Systematic Design and Implementation of Large-Capacity Power Transformer

Yeong-Hwa Chang [a], Chang-Hung Hsu [a,b], Ching-Pei Tseng [c]

[a] Department of Electrical Engineering, Chang Gung University, Tao-Yuan, Taiwan, R.O.C.
[b] Department of Electric Machine, Fortune Electric Ltd, Co., Tao-Yuan, Taiwan, R.O.C.
[c] Department of Physics, Institute of Nuclear Energy Research, Tao-Yuan, Taiwan, R.O.C.
Corresponding author: Dr. Y.-H. Chang, Tel.: + 886-3-2118800-5315;
Fax: + 886-3-2118026; E-mail: yhchang@mail.cgu.edu.tw

Abstract: - In this paper, the design and implementation considerations of a large-capacity three-phase power transformer operating at 7.5MVA are investigated. Both of the silicon steel core and amorphous core are considered. Based on the measured magnetic properties, it is obtained that the lowest core loss occurs under the circumstance annealed at 360℃. Some practical considerations about the transformer design and core manufacturing are explained in detail. Experimental results illustrate that the amorphous-cored transformer has lower core loss than the counterpart of conventional silicon steel core transformer.

Key-Words: - Power transformer, amorphous core, core loss, core stacking.

1 Introduction

Power and distribution transformers are widely used in the world. Due to the reason of energy shortage, the total energy loss has been a typical research subject for the electrical power equipments such as motors and transformers [1]. In general, the energy loss of motors and transformers is almost equal to amount that a large-capacity power station provides. Basically, the major part of the energy loss is caused by the excitation of magnetic core. Hence, to improve the efficiency, materials with lower core loss are intended to be used. It was known that amorphous cores offer the potential of significantly reducing core losses of motors and transformers by more than 70% [2]. Also, during the process of electricity conversion, the core loss and CO_2 gas discharge of amorphous-cored transformers are relatively less.

In earlier age, when amorphous alloys were first fabricated by liquid quenching from the metal, practical applications were not considered seriously [3]. The first indication for possible use of this typical of materials was given by a successful quenching of an inexpensive Fe–P–C alloy, which was strongly ferromagnetic at room temperature. This alloy was somewhat brittle and therefore was not suited for practical use. This drawback was mitigated by adding composition material such as Si, Ge, Al, etc. to the Fe–P–C alloy, which in turn made the quenched alloys more stable.

The earlier equipment could make the material in a ribbon of up to only 2–3mm in width, again limiting its use. In last decade, wider ribbon 213mm with improved quality became available, which opened up possibilities of various applications in efficient energy-conversion devices including utility transformers. The utility transformers were operated at 1.7~1.9 (T) flux levels, which had to be reduced to make them more efficient. Fe-based amorphous metals have saturation inductions near 1.6 (T), which came closer to the decreasing operating flux induction of conventional silicon steel core transformers.

Although the energy crisis concepts have been appeared, energy demand and cost are increasing and will increase in future. In this viewpoint of energy saving, decreasing energy losses in the power transformer is a very important issue. In light of these emerging problems, amorphous metal-based transformers are playing a vital role in mitigating them. There are several amorphous alloys in market and among them the Fe-B-Si alloys have exhibited better performance in transformers core [4-6]. In fact, this amorphous alloy shows a remarkable advantage over conventional silicon steel in core loss and exciting power. Therefore, this paper intends to address the main aspects related to the design and implementation of a 7.5MVA, 228 kV/11.4 kV, 60 Hz amorphous-cored power transformer, built with a three-phase three-leg type configuration. Experimental tests are presented to compare the magnetic loss property with conventional steel cores.

The rest of this paper is organized as follows. In Section 2, some characteristics of ferromagnetic materials and the key aspects of transformer design are discussed. The ideas of core stacking are introduced in Section 3. The manufacturing of amorphous core and silicon steel core are addressed in Section 4. In Section 5, measurement results are provided for performance validation and comparision. The conclusion is given in Section 6.

