimental studies and some approaches are given in these studies. The power-law function can be used to calculate the breakdown strength \(E\) (kV/mm) at the particular gap distance [20] and \(E\) is given by the following equation:

\[
E = Ad^{-n}
\]
where \( d \) is the gap distance in millimetres, where the breakdown strength to be calculated. \( A \) and \( n \) are constants depending on the characteristic of electrode geometry, and shape of impulse voltage.

### 3 Arrangement for high voltage winding with additional winding and tap winding

In a standard additional winding transformer, the additional winding can be placed adjacent to the high voltage winding. However, during the presence of tap winding, there are two possible ways to place the additional winding, i.e. before tap winding or after tap winding.

If the additional winding is placed before tap winding, as shown in Fig. 2a, the outer diameter of tap winding will increase and that will result in more copper. If additional winding would be placed after tap winding, as shown in Fig. 2b, it will require more copper from tap winding to on-load tap changer (OLTC). Also, the distance between tap winding and additional winding needs to be increased because taps must go to OLTC from top and bottom, and cannot go through the additional winding. Also, eddy losses caused by the tap winding effect the additional winding losses. Generally, additional windings are larger than the tap windings, and this position will increase the use of the copper and increase the overall cost and copper losses of the transformer.

Another way of placing additional and tap windings is to put on each other (in the same sequence) with the same inside diameter; this position can minimise all problems. Fig. 3 shows that type of arrangement. The distance between windings must be selected carefully so, in overvoltage situations, insulations must not be affected.

If additional winding is separated into three parts for equal magnetic balance; tap winding is divided into two parallel branches for the same reason. More separations could be made to reduce the induced voltage on winding parts, but it will increase manpower for the transformer.

The most crucial part for designing the tap and additional winding together is to make the two windings with the same inner and outer diameter. This is one of the most important steps because if there is a difference occurs in winding size; it will cause additional forces in short-circuit conditions and winding can be deformed and affect the working and stability of the power system.

The distance between tap winding and additional winding is also a key factor.

Another advantage of this design is that less copper will be used for the designing of the transformer. Approximately 2 tonnes of less copper will be used in the proposed design as compared to the previous standard design, as shown in Fig. 2. The proposed design will also decrease the size of the transformer and less oil, core and tank materials will be needed.

### 4 Analysis and results

In this study, the FEM was used to optimise the distance between the tap and additional windings. FEM is a numerical method, which can be used for the solutions of mathematical, physics and engineering problems. FEM is a useful and widely used tool for solving electromagnetic problems in the design of power transformers. Approximately a large percentage of transformer failures are caused by insulation deformations due to excessive electrostatic stress of the insulation. FEM provides a more accurate measurement of electrical stress.

There are lots of software available to simulate and calculate the power transformer's lightning impulse distribution. In this study, SLIM FEM program is used to determine the distribution of impulse through different materials. Finding voltages between the windings was the first part of the simulation. The second part was to calculate withstand ability of oil and other dielectric parts to voltage stress.

Another major concern at the design stage is that additional winding also effects when it is not in use. Additional winding will not be earthed when it is not in operation and voltage can be induced on its ends. So splitting winding in more than one part is also a good solution to this problem because fewer turns will induce fewer voltages.

In this work, both additional winding and tap winding are designed as disc winding. A simple layout of winding is shown in Fig. 3.

Another advantage of this design is that less copper will be used for the design of the transformer. Approximately 2 tonnes of less copper will be used in the proposed design as compared to the previous standard design, as shown in Fig. 2. The proposed design will also decrease the size of the transformer and less oil, core and tank materials will be needed.
test, lightning impulse test (BIL), long-duration frequency test and short-duration power frequency test with partial discharge measurement [14].

In Fig. 3, the current direction is shown by big black arrows. The red rectangle box shows the connection to be able to change the voltage level from 300 to 420 kV. The insulation level of neutral point and winding is also an important design parameter for the high voltage transformer. Windings insulation can be uniform or non-uniform. If all ends of the winding connected to terminals have the same rated insulation level, that kind of insulation is known as uniform insulation of a transformer. If the neutral terminal end for direct or indirect connection to the earth, and is designed with a lower insulation level than assigned for the line terminal, this kind of insulation is known as non-uniform insulation of a transformer winding [21].

In graded insulation, mostly the entrance of the winding withstands maximum value. Winding impulse levels reduces more than its 3/4 value when it reaches to the middle of the winding [14]. This varies with the type and layout of the winding such as disc, interleaved disc, and layer. In this study, SLIM FEM software was used to calculate the BIL levels, as shown in Fig. 4. The only additional winding situation could be simulated since it is expected to have more effect on additional and the fine (tap) winding. Also, a lightning impulse is greater when the additional winding is in operation.

