Technical and economical evaluation of distribution transformer with amorphous metal core in Indonesia

B B S D A Harsono*, J Hartono, N W Priambodo, H B Tambunan, D R Jintaka, K M Tofani and M Ridwan
Transmission and Distribution Department, PLN Research Institute, Jakarta, Indonesia

*brian.adiputro@pln.co.id

Abstract. High efficiency electrical equipment usage is an alternative solution to support carbon emission reduction in Indonesia. In this research, new distribution transformer design using amorphous metal core (AMDT) was evaluated by conducting laboratory testing and field installation. According to the laboratory test result upon 4 samples, AMDT had 60.91 – 67.35% smaller no-load loss but 0.58 – 9.79% higher load loss compared to national standard requirement (although the load loss value of AMDT was within total losses tolerance). One AMDT sample failed during impulse test which should be followed up further by conducting insulation testing and design evaluation. Since the AMDT sample used 5-legged core design, the weight of the AMDT was heavier than conventional cold rolled grained oriented (CRGO) silicon steel transformer; thus, the construction planning and design should be re-evaluated for AMDT installation. According to total cost calculation based on life cycle approach by using obtained data and related assumptions, it was found that AMDT would potentially give higher economic benefit than conventional CRGO silicon steel transformer when the load factor (LF) is below 79% for 100 kVA AMDT, below 78% for 50 kVA AMDT, and below 68% for 25 kVA AMDT.

1. Introduction

According to the reference, national electrification data of Indonesia in 2018 is approximately 98.3% with 100% target at 2020 [1]. In the future, the addition of distribution transformer on the existing grid is no longer to achieve 100% electrification ratio but to improve the reliability of distribution grid by reducing the load factor of each individual installed distribution transformer. On the other hand, low loss transformer with amorphous core (AMDT) has become an alternative approach to introduce more efficient transformer [2-4]. Previous research had conduct in depth economic comparison between AMDT and conventional CRGO transformer, with consideration of annual owning cost which include initial cost, financial value of no-load and load loss, and several assumptions regarding load factor and transformer lifetime [4-7]. Load factor is very specific to the distribution transformer installation location; since there’s no research been conducted to evaluate specific load factor for economic evaluation of distribution transformer in Indonesia, this research was conducted to provide required data for better economic evaluation of distribution transformer (both conventional distribution transformer and AMDT) in Indonesia. In this research, 4 samples of amorphous metal distribution transformer (AMDT) was tested on laboratory and 3 of them were installed on the existing grid to evaluate the operational characteristic. The output of the laboratory testing and field installation were compiled and used to calculate the economical evaluation of the AMDT compared to conventional cold rolled grained oriented (CRGO) transformer which stated on national standard SPLN D3.002-1 [8].
2. Method
The proposed evaluation process requires two main parts: technical/performance evaluation and economical evaluation. For technical/performance evaluation, laboratory testing and field installation were performed. For laboratory testing, several tests were conducted to evaluate the no-load loss and the load loss performance of the AMDT (e.g., winding resistance, no-load loss test, and load loss test). The result was evaluated to check the characteristic of no-load loss and load loss of AMDT toward the requirement as stated in national standard. On-field installation was conducted to obtain load factor (LF) profile of the distribution customer which latter also be used along with laboratory data to evaluate the AMDT in economical perspective. Economical evaluation proposed in this paper considered the life cycle phase which stated in IEC 60300-3-3 [9]. The annual life cycle cost for a certain lifetime was projected to present value to obtain the owning cost of AMDT. Comparison with owning cost of conventional iron core distribution transformer is performed with load factor variation.

3. Results and discussion
3.1. Distribution transformer economic evaluation
3.1.1. Distribution transformer losses. Losses of distribution transformer can be divided into two parts, namely No-load loss and Load loss. No-load loss is reactive power which is absorbed by the transformer when nominal voltage is applied to any of the winding with other winding left open. On operational condition, no-load loss present when the distribution transformer is energized and have independent correlation with load current. Load loss is active power which is absorbed by the transformer when nominal current flow on the any winding when the other winding being short circuited. On operational condition, load loss present when the distribution transformer is supplying load and have dependent correlation with load current.

3.1.2. Distribution transformer with amorphous metal core. Distribution transformer with CRGO core takes major portion in world distribution grid. With the development of material science technology, amorphous metal is used to replace the iron material in conventional distribution transformer. According to the reference, amorphous metal has higher specific resistance and smaller B-H curve compared to CRGO; hence, amorphous metal lowers the hysteresis component of magnetic losses [2-3]. Smaller B-H curve reduce the no-load loss of the AMDT up to 70-80% lower than CRGO transformer [2-4]. However, amorphous metal has several drawbacks: low magnetic induction saturation, thermal instability, mechanical brittleness, and low stacking factor [10-11].