2 Considerations of design

2.1 Magnetic properties of Fe-based amorphous materials

In this paper, the Fe-B-Si amorphous alloy SA1 is considered for the design of power transformer core. The magnetic properties of the ferromagnetic core materials, compared to the grain-oriented silicon steel, will be exploited by the B-H curves shown in Fig. 1. From Fig. 1, it can be seen that the saturation flux density of the grain-oriented silicon steel is about 2.0 (T). However, annealed at 360℃ with a DC magnetic field density 800A/m, the saturation flux density for the amorphous alloys is only 1.56 (T). Since the amorphous core has lower operational induction, the reduction of core loss is of concern. In practice, the operational magnetic induction is set about 1.35 (T). Thus the magnetic improvement of lower core loss and lower exciting power can be obtained.

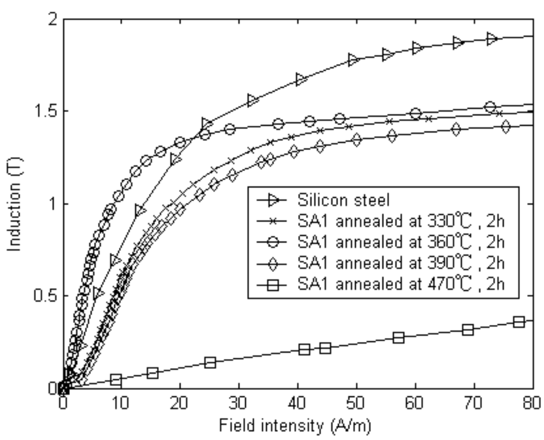


Fig. 1. The measured B-H curves.

2.2 Transformer design parameters

Magnetic induction and the impedance voltage ratio are essential to be determined for the design of transformers. These parameters are determined from estimates of suitable values for the magnetic flux density B_m, the full load of winding current for transformer. That depend on the way of transformers will be used, the next determine parameter are winding space factor and the stacking factor, respectively.

Besides, the primary and secondary windings parameter must be considered the window area. The winding space factor is defined by the ratio between the total conductor cross-section area and the window area. The full-load of winding current density is limited by conductor resistance loss and heat dissipation. The core stacking factor is defined by the ratio between the ferromagnetic material cross-section area and the total core cross-section area.

The thickness of a sheet of grain oriented silicon is normally higher than 0.9mm. The thickness of amorphous alloy ribbon is much smaller that causes possible uneven surfaces and the associated stacking factor is less than the counterpart of silicon steel (about 80% to 95%). In this paper, the addressed amorphous alloy SA1 is a product of the Hitachi Corporation, Japan. The geometric dimensions of the amorphous alloy core are shown in Fig. 2 (a), (b). The cross-section area of core is calculated as

$$A_C = \frac{10^4}{4.44 \times B_m \times f \times \delta} \cdot \frac{V}{N} \qquad (1)$$

where f is the power frequency, Bm is magnetic flux density in tesla, δ is core stacking factor, the V/N is volts per turn ratio, respectively. Fig. 2(c) illustrates the winding distribution. The voltage per turn of the winding is calculated as

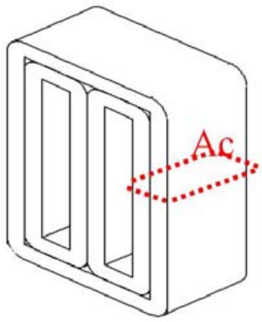
$$V/T = \left\{ \frac{0.395 \times E_{kVA} \times \left(\frac{\alpha_1 + \alpha_2}{3} + \alpha_3 \right) \times \left(\frac{Lm_1 + Lm_2}{2} \right)}{S \times \%IX \times Wl} \times \frac{\left(\frac{\alpha_1 + \alpha_2 + \alpha_3}{Wl \times \pi} - 1 \right)}{S \times \%IX \times Wl} \times \frac{2f}{100} \right\}^{1/2} \qquad (2)$$

where E_{kVA} is the capacity of transformer, S is the number of phase, α_1 is the rolling thickness of primary winding, α_2 is the rolling thickness of secondary voltage, α_3 is the insulation space between primary and secondary windings, Lm_1 is the average length of inside winding, Lm_2 is the average length of outside winding, wl is the height of winding. In practice, the height of primary winding and secondary winding are the same. Let %IR be denoted as resistance voltage percentage

