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某600 MW机组低压-发电机联轴节螺栓结构优化分析

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摘 要:针对某600 MW机组低压-发电机转子联轴节两侧轴振突跳、连接螺栓弯曲和轮盘错位问题,在研究螺栓伸长量和传递扭矩关系的基础上,提出四凸台螺栓优化结构以代替原有三凸台螺栓结构,采用三维非线性接触有限元进行不同工况下两种螺栓结构的计算分析,对比计算结果,说明四凸台优化方案能够在各种工况有效安全传递扭矩,保证机组安全运行。

关 键 词:低压-发电机转子;联轴节;三凸台螺栓;四凸台螺栓;扭矩;有限元

中图分类号:TK263;O241 文献标识码:B

引 言

汽轮机组采用刚性联轴节螺栓紧配连接工艺,通过螺栓预紧,在轮盘配合面产生摩擦力以传递扭矩,不恰当的连接方式有可能导致转子不同心和振动值偏大[1]。某实际运行的600 MW机组低-发联轴节两侧轴瓦振动在机组升负荷过程中曾多次出现突跳故障,且检修发现连接螺栓已明显弯曲,配合面严重错位。针对这个问题,首先分析了螺栓伸长量与传递扭矩之间的关系,然后建立了有限元模型,利用三维非线性接触有限元计算对连接螺栓和进行计算和结构优化,最终提出了改进方案,并实际应用。

某600 MW机组低压-发电机联轴节如图1所示。其连接螺栓采用三凸台结构,3个凸台分别与发电机转子、盘车齿轮和低压转子的螺栓孔配合,在盘车齿轮两侧的摩擦面上并无凸台,可见,在正常状态下,这种三凸台连接螺栓不能够承受剪切力,低发联轴节不能靠摩擦力和螺栓承受剪切力来传递扭矩。运行中多次发生低发联轴节错位,说明该机型摩擦传扭能力不足,所以对其传扭能力进行计算。

1 联轴节有限元模型优化分析

1.1 联轴节传扭力理论计算

当联轴节传递的扭矩 T 大于或等于接触面最大静摩擦力产生的扭矩 T_{fmax} 时,联轴节发生错位或处于错位的临界状态,在给定摩擦系数的前提下,联轴节接触面之间的最大静摩擦力由螺栓伸长量 Δl(即螺栓预紧力)决定,即:

$$f=\mu\sum_{i=1}^{24}P_i \tag{1}$$

式中:P_i—第 i 根螺栓的预紧力。

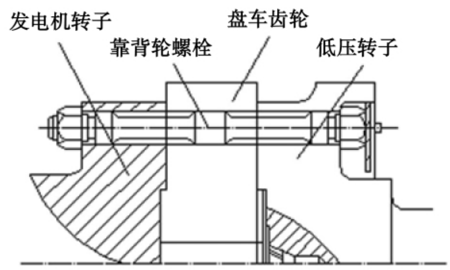

图1 低发联轴节结构简图

Fig. 1 Structural sketch of a coupling for a low voltage generator rotor

P_i 可以用螺栓伸长量 Δl_i 表示:

$$P_i=A_{ef}E\Delta l_i/l_{ef} \tag{2}$$

式中:A_{ef}—螺栓有效横截面面积;l_{ef}—螺栓有效长度。

联轴节接触圆面上摩擦力分布的平均半径为:

$$\bar{R}=\frac{1}{R_1-R_2}\int_{R_2}^{R_1}r\mathrm{d}r=\frac{R_1+R_2}{2} \tag{3}$$

根据式(1)~式(3),联轴节最大摩擦力产生的扭矩 T_{fmax} 与螺栓伸长量 Δl 之间的关系为:

$$T_{fmax}=f\bar{R}=\frac{\mu(R_1+R_2)A_{ef}E}{2l_{ef}}\sum_{i=1}^{24}\Delta l_i \tag{4}$$

当联轴节传递的扭矩 T 小于接触面最大静摩擦力产生的扭矩 T_{fmax} 时,联轴节轮盘之间不发生错位,接触面为静摩擦。而静摩擦系数为变值,随传递的扭矩的增加而增加,这时摩擦力产生的扭矩等于联轴节传递的扭矩,即:

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$$T_f = T \quad (5)$$

几何尺寸和材料参数根据实际机组选取，所得螺栓伸长量和摩擦力传扭关系如图 2 所示。由图可知：(1) 当最大静摩擦力产生的扭矩小于或等于传递的扭矩时，联轴节的传扭能力与螺栓伸长量（或预紧力）成正比。(2) 按厂家要求螺栓伸长量 0.62 mm 计算，则低发联轴节能够传递的最大扭矩为 7.07×10^5 N·m，仅相当于传递 222 MW 负荷，此时低发联轴节摩擦传扭能力不足。(3) 该 600 MW 汽轮机组在额定功率下运行时传递的扭矩为 1.91×10^6 N·m，若全部扭矩都由摩擦力来传递，螺栓伸长量至少为 1.67 mm。检查发现盘车齿轮与联轴节接触不良，根据式(4)，这将造成联轴节接触圆面上摩擦力分布的平均半径减小，使联轴节传扭能力下降。