3.1.3. Economical evaluation of distribution transformer. The economical evaluation of an equipment should consider every cost in each life cycle phase. Referring to IEC standard, there are 6 cycle of an equipment: concept and definition, design and development, manufacturing, installation, operation and maintenance, and disposal [9]. According to reference, those cycle can be reflected into 3 cost components: initial cost, operating cost and disposal cost [12]. On the other hand, total owning cost (TOC) is a common method to evaluate the economic characteristic of electrical equipment such as distribution transformer [9]. TOC method combines the economic value of initial acquisition and financial value of transformer losses during its lifetime by using following Equation [13].

\[
TOC = I_c + A \cdot P_0 + B \cdot P_k
\]

\[
A = \frac{(1+i)^n-1}{i(1+i)^n} \cdot C_{kwh} \cdot HPY
\]

\[
B = \frac{(1+i)^n-1}{i(1+i)^n} \cdot C_{kwh} \cdot HPY \cdot \left(\frac{I_l}{I_p}\right)^2
\]
Where $I_C$ is initial acquisition cost of the transformer (currency), $A$ is the financial value of no-load loss (currency/kW), $P_n$ is no-load loss (kW), $B$ is the financial value of load loss (currency/kW), $P_L$ is load loss (kW), $i$ is interest rate (%), $n$ is the lifetime of the transformer (year), $C_{kwh}$ is energy cost (Currency/kWh), $HPY$ is operational hours of the transformer in a year, $I_l$ is loading current (A), and $I_r$ is rated current (A).

3.1.4. Laboratory testing, field installation and economical evaluation result. Four samples of AMDT, namely: sample A (AMDT 100 kVA from manufacture A), sample B (AMDT 100 kVA from manufacture B), sample C (AMDT 50 kVA), and sample D (AMDT 25 kVA), were tested on the laboratory. To verify the dielectric quality of the sample before field installation, all samples was tested with standard lightning impulse with 125 kV BIL. Both laboratory result and operational data record on the field were used as parameter in the economical evaluation afterward.

3.1.5. Laboratory testing. Both no-load and load loss of distribution transformer can be measured by conducting laboratory testing, where the supply was injected on the primary winding with the secondary winding is either open (for no-load loss test) or short circuited (for load loss test). Rated voltage is applied on the primary side (20 kV) for no-load loss test, while rated current is applied on the primary side for load loss test. As a part of load loss test, the winding resistance test and also temperature measurement were performed during testing; this part become important aspect due to the fact that load loss was presented at $75^\circ$ C value. The result of the no-load loss test is shown in Table 1 and Table 2.

| Table 1. No-load loss test result. |
|-----------------------------------|
| Sample A | Sample B | Sample C | Sample D |
| No-load loss (W) | 68.57 | 79.02 | 44.46 | 29.32 |

| Table 2. Load loss test result. |
|----------------------------------|
| Load loss with Test Current correction ($P_{corr}$) | Unit | Sample A | Sample B | Sample C | Sample D |
| Correction factor 75°C ($\alpha_2$) for Al | Watt | 1,279.934 | 1,225.857 | 708.293 | 397.946 |
| Correction factor 75°C ($\alpha_2$) for Cu | - | 1.1798637 | 1.1809474 | 1.1741683 | 1.1789363 |
| Load loss at 75°C ($P_{LL, 75^\circ}$) | Watt | 1,491.276 | 1,428.173 | 826.240 | 466.621 |

3.1.6. Field installation. Standard 1.2x50 microsecond impulse test were performed on 4 AMDT sample before installation process. With 125 kV impulse voltage injected to the primary side, sample D failed with explosion sound from the inside of the tank which might indicate internal insulation breakdown. Therefore, only 3 AMDT sample were installed on the existing distribution grid. Recording device was equipped on each sample to record power, energy, and also load factor. The recorded data is shown in Table 3.

| Table 3. Field installation recording result. |
|---------------------------------------------|
| AMDT | Sample A | Sample B | Sample C |
| Total Energy (Watt Hour) | 58,694,680.96 | 4,963,383.45 | 15,657,637.37 |
| Recording time (hour) | 1936 | 126.25 | 383 |
| $W_{max}$ (Watt) | 96,525,7 | 93,730.69 | 48,383.81 |
| Load factor (LF) | 0.3141 | 0.4194 | 0.8449 |
3.1.7. Economical evaluation. As explained on chapter 3.3, the proposed economical evaluation used initial cost, maintenance cost and disposal cost. Since the distribution transformer in Indonesia was operated as run to fail asset, the disposal cost and maintenance cost for this evaluation is equal to zero. Therefore, the economical evaluation used 2 aspects: initial cost (consist of acquisition cost and installation cost) and annual cost (consist of financial value of no-load loss and load loss). According to laboratory test, field installation and related references, the parameter used for the economic evaluation can be assumed as follow:

- No-load loss and load loss for the AMDT calculation is based on the laboratory test result. For the conventional CRGO transformer, the no-load loss and load loss value is based on the national standard.
- Based on the field installation recording data (Table 3), the LF range used in the calculation is 31.41% - 84.49%.
- According to reference, life time of transformer is 20 years for load factor less than 65% [14]. Significant life time reduction occurred due to the increase of load factor e.g. 14 – 14.5 years for load factor 65 – 70% [15 – 18].
- The parameter of conventional CRGO transformer referred to national standard.