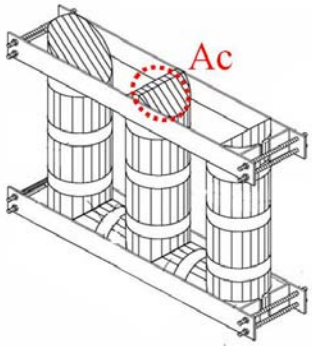
$$\%IR = \frac{P_w}{E_{kVA}} \times 100 \qquad (3)$$

where the P_w is the winding loss. The impedance voltage percentage is define as following

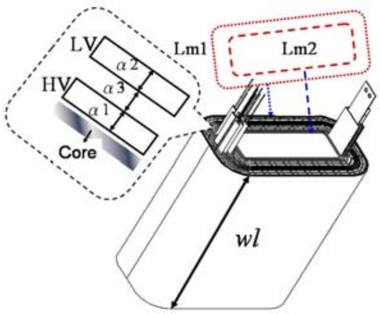
$$\%IZ = \sqrt{(\%IX)^2 + (\%IR)^2} \tag{4}$$



(a)



(b)



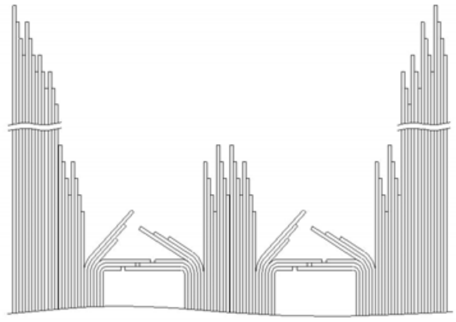
(c)

Fig. 2. The geometric dimension of transformer design: (a) amorphous core, (b) silicon steel, (c) transformer winding.

3 Core stacking

3.1 Amorphous core

An amorphous ferromagnetic magnetic strip material provides improved magnetic and electrical characteristics resulting from inherently lower magnetic losses. These improved characteristics are the result in part of the slice and higher electrical resistivity of the material. Accordingly, amorphous material transformer cores can be improved magnetic loss characteristics over comparable transformer cores fabricated, for example, including improved core stacking method. Such improved magnetic loss results in changed transformer operating efficiency, it must satisfied that offer corresponding improvement in the operating efficiency of the energy conversion system in which it is electromagnetic property were obtained. Amorphous ferromagnetic material, it is usefully in the aforementioned electrical equipment application. And it was typically manufacturing in continuous strips or ribbons of about 0.025mm thickness. Such amorphous strips or ribbons have relatively high tensile strengths, but also have relatively poor ductility.



(a)

Core Type

A length	mm	2000
B length	mm	800
C length	mm	250
Ribbon Width (D)	mm	174
Stack Factor	%	85%
Core Weight	kg	41
Ribbon denier	g/m/inch	4.3
Group correction	group	0
Lap correction	mm	0
Corner Radius	mm	6.4
Ribbon/cut	ribbon	10
Ribbon/group	ribbon	30
SiFe thickness	mm	0.33
Overlap	mm	18
Lap Type	F/V	F
Cut length increment	mm	1.6
Group length increment	mm	5.20
Start length	mm	5608
End length	mm	7166
Outer SiFe sheet	mm	7349
Short inner SiFe sheet	mm	880
Long inner SiFe sheet	mm	4775
Group index spacing	mm	18
Set index spacing	mm	18.2

Do Not Change	
K1	0.0051
K2	393.7
K3	0.0005

Cut per group	3
No. of Group	300
Core Net Area sq.cm	369.8
Group per Set	7
No. of Set	43
Group in last set	6

(b)

