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高压电机纯环氧绝缘系统的性能研究

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Research on Pure Epoxy Insulation System of High Voltage Motor

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Abstract: With the increasing promotion of national energy conservation and emission reduction policies, hydropower, turbine power generation and wind power generation have developed rapidly, and various generators and motors are developing in the direction of high voltage and miniaturization. It is the key to reduce the volume of the motor at the same power, reduce the insulation size (including inter-turn insulation and main insulation) and increase the slot full rate. The reduction of insulation size is a contradiction with insulation quality and insulation reliability. Only a scientific and reasonable insulation structure can make the motor not only have excellent performance, but also meet the needs of larger power and smaller volume. The insulation thinning of high voltage motor can improve the heat dissipation capacity of main insulation, reduce the temperature rise of motor, and reduce the aging of insulation near copper wire caused by temperature rise. In addition, reducing the insulation thickness can increase the utilization rate of the slot, reduce the size of the motor under the same temperature rise, and reduce the copper consumption and mechanical energy consumption. High voltage motor insulation thinning is an important way to improve motor efficiency and reduce manufacturing costs, but to achieve insulation thinning, it is necessary to develop new high-performance insulation materials and optimize integrated insulation system, without reducing electrical insulation, aging and other properties of the premise of insulation thinning. Electromagnetic wire, mica tape with less glue, environmental protection epoxy vacuum pressure impregnation (VPI) resin and high resistance anti-halo material are studied, and integrated insulation system is optimized for systematic performance evaluation. The results show that the optimized 10 kV insulation system has the insulation thickness between turns 0.40 mm, the main insulation thickness 1.8 mm, the corona voltage ≥1.7 U_N, and the electric aging life ≥350 h. At the same time, it has excellent electrical insulation performance and meets the technical requirements of high voltage motor.

Key words: high voltage motor; insulation thinning; high efficiency motor

摘　要:随着国家节能减排政策的推广,水力发电、汽轮发电和风力发电得以迅速发展,各种发电机和电动机都朝着高电压、小型化方向发展。在同功率下缩小电机体积,减少绝缘尺寸(包括匝间绝缘和主绝缘)提高槽满率是关键。而绝缘尺寸的减少与绝缘质量及绝缘可靠性相矛盾,只有科学合理的绝缘结构才能使电机既具有优良的性能,又能满足更大功率和更小体积的需要。高压电机绝缘减薄,可以提高主绝缘散热能力,降低电机温升,减少铜导线附近绝缘因温升造成的老化。另外,减薄绝缘厚度可以增加槽利用率,在同样的温升下缩小电机尺寸,铜耗和机械能耗减少。绝缘减薄是提高电机效率、降低制造成本的重要途径,但要实现绝缘减薄,需要研发新型的高性能绝缘材料并优化集成绝缘系统,在不降低电气绝缘性能的前提下,实现绝缘减薄。对电磁线、少胶云母带、环保型环氧真空压力浸渍(VPI)树脂及高阻防晕材料进行研究,并优化集成绝缘系统,进行系统性的性能评定。研究结果表明:优化后的10 kV 绝缘系统匝间绝缘厚度为 0.40 mm,主绝缘厚度为 1.8 mm,起晕电压≥1.7 U_N,电老化寿命≥350 h。同时,其具有优良的电气绝缘性能,满足高压电机的技术要求。

关键词:高压电机;绝缘减薄;高效电机

0　引言

随着中国经济的高速发展,能源需求也持续增加,各大生产电机企业均把重心投入到高效节能电机这一板块。大功率、小体积是高压电机领域的发展方向[1]。在同功率下缩小电机体积,不

仅可节约制造成本,提高电机热性能、降低电机温升[2-3],还可减少电机重量,便于运输、使用和安装。减薄高压电机的主绝缘厚度是提高电机绝缘系统技术水平的前提[4]。因此,研究绝缘厚度的减薄具有十分重要的意义[5]。

目前,国内各家电机生产企业虽然大多从多胶模压体系转化成中胶、少胶真空压力浸渍(Vacuum Pressure Impregnation, VPI)体系,绝缘厚度相比较以前有大幅度的降低[6],但与国外电机企业相比,国内还是有较大的差距,同时也影响了中国电力发展时期电机产业的国际化市场竞争力[7]。