Transformer designers use the design impulse level (DIL) to simplify the insulation design process. Four test values will be converted to one equivalent test level, which is the maximum of equivalent one-minute power-frequency voltage levels during the four different tests [14].

The results show that the highest impulse was not on the additional winding, which was close to the high voltage winding. The highest impulse, 632 kV was between the second part of additional winding and the first part of tap winding, as shown in Fig. 4.

When calculated highest impulse values converted to DIL levels (via dividing these values by 2.4); an analysis level of 272 kV would be calculated. Analyses will be made with this value and the part of the winding where the maximum DIL level occurs.

Results show the probability of electrical discharge in the windings. For most electrical heat tracing design, safety factors specified are, in fact, between 10 and 50% [22]. For the transformer, a 10% margin between oil dielectric strength and impulse distribution is accepted as safe.

This transformer's design allows distances up to 50 mm. After 50 mm, the transformer will be more expensive and the outer diameter of the active parts and transformer tanks will also be increased. However, finding a distance of fewer than 50 mm will decrease the cost and weight of the transformer.

For the first simulation, the shortest distance between additional and tap winding (Path B) was taken as 30 mm. However, from the FEM analysis, the distance safety margin was calculated as 7%. This margin is not acceptable on withstanding impulses for high voltage transformers since the transformer operates at high voltages, a 7% safety margin can be risky. The distance was increased up to 34 mm and for the distance of 34 mm the safety margin was less than ten.

During the second part of the simulation, the shortest distance (Path B) was taken as 36 mm because the safety margin for 35 mm was calculated as approximately ten and for safety reasons 36 mm was taken instead of 35 mm. Fig. 5 shows the placement of cellulose materials for 36 mm.

In Fig. 5, pink(1), blue(2), green(3) and red(4) elements show end ring, angle rings, insulation paper of copper and simulation path, respectively. End ring, angle rings and insulation paper all are made from the pressboard (cellulose) based material and non-conductor. During the simulation, the distance safety margin was calculated as >10% for each of the winding.
To compare the results of the distance between the tap and additional winding, 45 mm was also examined. The main aim of taking 45 mm is to compare the results of the optimised distance with a higher distance. The placement of cellulose materials for 45 mm is shown in Fig. 6.

The distance can be increased up to 50 mm for more safety margin, but it will just increase the cost and the size of the transformer as 36 mm shows satisfactory results.

### 4.1 Comparison of the results

Optimisation of the distance between the tap and additional winding mainly affects the maximum stresses, price, and weight of the transformer. The simulation results of maximum stress of the 36 and 45 mm are shown in Figs. 7 and 8.

The comparison of the price for the distance of the 30, 36, 45, and 50 mm between the tap and additional winding is shown in Table 1.

Results show that by using a 36 mm distance between the tap and additional winding, the price of the transformer has decreased by 1041 € as compared to the 50 mm difference. The negative sign in the table shows that the price of the transformer with a distance of 30 mm will be 363 € cheaper as compared to the 36 mm distance between the tap and additional winding. The difference in the price between the distance of 36 and 45 was 678 €.

Table 2 shows the comparison of the weight for the distance of the 30, 36, 45, and 50 mm between the tap and additional winding.

Results show that by using a 36 mm distance between the tap and additional winding, the weight of the transformer has decreased by 700 kg as compared to the 50 mm difference. On the other hand, a negative sign shows that the weight of the transformer with a distance of 30 mm will be 238.7 kg lesser than the 36 mm distance between the tap and additional winding. The difference in the weight between the distance of 36 and 45 mm was ~461.6 kg.

### 4.2 Analysis results of the optimised distance

This section shows the stress analysis and safety margin results by taking a 36 mm distance between the tap and additional winding. Fig. 9 shows the simulation results of the electric potential distribution for the 30 mm distance between the tap and additional winding. However, 30 mm distance between the tap and additional winding did not fulfil the standard of the minimum safety margin due to which distance between the tap and additional winding cannot be taken as 30 mm.

The FEM results show that the optimised distance between the tap and additional winding can be taken as 36 mm because it fulfils the standard of the minimum safety margin and it is also cheaper and lighter as compared to the 45 and 50 mm. There are three main and risky paths between additional winding and fine winding, i.e. A, B, C, as shown in Fig. 10. The middle path (Path B) is one of the riskiest and suspicious for discharge as the windings are close to each other.