No	Length	No	Length	No	Length	No	Length	No	Length	No	Length	No	Length	No	Length	No	Length	No	Length
1	5608.0	31	5764.0	61	5920.0	91	6076.0	121	6232.0	151	6388.0	181	6544.0	211	6700.0	241	6856.0	271	7012.0
2	5613.2	32	5769.2	62	5925.2	92	6081.2	122	6237.2	152	6393.2	182	6549.2	212	6705.2	242	6861.2	272	7017.2
3	5618.4	33	5774.4	63	5930.4	93	6086.4	123	6242.4	153	6398.4	183	6554.4	213	6710.4	243	6866.4	273	7022.4
4	5623.6	34	5779.6	64	5935.6	94	6091.6	124	6247.6	154	6403.6	184	6559.6	214	6715.6	244	6871.6	274	7027.6
5	5628.8	35	5784.8	65	5940.8	95	6096.8	125	6252.8	155	6408.8	185	6564.8	215	6720.8	245	6876.8	275	7032.8
6	5634.0	36	5790.0	66	5946.0	96	6102.0	126	6258.0	156	6414.0	186	6570.0	216	6726.0	246	6882.0	276	7038.0
7	5639.2	37	5795.2	67	5951.2	97	6107.2	127	6263.2	157	6419.2	187	6575.2	217	6731.2	247	6887.2	277	7043.2
8	5644.4	38	5800.4	68	5956.4	98	6112.4	128	6268.4	158	6424.4	188	6580.4	218	6736.4	248	6892.4	278	7048.4
9	5649.6	39	5805.6	69	5961.6	99	6117.6	129	6273.6	159	6429.6	189	6585.6	219	6741.6	249	6897.6	279	7053.6
10	5654.8	40	5810.8	70	5966.8	100	6122.8	130	6278.8	160	6434.8	190	6590.8	220	6746.8	250	6902.8	280	7058.8
11	5660.0	41	5816.0	71	5972.0	101	6128.0	131	6284.0	161	6440.0	191	6596.0	221	6752.0	251	6908.0	281	7064.0
12	5665.2	42	5821.2	72	5977.2	102	6133.2	132	6289.2	162	6445.2	192	6601.2	222	6757.2	252	6913.2	282	7069.2
13	5670.4	43	5826.4	73	5982.4	103	6138.4	133	6294.4	163	6450.4	193	6606.4	223	6762.4	253	6918.4	283	7074.4
14	5675.6	44	5831.6	74	5987.6	104	6143.6	134	6299.6	164	6455.6	194	6611.6	224	6767.6	254	6923.6	284	7079.6
15	5680.8	45	5836.8	75	5992.8	105	6148.8	135	6304.8	165	6460.8	195	6616.8	225	6772.8	255	6928.8	285	7084.8
16	5686.0	46	5842.0	76	5998.0	106	6154.0	136	6310.0	166	6466.0	196	6622.0	226	6778.0	256	6934.0	286	7090.0
17	5691.2	47	5847.2	77	6003.2	107	6159.2	137	6315.2	167	6471.2	197	6627.2	227	6783.2	257	6939.2	287	7095.2
18	5696.4	48	5852.4	78	6008.4	108	6164.4	138	6320.4	168	6476.4	198	6632.4	228	6788.4	258	6944.4	288	7100.4
19	5701.6	49	5857.6	79	6013.6	109	6169.6	139	6325.6	169	6481.6	199	6637.6	229	6793.6	259	6949.6	289	7105.6
20	5706.8	50	5862.8	80	6018.8	110	6174.8	140	6330.8	170	6486.8	200	6642.8	230	6798.8	260	6954.8	290	7110.8
21	5712.0	51	5868.0	81	6024.0	111	6180.0	141	6336.0	171	6492.0	201	6648.0	231	6804.0	261	6960.0	291	7116.0
22	5717.2	52	5873.2	82	6029.2	112	6185.2	142	6341.2	172	6497.2	202	6653.2	232	6809.2	262	6965.2	292	7121.2
23	5722.4	53	5878.4	83	6034.4	113	6190.4	143	6346.4	173	6502.4	203	6658.4	233	6814.4	263	6970.4	293	7126.4
24	5727.6	54	5883.6	84	6039.6	114	6195.6	144	6351.6	174	6507.6	204	6663.6	234	6819.6	264	6975.6	294	7131.6
25	5732.8	55	5888.8	85	6044.8	115	6200.8	145	6356.8	175	6512.8	205	6668.8	235	6824.8	265	6980.8	295	7136.8
26	5738.0	56	5894.0	86	6050.0	116	6206.0	146	6362.0	176	6518.0	206	6674.0	236	6830.0	266	6986.0	296	7142.0
27	5743.2	57	5899.2	87	6055.2	117	6211.2	147	6367.2	177	6523.2	207	6679.2	237	6835.2	267	6991.2	297	7147.2
28	5748.4	58	5904.4	88	6060.4	118	6216.4	148	6372.4	178	6528.4	208	6684.4	238	6840.4	268	6996.4	298	7152.4
29	5753.6	59	5909.6	89	6065.6	119	6221.6	149	6377.6	179	6533.6	209	6689.6	239	6845.6	269	7001.6	299	7157.6
30	5758.8	60	5914.8	90	6070.8	120	6226.8	150	6382.8	180	6538.8	210	6694.8	240	6850.8	270	7006.8	300	7162.8