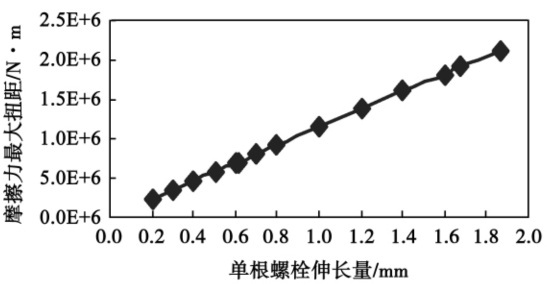

图 2 螺栓伸长量与传递扭矩关系曲线

Fig. 2 Curves showing the relationship between the elongation distance of a bolt and its torque transferred

1.2 有限元模型及约束加载

根据图 1 建立三凸台螺栓低发联轴节有限元模型如图 3 所示，单元和材料参数如表 1 所示。在模型发电机转子端面和轴线上施加全约束（$Ux = Uy = Uz = 0$），为了避免集中扭矩载荷产生应力集中，在低压转子端面外圈施加刚性区域，通过主节点加载扭矩，能够均匀地传递到约束面上，螺栓预紧力通过预紧力单元 PRETS179 施加。

目前，主流机组采用液压超紧配螺栓连接技术[2-3]，这种连接方式允许螺栓承受横向剪切力来增加传递扭矩能力。但考虑到实际结构情况，可采用四凸台螺栓代替三凸台螺栓。两种螺栓模型的约束加载及材料参数完全相同，只是螺栓结构有差别，四凸台螺栓有限元结构如图 4 所示，中间两个凸台分别处于两个轮盘接触面，承受横向剪切力以传递一部分扭矩，同时设计合适倒角以减小凸台过渡处应力集中系数。

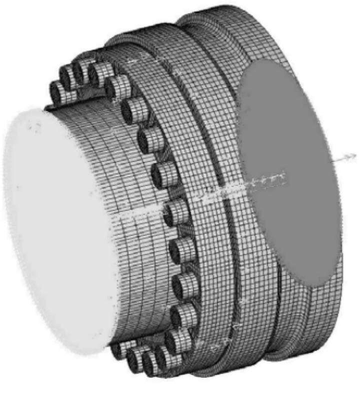

图 3 低发联轴节有限元模型

Fig. 3 Finite element model for the coupling of the low voltage power generator

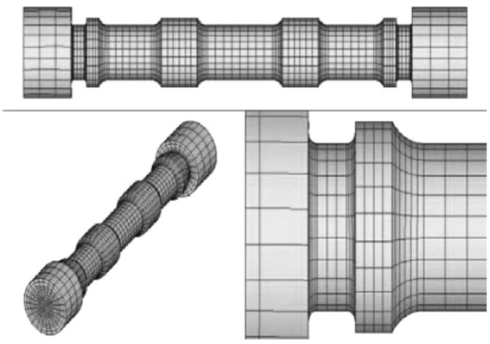

图 4 四凸台螺栓有限元示意图

Fig. 4 Schematic finite element diagram of a four-boss bolt

表 1 有限元模型材料参数

Tab. 1 Material parameters of a finite element model

实体结构	弹性模量 E/Pa	泊松比	密度 ρ/kg·m^{-3}	摩擦系数 μ
发电机转子	2.1×10^{11}	0.30	7 850	0.15
盘车齿轮	2.04×10^{11}	0.33	7 750	0.15
低压转子	2.04×10^{11}	0.33	7 750	0.15
螺栓	2.06×10^{11}	0.28	7 850	0.15

参照螺栓伸长量和传扭关系曲线，选取计算工况如表 2 所示。工况一为厂家标准预紧力（简称标准预紧力）和额定扭矩，讨论在正常工作情况下螺栓受力变形情况；工况二为标准预紧和两相短路，即扭矩为额定扭矩的 5.5 倍，考虑连接螺栓在冲击载荷下应力和变形情况；工况三为机组实际安装过程中，很难保证所有螺栓伸长量（预紧力）相同，为了模拟真实情况，对 24 根螺栓施加不同的伸长量载