高压电动机作为把电能转换成机械能的一种装置[8],随着世界工业的快速发展,其应用领域也更加广泛,其消耗电能量也快速上升[9]。据统计,电机耗电占全社会用电量的近60%,折算为碳排放,达到26亿吨碳,约占全国总量的25%[10]。节约能源对现在社会发展起着至关重要的作用,随着我国经济的发展,对于能源的使用越来越多。

减薄绝缘厚度代表着高压电机绝缘系统的技术水平[11],减薄绝缘能够显著降低电机制造成本,对减小电机体积,提高电机效率、提高电机功率密度值及降低温升等均具有重要意义[12-13]。因此要对绝缘系统中的绝缘材料进行综合考虑,在实现绝缘减薄的情况下,满足电机的使用寿命[14]。

高压电机减薄绝缘VPI处理之后使线圈绝缘各部件连续性和导热性好,槽满率高、防潮性能优异[15],在提高电机效率的同时也提高了电机的技术经济指标和运行可靠性,并且降低了整个电机的制造成本[16]。环氧酸酐树脂体系是国外三大主流VPI浸渍树脂之一,排放有机化合物(Volatile Organic Compounds, VOC)几乎为零,闪点高、饱和蒸汽压低、绝缘的整体致密性好,有利于高压电机减薄主绝缘厚度[17]。在国外环氧酸酐VPI树脂已广泛应用于大中型发电机以及兆瓦级以上风力发电机的制造[18-19]。

随着"碳达峰"、"碳中和"计划的不断推进,节能环保成为工业发展的方向。电机高效节能对于我国社会发展有着重要的意义[20],正向着高效化、轻量化方向不断发展。

1 试验

1.1 主要原材料

电磁线、玻璃布少胶云母带、聚酯薄膜少胶云母带、浸渍树脂、低阻带及高阻带均为巨峰股份生产。

1.2 试样制备

电磁线评定试样为羊角线棒,两根电磁线采用背靠背的形式绑扎后,浸渍树脂。试验线圈采用如图1所示的工艺制作。

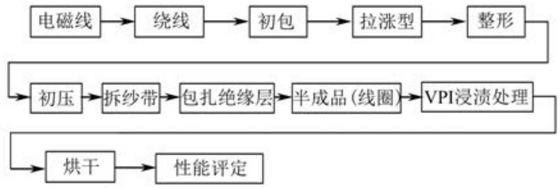

图1 线圈制作流程

Fig. 1 Coil manufacturing process

1.3 性能测试

绕组线圈的测试方法参考《JB/T12685-2016 高压电机定子线圈技术条件》。线圈直线部分采用铝箔电极包扎,介质损耗因数测试仪为上海杨高电器有限公司的YG9100,击穿电压测试仪为上海佳特高电压电气设备有限公司JTGN-150 kVA/150 kV,电老化测试仪为桂林赛盟检测技术有限公司IAV-50 kV/100 kVA。

2 结果与讨论

2.1 电磁线的性能对比

相比较于对地绝缘的减薄,导线绝缘减薄压缩电机槽型尺寸更多,意义更大。对于同等功率的电机,可以减小一个机座号去生产,节能降本。虽然导线绝缘减薄对电机缩小尺寸意义重大,但与此同时也会削弱其抵抗耐高频脉冲和过电压的能力,这就要求采用特殊的技术手段来提升导线绝缘的性能,以弥补因为导线绝缘减薄所造成的电气性能下降和寿命缩短。

10 kV电机匝间绝缘通常为聚酰亚胺薄膜聚酯薄膜云母带绕包、聚酯薄膜云母带绕包线或聚酰亚胺-氟46复合薄膜烧结聚酰亚胺薄膜云母带绕包,双边绝缘厚度为0.5 mm～0.6 mm。下面对比了四种电磁线的电老化性能,将电磁线制作为羊角线棒,浸漆固化后测试10 kV的电老化寿命,数据如表1所示。

从表1中数据可以看出,聚酯薄膜云母带绕包铜扁线电老化寿命较聚酰亚胺-氟46复合薄膜

烧结聚酰亚胺薄膜云母带绕包铜扁线长，改进型聚酰亚胺薄膜聚酯薄膜云母带绕包铜扁线电老化寿命比未改进电磁线的寿命长。改进型聚酰亚胺薄膜聚酯薄膜云母带绕包铜扁线中的聚酯薄膜云母的云母纸是经过特殊工艺处理，增加了云母纸间的密实程度，提高了云母带的老化寿命。另外，云母带中的胶黏剂中含有促进剂，可以提高树脂的反应活性，树脂流失量少，绝缘结构整体性好。