(c)

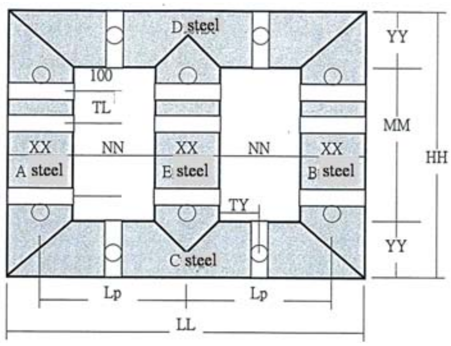
Fig. 3. The manufacturing of amorphous alloy core: (a) core joint, (c) core dimension specification, (c) ribbon cutting table (mm).

Especially, after being subjected to a controlled annealing process of a stress-relieving condition. Consequently, the furnace annealing with an amorphous ferromagnetic material is easily occurred

fracturing condition. Therefore, great care must be taken in the handling of the core of an electrical transformer fabricated of an amorphous material in order to minimize undesired fracturing of the amorphous material laminations of the core.
During the operations of core fabrication, annealing, forming of the core through a coil to form a core and coil assembly, and final transformer assembly, in general, during the post anneal operations of core joint opening, core forming and joint closing the amorphous ferromagnetic material is especially susceptible to fracturing and chipping. In Figure 3 is show the amorphous alloy core joint form and ribbon cutting table, respectively.

3.2 Silicon steel core

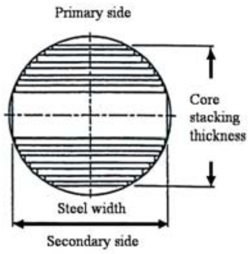
This paper presentation relates to electrical core structure approach, including conventional butt-lap joint structure and step-lap joint structures to improve electrical magnetic characteristics. Therefore, the stacked method of cores for large electrical power transformer of the core-form type conventionally use the butt-lap of core joint have been proposed in several years ago. In the butt-lap joint the ends of the leg and yoke laminations are mitered and butted together. The diagonal joints of the core are performed between each layer of laminations. While the butt-lap construction can form a good magnetic property, however, it has existed disadvantages. One is the manufacturing procedure will take many time with which laminations must be stacked in order to optimize magnetic performance. Another disadvantage is the amount of magnetic loss at the joints, which increases the excitation current and sound level required, respectively.
This step-lap joint of core has been used widely in last decade [9], in order to reduce core losses, it reduces the excitation current requirements, and it also reduces the sound level, compared with a similarly rated transformer constructed with a butt-lap joint. In Fig. 4 is shown the core form of the silicon steel material, in Fig. 4(a) is three-leg core joint form with diagonal and V-shape, in Fig. 4(b) is show core lamination specification, in Fig. 4(c) is cross section area form of the silicon steel core with circular type, respectively. In a step-lap joint manufacturing process, the joints created by the butting laminations of each layer are successively improving each layer joint structure. Each layers in the same direction to create at least three steps, and preferably at least six or seven, before the step pattern is repeated.



(a)

No.	LL	XX	NN	HH	MM	YY	Stacking thickness	Layer	Wight(Kg)
1	1620	310	345	2120	1500	310	79	295	1416
2	1610	300	355	2110	1510	300	32	119	555.8
3	1600	290	365	2100	1520	290	24	90	403.5
4	1590	280	375	2090	1530	280	19	71	308.8
5	1570	260	395	2070	1550	260	32	119	484.2
6	1550	240	415	2050	1570	240	25	93	350
7	1520	210	445	2020	1600	210	30	112	369
8	1490	180	475	1990	1630	180	23	86	243.4
9	1460	150	505	1960	1660	150	18	67	159.3
						Σ	282	1052	4290

(b)



NO.	Steel width	NO.	Steel width Stacking thickness
1	310	1	79
2	300	2	111
3	290	3	135
4	280	4	154
5	260	5	186
6	240	6	211
7	210	7	241
8	180	8	264
9	150	9	282

(c)

Fig. 4 The core joint of silicon steel: (a) three-leg core form with diagonal and V-shape, (b) table of core joint (c) cross section area of core parameter example.