During the simulation, the 272 kV DIL level was entered from point I. The voltage at point II will be equal to zero because, during the manufacturing of the transformer, this winding (point II) will be earthed.
The analysis was considered for two different conditions, i.e. oil with dissolved gasses and oil without dissolve gasses. Oil with dissolved gasses is riskier because dissolved gasses create (shortens) discharge paths. Both conditions are considered to make the analysis more realistic for transformer windings.

In Fig. 11, green dots, red lines and orange lines show the stress values of impulse at specific distances, dielectric strength curve of oil with dissolved gasses inside, and dielectric strength curve without dissolved gasses in oil, respectively. The results show that the stress values of impulse reduce with distance, but the slope of the oil curve is much higher than the slope of the impulse stresses. For path A, there are two different insulation materials with different dielectric strength. Fig. 12 shows the placement of insulation materials.

![Electric potential distribution of 36 mm](image1)

**Fig. 10 Electric potential distribution of 36 mm**

![Analysis results for the first path (path A)](image2)

**Fig. 11 Analysis results for the first path (path A)**

![Physical model of insulation for path A](image3)

**Fig. 12 Physical model of insulation for path A**

| Insulation material | Dielectric constant | Permittivity ε (F/m) × 10⁻¹² |
|--------------------|---------------------|-------------------------------|
| transformer oil    | 2.2                 | 19.47                         |
| pressed paper      | 4.2                 | 37.17                         |

**Table 3 Dielectric parameters of pressboard and oil**

The analysis was considered for two different conditions, i.e. oil with dissolved gasses and oil without dissolve gasses. Oil with dissolved gasses is riskier because dissolved gasses create (shortens) discharge paths. Both conditions are considered to make the analysis more realistic for transformer windings.

In Fig. 11, green dots, red lines and orange lines show the stress values of impulse at specific distances, dielectric strength curve of oil with dissolved gasses inside, and dielectric strength curve without dissolved gasses in oil, respectively. The results show that the stress values of impulse reduce with distance, but the slope of the oil curve is much higher than the slope of the impulse stresses. For path A, there are two different insulation materials with different dielectric strength. Fig. 12 shows the placement of insulation materials.

![Physical model of insulation for path B](image4)

**Fig. 13 Physical model of insulation for path B**

![Analysis results for the second path (path B)](image5)

**Fig. 14 Analysis results for the second path (path B)**

The dielectric parameters of the pressed paper and oil are shown in Table 3.

The total distance of path A was ~45 mm. Distance to the curve of impulse distribution is closest in the first part, at the distance of about 9 mm, curves get closest. At this point, the safety margin is calculated as 17.7%. This is concluded as very safe.

Secondly, the middle path (B) in Fig. 5 is analysed. This path is the closest path between two windings. This path is one of the most dangerous paths. However, due to the nine insulation protection, this path will not be as dangerous as expected. Fig. 13 shows the physical model of the path B.

Fig. 14 shows the analysis results for path B from the point I to II. For this path, the size of end rings was just 1 mm and ends rings were omitted in the results section. The total distance of path B was 36 mm. Impulse stress is nearly constant. This time; oil with the dissolved gas curve is closest to impulse stress at point II (close to 36 mm). At this point, the safety margin was calculated as 11.5%. Again, this result is accepted as safe. Customers generally ask for the safety margin close to 10% due to economic reasons.

Finally, the last part of Fig. 5 is analysed. We are expecting better results from the first path. Even if the paths are nearly equal (41 mm), there is more insulation protection on this path. This time, the end ring is considered too. The results are shown in Fig. 15.

The closest point of oil withstands ability to impulse stress is at the 39th millimetre of the path. The results of this analysis show the highest safety margin. The safety margin was calculated as 44.1%.

The simulation results show that 36 mm distance between the additional and tap windings fulfils the standard of the minimum safety margin. By decreasing the distance between the tap and additional winding to 36 mm, the transformer will become cheaper and lighter as compared to the 50 mm.
4.3 Experimental results

In this study, the distance between additional tap winding was optimised with the help of a FEM for the high voltage transformer with a power of 100 MVA and a voltage level of 300(420)/63/34 kV with YNyn0d11 connections. After finding the simulation results satisfactory, the transformer was manufactured with a similar distance at the BEST transformer, Turkey. The side view of the transformers is shown in Fig. 16.