By using Equation (1), (2), and (3) in conjunction with explained assumption, the comparison of owning cost between AMDT and CRGO transformer for a certain range of load factor were presented in Table 4, Table 5, Table 6.

Table 4. Comparison of owning cost between AMDT and CRGO transformer (100 kVA).

| LF  | Lifetime (year) | Predicted owning cost | Potential benefit of AMmDT |
|-----|-----------------|-----------------------|----------------------------|
|     |                 | CRGO transformer      | AMDT                       |
| 77  | 9.425           | 201,633,380           | 200,981,667                | 651,713                    |
| 78  | 8.7             | 197,970,632           | 197,936,495                | 34,136                     |
| 79  | 7.975           | 193,843,514           | 194,439,315                | -595,801                   |
| 80  | 7.25            | 189,220,151.6         | 190,458,237.8              | -1,238,086                 |

Table 5. Comparison of owning cost between AMDT and CRGO transformer (50 kVA).

| LF  | Lifetime (year) | Predicted owning cost | Potential benefit of AMmDT |
|-----|-----------------|-----------------------|----------------------------|
|     |                 | CRGO transformer      | AMDT                       |
| 76  | 10.15           | 132,572,602           | 132,156,201                | 416,401                    |
| 77  | 9.425           | 130,720,106           | 130,668,813                | 51,293                     |
| 78  | 8.7             | 128,621,458           | 128,946,172                | -324,714                   |
| 79  | 7.975           | 126,259,633           | 126,971,538                | -711,905                   |

Table 6. Comparison of owning cost between AMDT and CRGO transformer (25 kVA).

| LF  | Lifetime (year) | Predicted owning cost | Potential benefit of AMmDT |
|-----|-----------------|-----------------------|----------------------------|
|     |                 | CRGO transformer      | AMDT                       |
| 66  | 19.34           | 108,655,302           | 108,298,153                | 357,149                    |
| 67  | 18.13           | 108,157,933           | 108,012,270                | 145,663                    |
| 68  | 16.92           | 107,516,122           | 107,587,380                | -71,258                    |
| 69  | 15.71           | 106,714,459           | 107,008,039                | -293,580                   |
3.2. Discussion

Based on the laboratory test result in Table 1, it is found that no-load losses of the AMDT is 60.91-67.35% lower than national standard as shown in Table 7. According to the reference, non-uniform atom structure of amorphous metal and the absence of crystalline structure give benefit for easier core magnetization process which increase the electrical resistivity 2-3 times compared to CRGO core [3]. According to test result in Table 2, load loss of AMDT is 0.58-9.79% higher than national standard; AMDT had low magnetic flux density value, therefore it had to either increase the core cross section or increase the length of the winding as compensation. However, the total loss of the AMDT was still within the requirement stated by national standard (Table 8).

| Rated capacity | National standard [5] | AMDT | decrease |
|----------------|------------------------|------|----------|
| 25             | 75                     | 29.32| 60.91%   |
| 50             | 125                    | 44.46| 64.43%   |
| 100            | 210                    | 79.02| 62.37%   |
| 100            | 210                    | 68.57| 67.35%   |

Table 7. No-load loss comparison of AMDT and national standard.

| Rated capacity | AMDT | National Standard |
|----------------|------|-------------------|
|                | No-load loss | Load loss | Total loss | No-load loss | Load loss | 5% tolerance |
| 100            | 68.57         | 1491.28   | 1559.85    | 210          | 1420      | 1711.5       |
| 100            | 79.02         | 1428.17   | 1507.19    | 210          | 1420      | 1711.5       |
| 50             | 44.46         | 826.24    | 870.7      | 125          | 800       | 971.25       |
| 25             | 29.32         | 466.621   | 495.941    | 75           | 425       | 525          |

Table 8. Total loss comparison of AMDT and national standard.