In the step-lap joint, magnetic flux is only passing a fraction of that in the laminations leading to the joint air-gaps. In another word, the magnetic flux will be spread out where it crosses the lap portion of the air-gaps adjacent area. However, the way of a butt-lap joint in series manufacturing, it has about twice as much induction at the joint as in the laminations leading to the joint. It is point out the magnetic flux more crowds due to adjacent of air gaps is short distance of them, and much less than each layer per step. Thus, magnetic reluctance of the step-lap joint is much lower than that of the butt-lap joint; the core losses and no-load excitation current are lower than that for a conventional butt-lap core. The result is achievement of a given performance level with greater efficiency and smaller unit size. Thus, it would be desirable to provide a new and improved step-lap core, and new and improved methods of constructing electrical inductive apparatus which utilize a step-lap core, to facilitate the manufacture thereof such that the disadvantage of the step-lap core are achieve by higher assembly costs.

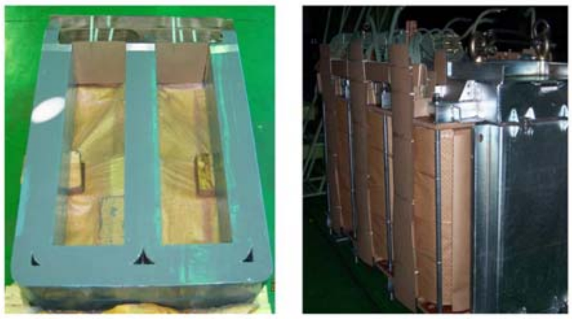
4 Transformer assembling

4.1 Amorphous core assembling

Transformers of amorphous cores, used in distribution and power applications, are typically of the wound-core type. Wound core transformers are generally utilized in high volume applications, such as power transformers, since the wound core design is conducive to automated, mass production manufacturing techniques. Electrical equipments have been developed to wind a ferromagnetic core strip around and through the windows of a preformed, multiple turns coil to produce a core and coil assembly. However, the most common manufacturing procedure involves winding or stacking the core independently of the preformed coils with which the core will ultimately be linked.

The latter arrangement requires that the core is formed with one or more joints for wound core and multiple joints for stacking core. Core laminations are separated at those joints to open the core, thereby permitting its insertion into the coil windows. It is well known that amorphous alloy cores are closed to toroidal joint form.

This procedure is commonly referred to as forming the core combined with coil. A typical process for the manufacturing of a wound amorphous core includes the following steps: ribbon inspection, slice cutting, lamination stacking, core forming and annealing. A finished core has a rectangular shape with the joint window in end of yoke. The core legs are rigid and the joint can be opened for coil insertion. However, the thickness of an amorphous lamination is only about 0.025mm that causes the core manufacturing to be relatively complicated. In quality of the process used to form the core from its annulus shape into rectangular shape is greatly dependent on the amorphous metal lamination stack factor, since the joint overlaps need to match properly from one end of the lamination stack factor, since the joint overlaps need to match properly from one end of the lamination to the other end in the stair-step fashion. If the core forming process is not carried out properly, the core can be over-stressed in the core leg and corner sections during the strip wrapping and core forming processes which will negatively affect the core loss and exciting power properties of the finished core. Core-coil configurations conventionally used in three phase amorphous metal transformers are; core type, comprising three limbs, and three coils; generally use core-coil configurations of three cores type, in Fig. 5.



(a) (b)

Fig. 5. The configurations of amorphous core transformer: (a) three-leg core, (b) assembled core and winding.

4.2 Silicon steel core assembling

The joint structure of the silicon steel is used step-lap method. Both of core corners and V shape of the joints between the leg and yoke will be incrementally form each layer to arrange stepped pattern. The joints between the leg of two sides and the upper and lower yoke joint are mitered, preferably at an angle of 45 degree with respect to the side edges of the laminations, with the miter joint in each layer of laminations being offset from layer to layer to create the desired step-lap pattern. The joints between the middle leg and upper and lower yoke joint structures are also step-lap joints, with the end of the laminations of the middle leg structures being combined with V-shaped. The yoke laminations have V-shaped notches dimensioned to complement the V-shaped end of the middle leg lamination of its layer, to provide low loss diagonal joints. The step-lap pattern steps incrementally in one direction for a predetermined number of steps and then returns to the starting point to repeat the same pattern. Beside, it is called a group in which a complete basic step-lap pattern can be obtained. A plurality of groups being superposed until the desired build step form core dimension is achieved.