表1　不同电磁线电老化寿命

Tab. 1　Electrical aging life of different electromagnetic wires

电磁线	绝缘厚度/mm	电老化时间/h
聚酰亚胺-氟46复合薄膜烧结	0.50	10.49
聚酰亚胺薄膜云母带绕包铜扁线	10.3	10.5
聚酯薄膜云母带绕包铜扁线	0.45	28
	33.7	36
聚酰亚胺薄膜聚酯薄膜云母带	0.40	25
绕包铜扁线	27.6	30
聚酰亚胺薄膜聚酯薄膜云母带	0.40	56
绕包铜扁线(改进型)	65	68

2.2　少胶云母带的性能对比

少胶云母带是对地绝缘，性能的优劣直接影响着绝缘系统的电老化寿命。少胶云母带主要由云母纸、胶黏剂和补强材料组成。研究高性能环氧胶粘剂，带有特定的化学基团，能够与VPI树脂发生化学交联反应，既能满足补强材料和云母纸的粘结性要求，又能促进浸渍树脂的固化，减少浸渍树脂的流失，提升绝缘整体性。通过改进，玻璃布少胶云母带的击穿电压较常规型云母带击穿电压提高20%以上。改进型玻璃布云母带JF-5442-1A、聚酯薄膜云母带JF-5442-1DA的技术指标如表2、表3所示。

表2　玻璃布云母带性能

Tab. 2　Performance of glass cloth mica tape

参数名称	常规型	改进型
厚度/mm	0.135	0.136
干燥材料单位面积总质量/($g \cdot m^{-2}$)	199.1	203.7
云母纸含量/($g \cdot m^{-2}$)	160.8	164.2
玻璃布含量/($g \cdot m^{-2}$)	22.2	22.2
胶黏剂含量/%	8.1	8.5
击穿电压/kV	2.0	2.5
拉伸强度/[$N \cdot (10\ mm)^{-1}$]	113	112

2.3　VPI浸渍树脂

环氧酸酐绝缘系统是世界公认的性能优异的绝缘系统。由于采用了酸酐固化剂，树脂容易吸潮，引起粘度增长，不利于使用维护。本次研究的浸渍树脂为JF-9965，以环氧树脂为主体搭配特种固化剂，采用高沸点、高闪点及低毒性的反应单体组成。浸渍树脂的基本性能如表3所示。

从表中3可知，浸渍树脂的挥发分<2%，符合环保要求。该树脂的粘度低，常温浸渍即可满足10 kV定子的浸透性要求。据经验60 ℃/96 h的粘度增长相当于常温放置半年粘度增长，从表中数据可以看出粘度增长比较小，树脂稳定性好。

表3　浸渍树脂性能

Tab. 3　Impregnated resin properties

序号	参数名称	试验条件	检测值
1	外观	目测	浅棕黄色透明液体
2	粘度/S	25 ℃±1 ℃	36
3	凝胶时间/s	135 ℃±2℃	580
4	挥发分/%	150 ℃±2℃、2 h	1.2
5	工频电气强度/($MV \cdot m^{-1}$)	常态	28.5
6	体积电阻率/($\Omega \cdot m$)	常态	6.2×10^{14}
7	介质损耗因数/%	常态	0.31
		155 ℃±2℃	1.34
8	贮存稳定性(闭口法60 ℃±2 ℃，96 h)/倍		0.11

2.4　高阻表面电阻率

高阻带的表面电阻率随电压的变化情况对起晕电压影响很大。通过对不同碳化硅的筛选，所制备的高阻带非线性系数如表4所示。

表4　高阻带的非线性系数

Tab. 4　Nonlinear coefficient of high stopband

序号	表面电阻率/GΩ			非线性系数	
	0.5 kV	2.5 kV	5 kV	$\beta 1$	$\beta 2$
1	2 340	17.44	0.025 6	2.45	2.61
2	3 320	30.72	0.036	2.34	2.70
3	1 156	2.612	0.010 4	3.05	2.21
4	2 060	14.72	0.027 6	2.47	2.51
5	1 640	12.28	0.022 56	2.45	2.52

3　绝缘系统性能测试

采用改进型聚酰亚胺薄膜聚酯薄膜云母带绕包铜扁线，主绝缘为玻璃布少胶云母带和聚酯薄膜少胶云母带混合绕包，主绝缘厚度约1.8 mm。按照第2部分制作线圈，线圈烘干后按照《JB/