All the tests of the transformers were performed at the BEST transformer laboratories, which are equipped with state-of-the-art testing devices. All the procedures and routine tests are conducted on the transformer following TS 267 and IEC-60076 standards. Fig. 17 shows the setup of the transformer during the experimental tests.

The tests which were conducted on the transformers are applied voltage test, basic insulation level, conversion ratio measurement and connection group assignment, DC insulation resistance measurement, induced voltage test, loss angle and capacitance measurement, no-load loss and no-load current measurement, on-load loss and short-circuit voltage loss, SI test, voltage regulation and efficiency measurement tests, and winding resistance measurement.

SI test and lightning impulse test are the most important tests to determine the insulation strength of the transformer. A standard impulse wave is defined in IEC-60076 [21, 23] and illustrated diagrammatically in Fig. 18. Fig. 18 shows the time parameters of the standard impulse voltage. In Fig. 18, point 0’ is known as virtual origin, which is instant at which a straight line is drawn through the 30 and 90% (point X and Y) and passes to the timeline [23]. The time T is the instant time when the impulse is between 30 and 90% of the peak value. The front time T1 is the time taken by the voltage to reach to its 1′ (virtual maximum value) starting from 0′ (virtual origin) and it is ∼1.67 times of the time T. A time interval from the 0’ to the maximum value of a voltage is known as the peak time (Tpeak). The tail time T2 is the time interval between the 0’ and the instant when the voltage has first decreased to half the maximum value of the voltage.

The standard lightning impulse voltage is a lightning-impulse with a front time (T1) of the 1.2 µs with a tolerance of ±30% and it has the tail time (T2) of 50 µs with a tolerance of ±20%. Table 4 shows the experimental results of the lightning impulse test of the transformer.

The SI test was performed at the laboratory to confirm the withstand of the transformer's insulation against excessive voltages which mainly occur during the switching. During the test of the SI voltage test, the insulation between windings, winding and earth and withstand between different terminals of the transformer was checked.

According to the IEC 60076-4, there are no strict values specified for the T1 of a SI voltage. However, it should be sufficiently long enough to ensure essentially uniform distribution of voltage. This condition generally requires front times of 100 µs or more [21, 23]. Another important time for the SI voltage is Td. Td is the instant time when the impulse is above 90%, as shown in Fig. 18. According to the IEC 60076-4, Td must be greater than or equal to 200 µs and the tail time T2 must be greater than or equal to 500 µs. Table 5 shows the experimental results of the SI test of the transformer.

The voltage test was also performed for the rated frequency and higher frequency according to the IEC 60076 [21]. The summary of the voltage test at the rated frequency and higher frequency is shown in Table 6.
There was no collapse of the test voltage occurs during the voltage test and transformer passed all the routine tests.

5 Conclusion

Finite element analysis shows that the selected distance 36 mm is enough for safe operation. It could be increased if more safety margin is required, but as stated, 10% is enough for safe operation. The manufacturing process of the high power transformer and material quality is also very crucial. In any case of an error in insulation material, dielectric strengths can be affected. By using the proposed design, at least 2000 kg of less copper will be used as compared to the previous standard design. Copper losses of the transformer are also reduced due to the less use of the copper.

The suggested layout minimises the size and weight of the transformer. Optimisation of the transformer's windings not only decreases the size of the transformer but also decreases its cost. The lifetime of the transformer will also be increased by minimising the transformer losses. The FEM results are also verified by making a prototype transformer. Experimental results show that the suggested distance is safe for future lightning and overvoltage situations.

6 Acknowledgments

The authors acknowledge the contributions of Balikesir Elektromekanik Sanayi Tesisleri AŞ (BEST Transformer) for manufacturing transformer with the suggested layout.