To qualify as a step-lap pattern, the core joint form must have at least three steps, but better results from the typically performance of magnetic loss, exciting power and noise obtained when using more than three steps. Six or seven steps have been found to be excellent, and the magnetic core will be descried as having six steps, for purposes of example. Core-coil configurations conventionally used in three phase silicon steel core transformers are; core type, comprising three limbs, and three coils; generally use core-coil configurations of three cores type, in Fig. 6.

(a) (b)

Fig. 6. The configurations of silicon steel transformer: (a) three-leg core, (b) assembled core and winding.

5 Experimental results

The designed 7.5 MVA power transformer is implemented with amorphous alloy core and silicon steel core, respectively. The design factors and measured performance are summarized in Table. 1. First, since the design specifications are quite similar, the winding losses are almost the same. Particularly, it is noted that the core loss of SA1 alloy core is about 30% less than the amount of M5 silicon steel core. Thus, as for the energy saving, the amorphous materials are more appropriate for the core usage. In summary, the total loss, including the core loss and winding loss, of the amorphous-cored transformer is relatively less than the counterpart of silicon steel transformer. From Table 1, it can be concluded that the proposed amorphous core can provide better performance of lower core loss, lower excitation current and higher operation efficiency than the conventional silicon steel core.

6 Conclusion

In this paper, some key aspects in the design and implementation of an amorphous-cored power transformer with capacity 7.5MVA are investigated. Both of amorphous core and silicon steel core with step-lap manufacturing were introduced in detail. Based on the measured magnetic properties, it is obtained that the lowest core loss occurs annealed at 360℃. Compared to conventional silicon steel core, measurement results illustrate that the amorphous core transformer has significant improvement in core loss reduction.

Table 1. The transformer testing results.

Category	Amorphous alloy (SA1)	Silicon steel (M5)
Capacity (MVA)	7.5	7.5
Phase	3	3
Frequency (Hz)	60	60
Winding		
Primary/Secondary (kV)	22.8/11.4	22.8/11.4
Voltage/Turn	33.35	33.35
Exciting current (%)	0.07	0.24
Impendence voltage (%)	8.44	6.46
Winding loss (W)	50000	49533
Core		
Limb type	3	3
Space factor (%)	0.85	0.95
Lamination	25step×10slice	6step×2slice
Thickness of laminations (mm)	0.025	0.3
Gravity ratio (g/cm^2)	7.19	7.48
Flux induction (T)	1.27	1.73
Core loss (W)	2080	6210
Total loss (W)	52080	55743
Efficiency (%)	99.31	99.08

References:

[1] R. Hasegawa, Applications of amorphous magnetic alloys, *Journal of Materials Science and Engineering A,* Vol.375-377, No.15, 2004, pp. 90-97.

[2] H. W. Ng, R. Hasegawa, A. C . Lee, L. A. Lowdermilk, Amorphous alloy core distribution transformers, *Proceedings of the IEEE*, Vol.79, No.11, 1991, pp. 1608-1623.

[3] R. Hasegawa, Advances in amorphous and nanocrystalline magnetic materials, *Journal of Magnetism and Magnetic Materials*, Vol.304, No.2, 2006, pp. 187-191.

[4] Y. Ogawa, M. Naoe, Y. Yoshizawa, R. Hasegawa, Magnetic properties of high B_s Fe-based amorphous material, *Journal of Magnetism and Magnetic Materials*, Vol. 304, No. 2, 2006, pp. e675-e677.

[5] R. Kolano, J. Pinkiewicz, N. Wójcik, J. Sobota, J. Szynowski, An effect of manufacturing conditions on the properties of a 250 kVA three-limb three-phase distribution amorphous transformer, *Journal of Magnetism and Magnetic Materials*, Vol. 215-216, No. 2, 2000, pp. 792-794.

[6] P. Marketosa, T. Meydan, D. Snellb, Performance of single-phase transformer cores assembled from consolidated stacks of electrical steels, *Journal of Magnetism and Magnetic Materials*, Vol. 254-255, 2003, pp. 612-614.