T12685-2016 高压电机定子线圈技术条件》进行测试。

3.1 常态介质损耗因数及增量

线圈常态介质损耗因数见图 2。由图可知，0.2 U_N 下的介质损耗因数均小于 1.5%，满足 GB/T12685 的技术要求。在 2 kV 和 10 kV 之间，随着电压的升高，介质损耗因数的增量很小，说明线圈的绝缘整体性好，气隙少。

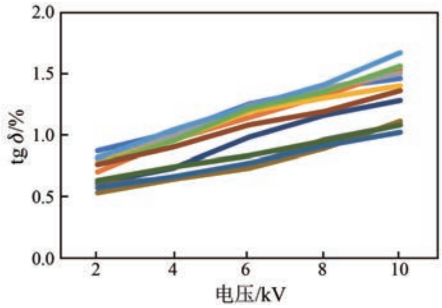

图 2 常态介质损耗因数

Fig. 2 Normal dielectric loss factor

3.2 热态介质损耗因数及击穿电压

介质损耗是反映绝缘材料品质的关键参数，绝缘材料在电场作用下，由于介质电导和介质极化的滞后效应，在绝缘内部引起能量损耗，损耗越大电机的温度越高，影响使用寿命。线圈热态介质损耗因数如图 3 所示。

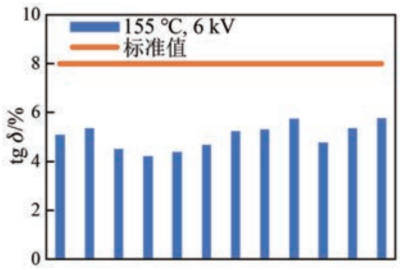

图 3 热态介质损耗因数

Fig. 3 Thermal dielectric loss factor

由图 3 可知，155 ℃的介质损耗因数在 5%左右，满足 GB/T12685 的技术要求，按照 JB/T50133 中型高压电机少胶整浸线圈产品质量分等属于优等品。

3.3 起晕电压

定子绕组表面电晕放电会侵蚀表面绝缘材料，影响电机绝缘故障。线圈的起晕电压测试数据如图 4 所示。起晕电压除受环境的影响外，还取决于高阻带的电压电阻特性，经过对碳化硅的筛选，所制备的线圈起晕电压均满足＞17 kV 的技术要求，高阻带具有良好的非线性系数。