The increase of core cross section or winding length might affect the design and construction of the AMDT. All AMDT sample used in this research has 5 leg core which is 14 – 53% heavier than conventional CRGO transformer with 3 leg core design. This additional weight should be considered for construction evaluation before installing AMDT on the existing distribution grid. Another design evaluation needs to be considered is the dielectric strength which prevent the occurrence of short circuit during operational voltage and overvoltage event (e.g. switching overvoltage, lightning overvoltage). Since one of the AMDT sample failed during standard impulse test, further dielectric testing should be performed and initial design should be re-evaluated. Note that only 4 sample available for testing; therefore, more sample is required to obtain more comprehensive evaluation of AMDT technical characteristic.

Since the distribution transformer is run to fail asset in Indonesia, the economic evaluation relied on initial cost and annual financial value of the losses. Although the no-load loss of the AMDT is smaller than conventional CRGO transformer, the initial price of AMDT is higher (AMDT initial cost is ±1.4 times than conventional CRGO transformer). Therefore, AMDT would potentially give more benefit than conventional CRGO transformer if it’s operated at low load factor condition (<79% load factor for AMDT with rated capacity 100 kVA, <78% load factor for AMDT with rated capacity 50 kVA, and <68% load factor for AMDT with rated capacity 25 kVA). This calculation result showed that the load factor of the distribution grid should be considered before applying AMDT on the existing grid. In the future research, recorded load factor and life time data can be used to improve the economic evaluation accuracy for distribution transformer in Indonesia.
4. Conclusion
Technical and economic evaluation of AMDT is presented in this paper. Laboratory test result showed that AMDT would potentially satisfy the national standard. Further testing and more sample are required to evaluate AMDT technical characteristic more comprehensively. According to the calculation result, AMDT gives more potential benefit if it’s operated at load factor less than 80%. This value can be improved by adding another parameter or assumption which represent the real operational condition on the field.

References
[1] Rencana Usaha Penyediaan tenaga Listrik PT Perusahaan Listrik negara (Persero) Tahun 2016 s.d. 2025
[2] Kamaraj V V and Jayadev B 2004 Losses in Distribution Transformers and Benefits in Restructuring with Amorphous Core Technology National Power Systems Conference 669-674
[3] DeCristofaro N 1998 Amorphous Metal in Electric-Power Distribution Applications Material Research Society Bulletin 23 5 50-56
[4] Yurekten S, Kara A and Mardikyan K 2013 Energy Efficient Green Transformer Manufacturing with Amorphous Cores International Conference on Renewable Energy Research and Applications 534-536
[5] Eliasson A, Elving H and Ramanan V R 2010 Amorphous metal core material shows economic and environmental benefits when pre-existing transformers are to be replaced within vattenfall group’s distribution network IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe) 1-7
[6] Knutson T 2015 Conducting distribution transformer evaluations using the total ownership cost method IEEE Rural Electric Power Conference 97-101
[7] Agha A 2018 Economic Evaluation of Transformer Selection in Distribution System Jordan Journal of Electrical Engineering 88-99
[8] SPLN D3.002-1:2007 Spesifikasi Transformer Distribusi Bagian 1: Transformer Fase Tiga, 20 kV-400 V dan Transformer Fase Tunggal, 20 kV-231 V dan 20/√3 kV-231 V
[9] IEC 60300-3-3 Dependability management – Part 3-3: Application guide – Life cycle costing
[10] Ezure S, Imai Y, Sato H, Yamada S, Yamanaka K and Saito S 1994 Long-term reliability of amorphous alloy wound core distribution transformers IEEE transactions on power delivery 9 1 249-256
[11] Hasegawa R 2005 Applications of amorphous magnetic alloys. In Properties and Applications of Nanocrystalline Alloys from Amorphous Precursors 189-198 (Dordrecht: Springer)
[12] Jeromin I, Balzer G, Backes J and Huber R 2009 Life cycle cost analysis of transmission and distribution systems CIRED, Prag 8 11
[13] Carlen M, Xu D, Clausen J, Nunn T, Ramanan V R and Getson D M 2010 Ultra high efficiency distribution transformers IEEE PES T&D 1-7
[14] IEEE Std C57.91-1995 IEEE Guide for Loading Mineral-Oil-Immersed Transformers
[15] Rawal P and Pandya V 2015 Distribution Transformer Future Failure Prediction using Extreme value model International Journal of Engineering Research and Development 68-72
[16] Jimenez V A, Will A L, Gotay Sardiñas J and Rodriguez S A 2018 Adjustment of model parameters to estimate distribution transformers remaining lifespan
[17] Patel D 2018 Transformer Replacement Program Low-Voltage Dry-Type 25-300 kVA Transformer; Implementation Manual (Nationalgrid)
[18] Amrita A A N, Ariastina W G and Manuaba I B G 2018 Study of Transformer Lifetime Due to Loading Process on 20 kV Distribution Line Journal of Electrical, Electronic and Informatics 2 2 25-28