7 References

[1] Meslehodini, M.R., Shahmohammadi, A., Majidi, M., et al.: 'Comparative study of the effect of various shields on lightning electric field in power transformer windings'. IEEE Trondheim PowerTech, Trondheim, Norway, June 2011, pp. 1–4
[2] Banerjee, C.M., Dutta, S., Baral, A., et al.: 'Time-varying model for the effective diagnosis of oil-paper insulation used in power transformers', IET Gener. Transm. Distrib., 2019, 13 (9), pp. 1527–1534
[3] Khaligh, A., Vakilian, M.: 'Power transformers internal insulation design improvements using electric field analysis through finite-element methods', IEEE Trans. Magn., 2008, 44 (2), pp. 273–278
[4] Zitouni, M., Guerbou, F., Boukezzi, L., et al.: ‘Modelling by design of experiments method of the AC breakdown voltage of transformer oil point-plane gaps with insulating barrier’, IET Gener. Transm. Distrib., 2016, 10 (1), pp. 232–239
[5] Yea, M., Han, K.J., Park, J., et al.: ‘Design optimization for the insulation of HVDC converter transformers under composite electric stresses’, IEEE Trans. Dielectr. Electr. Insul., 2018, 25 (1), pp. 253–262
[6] Florkowski, M., Furgal, J., Kaniewski, M.: ‘Propagation of overvoltages in distribution transformers with silicon steel and amorphous cores’, IEEE Trans. Transm. Distrib., 2015, 9 (16), pp. 2760–2767
[7] Sima, W., Sun, P., Yang, M., et al.: ‘Impact of time parameters of lightning impulse on the breakdown characteristics of oil paper insulation’, High Volt., 2016, 1 (1), pp. 18–24
[8] Dombeck, G., Nadolny, Z.: ‘Measurements of the selected thermal properties of insulating liquids used in the high voltage power transformers’, Comput. Appl. Electr. Eng., 2013, 31 (2), pp. 189–198
[9] Cui, Y., Ma, H., Saha, T., et al.: ‘Multi-physics modelling approach for investigation of moisture dynamics in power transformers’, IET Gener. Transm. Distrib., 2016, 10 (8), pp. 1993–2001
[10] Yang, Q., Chen, Y., Han, R., et al.: ‘Transient overvoltage response performance of transformer windings with short-circuit fault’, IET Gener. Transm. Distrib., 2018, 12 (10), pp. 2265–2272
[11] Abbasi, E., Malik, O.P.: ‘Failure rate estimation of power transformers using inspection data’. Int. Conf. on Probabilistic Methods Applied to Power Systems, Beijing, China, October 2016, pp. 1–4
[12] Zienkiewicz, W.: ‘Transformer electrical insulation’, IEEE Trans. Dielectr. Electr. Insul., 2012, 19 (6), pp. 1841–1842
[13] Prevost, T.A., Oommen, T.V.: ‘Cellulose insulation in oil-filled power transformers: part I – history and development’, IEEE Electr. Insul. Mag., 2006, 22 (1), pp. 20–35
[14] Kulkarni, S.V., Khaparde, S.A.: ‘Transformer engineering: design, technology, and diagnostic’ (CRC Press, New York, USA, 2016, 2nd edn.)
[15] Bellaschi, P.L., Teague, W.L.: ‘Dielectric strength of transformer insulation’, Trans. Am. Inst. Electr. Eng., 1957, (57), pp. 164–171
[16] Güzelbeyoğlu, N.: ‘Improvements to impulse distribution in transformer windings’. PhD dissertation, Istanbul Technical University, 1975
[17] Youhua, G., Dan, G., Yanbin, L., et al.: ‘Impact of time parameters of lightning overvoltages on the transient response of insulating liquids used in the high voltage power transformers’, IET Gener. Transm. Distrib., 2016, 10 (8), pp. 1993–2001
[18] Naidu, M.S., Kamaraju, V.: ‘High voltage engineering’ (McGraw-Hill Education, New Delhi, India, 2004)
[19] Tschudi, D.J., Schultz, K., Prevost, T., et al.: ‘Experimental evidence of transformer insulation design methods’. Int. Symp. on High Voltage Engineering, Quebec, Canada, August 1997
[20] Liu, Q., Wang, Z.D.: ‘Breakdown and withstand strengths of ester transformer liquids in a quasi-uniform field under impulse voltages’, IEEE Trans. Dielectr. Electr. Insul., 2013, 20 (2), pp. 571–579
[21] IEC 60076-3: ‘Power transformers – part 3: insulation levels, dielectric tests and external clearances in air’, 2018
[22] IEC 60076-4: ‘Power transformers – part 4: guide to the lightning impulse and switching impulse testing – power transformers and reactors’, 2002

Table 5 Experimental results of the SI test

| Winding | Voltage, kV | $T_1$, µs | $T_6$, µs | $T_2$, µs | Result |
|---------|------------|-----------|-----------|-----------|--------|
| HV      | 734.2      | 211.6     | 293.4     | 2220      | succeed |
| HV      | 1050       | 212.7     | 293.3     | 1900      | succeed |

Table 6 Voltage test at rated and higher frequency

| Winding | Voltage, kV | Frequency, Hz | Time, s | Result |
|---------|------------|--------------|--------|--------|
| HV + Add| 140        | 50           | 60     | succeed |
| HV + Add| 570        | 130          | 47     | succeed |