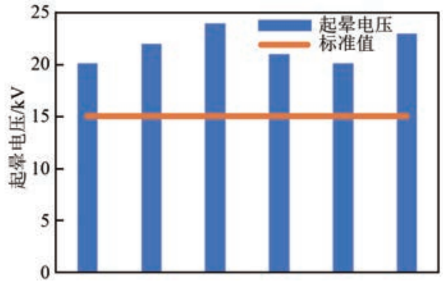

图 4 起晕电压

Fig. 4 Corona onset voltage

3.4 击穿电压

线圈的击穿电压测试数据如图 5 所示。

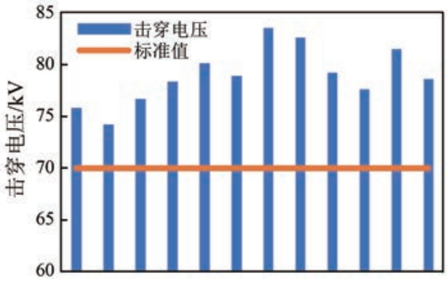

图 5 击穿电压

Fig. 5 Breakdown voltage

由图 5 可知，线圈的击穿电压均大于标准要求，具有良好的电性能，绝缘系统整体致密性好。

3.5 电老化寿命

两种线圈的在 2.53 U_N 下老化寿命数据如图 6 所示。

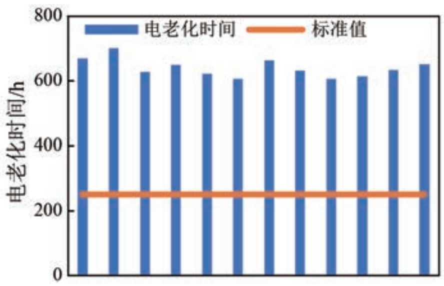

图 6 电老化寿命

Fig. 6 Electrical aging life

由图 6 可知，线圈的老化寿命远高于标准要求，具有优异的电气可靠性。

4 结语

对绝缘材料及系统进行评定研究，得出如下

结论：

1）通过对电磁线的电老化对比，采用云母带绕包铜扁线具有较高的电老化寿命。

2）减薄绝缘系统的常态介质损耗因数及增量，热态介质损耗因数满足技术要求，且达到优等品水平，其中热态介损值≤6%。

3）减薄绝缘系统的电老化寿命远高于标准要求，2.53 U_N 电老化寿命≥600 h。

通过考虑绝缘材料性能提升及材料间相容性，制备高压电机绝缘在减薄绝缘厚度的基础上仍具有较高的可靠性，提高了电机效率，减少制造成本。目前本研究的高性能绝缘系统已经在行业内批量使用，效果良好。

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Research on Pure Epoxy Insulation System of High Voltage Motor

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Key words: high voltage motor; insulation thinning; high efficiency motor

In this paper, the electromagnetic wire, low-glue mica tape, environmentally friendly epoxy vacuum pressure impregnation (VPI) resin and high-resistance anti-corona materials are studied, and the integrated insulation system is optimized for systematic performance evaluation. The results show that the optimized 10 kV insulation system has an interturn insulation thickness of 0.40 mm, a corona onset voltage of $\geqslant$1.7 U_N, and an electrical aging life of $\geqslant$ 350 h. After thinning insulation VPI treatment of high-voltage motor, the continuity and thermal conductivity of each component of coil insulation are good, the slot full rate is high, and the moisture proof performance is excellent. While improving the efficiency of the motor, it also improves the technical and economic indicators and operational reliability of the motor, and the manufacturing cost of the whole motor is reduced instead. While reducing the insulation thickness, it has excellent electrical insulation performance and meets the technical requirements of high-voltage motors.

Compared with the thinning of the ground insulation, the thinning of the wire insulation is more significant for the compression motor groove size. For the same power motor, you can reduce a seat number to production, energy saving and cost reduction. Although the thinning of wire insulation is of great significance to the reduction of the size of the motor, it will also weaken its ability to resist high-frequency pulses and overvoltages. This requires the use of special technical means to improve the performance of wire insulation to make up for the reduction of electrical performance and shortened life caused by the thinning of wire insulation. Epoxy anhydride insulation system is recognized as an excellent insulation system in the world. Due to the use of anhydride curing agent, the resin is easy to absorb moisture, causing the viscosity to increase, which is not conducive to use and maintenance. The impregnating resin of this study is JF-9965, with epoxy resin as the main body with special curing agent, using high boiling point, high flash point, low toxicity of the reaction monomer composition. The low-glue mica tape is mainly composed of mica paper, adhesive and reinforcing material. The study of high-performance epoxy adhesives with specific chemical groups can chemically crosslink with VPI resin, which can not only meet the bonding requirements of reinforcing materials and mica paper, but also promote the curing of impregnating resin, reduce the loss of impregnating resin and improve the integrity of insulation.

The electrical aging life of different electromagnetic wires, the performance of glass cloth mica tape, the performance of impregnated resin, the high resistance surface resistivity and the normal dielectric loss factor and increment of the insulation system, the thermal dielectric loss factor and breakdown voltage, corona voltage, breakdown voltage and electrical aging life test are carried out.

It can be seen from the results that the dielectric loss factor at 0.2 U_N is less than 1.5%, which meets the technical requirements of GB / T12685. Between 2 kV and 10 kV, with the increase of voltage, the increment of dielectric loss factor is very small, which indicates that the

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insulation integrity of the coil is good and the air gap is small.

After analysis and discussion, the following conclusions can be drawn:

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1) By comparing the electrical aging of the electromagnetic wire, the use of mica tape wrapped copper flat wire has a higher electrical aging life.

2) The normal dielectric loss factor, increment and thermal dielectric loss factor of the thinning insulation system meet the technical requirements, and reach the level of superior products, in which the thermal dielectric loss value is less than or equal to 6%.

3) The electrical aging life of the thinning insulation system is much higher than the standard requirement, and the electrical aging life of 2.53 U_N is more than 600 h.

By improving the performance of insulation materials and considering the compatibility between materials, the preparation of high-voltage motor insulation still has high reliability on the base material with reduced insulation thickness, which improves the efficiency of the motor and reduces the manufacturing cost. At present, the high-performance insulation system of this study has been used in batches in the industry, and the effect is good.