荷，数据来自实际机组测量，即在不均匀预紧力和额定扭矩下计算连接螺栓的应力和变形情况。

表2　加载工况表

Tab. 2 Table of loading operating conditions

	加载工况	螺栓伸长/mm	施加扭矩/N·m
工况一	标准预紧 额定扭矩	0.62	1.91×10^6
工况二	标准预紧 两相短路	0.62	1.05×10^7
工况三	不均匀预紧 额定扭矩	—	1.91×10^6

2　计算结果分析

对两种联轴节有限元模型进行加载求解，所得结果如表3所示，分析可知：

（1）工况一，即在螺栓伸长0.62 mm，额定扭矩下三凸台螺栓最大等效应力为1 790 MPa，出现在螺栓凸台处，因为在扭矩下螺栓发生弯曲变形而与轮盘发生接触挤压，加之结构突变导致应力集中，使该处应力最大；而四凸台螺栓最大等效应力为682 MPa，也出现在螺栓凸台处，原因和三凸台相同，但应力显著减小。三凸台螺栓最大合位移为5.06 mm，出现在施加扭矩端轮盘外侧，因为螺栓随轮盘错位而发生明显弯曲变形；四凸台螺栓最大合位移为0.62 mm，出现在施加扭矩轮盘外侧，原因和三凸台相同，变形明显减小。

（2）工况二，即在螺栓伸长0.62 mm，扭矩为额定扭矩5.5倍（两相短路冲击）下三凸台螺栓最大等效应力为13 800 MPa，出现在螺栓凸台处，最大合位移33.6mm，出现在施加扭矩轮盘外侧，原因和工况一相同，应力远大于材料屈服极限930 MPa，发生严重弯曲变形和大面积屈服，故不能承受两相短路冲击；四凸台螺栓最大等效应力为1 010 MPa，最大合位移为2.54 mm，由于凸台结构能够承受剪切力，弯曲变形和最大应力远小于三凸台螺栓，有较好的抗两相短路冲击能力。

（3）工况三，即考虑实际运行中螺栓不均匀预紧，额定扭矩情况下，周向均布的24根螺栓变形和等效应力不同，三凸台螺栓最大等效应力为2 000 MPa，发生在凸台处，最大合位移为5.76 mm，出现在扭矩施加轮盘外侧；四凸台螺栓最大等效应力为668 MPa，最大合位移为0.65 mm，可以看出在不均匀预紧情况下，四凸台螺栓依然可以有效传递额定扭矩。

表3　3种加载工况下应力和位移对比

Tab. 3 Contrast of tensions and displacements under three loading operating conditions

加载工况	三凸台螺栓联轴节		四凸台螺栓联轴节	
	最大等效应力/MPa	最大合位移/mm	最大等效应力/MPa	最大合位移/mm
工况一	1790	5.06	682	0.62
工况二	13800	33.6	1010	2.54
工况三	2000	5.76	668	0.65

3　结　论

（1）低发联轴节采用三凸台螺栓连接，在额定工况下，无论怎样选择螺栓伸长量，都存在着螺栓应力超过材料屈服极限的问题。在标准螺栓伸长0.62 mm下，单靠轮盘面摩擦力仅能传递约三分之一额定扭矩，发生两相短路时，局部应力超过屈服极限数倍，机组运行安全不能得到保障。

（2）改用可承受剪切的四凸台螺栓连接，低发联轴节的传扭能力受螺栓紧力不均的影响较小，能将机组额定工况下的最大应力限制在材料屈服极限之下，机组发生发生两相短路时的最大应力也被控制在与材料屈服极限相当的水平，因此可确保机组运行安全。

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（丛　敏　编辑）

Journal of Engineering for Thermal Energy & Power. – 2012,27(3). –282 ~ 286

With a large-sized warship-purposed main steam turbine serving as the object of study and its structural characteristics being fully considered, a lumped parameter dynamic-state simulation mathematic model was established for the characteristics of the steam turbine. On the Simu Works thermal system platform, built was a corresponding simulation model. A dynamic state simulation was performed of the steam turbine in various operating conditions including the steady state operating conditions, acceleration, deceleration and astern-going processes. The simulation results show that the model in question enjoys a relatively high precision and its dynamic tendency is rational, capable of reflecting the real working conditions of the parts and components. The model under discussion can also be used for simulating warship-purposed power systems. **Key words:** warship-purposed main steam turbine, steam turbine simulation, steady-state simulation, dynamic-state simulation

动态基准温度对回热系统加热器㶲效率影响分析 = Analysis of the Influence of the Dynamic-state Reference Temperature on the Exergy Efficiency of the Heater in a Recuperator System

[刊,汉] LI Yong-hua, LIU Wei-ting (College of Energy Source and Power Engineering, North China University of Electric Power, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. – 2012,27(3). –287 ~ 292

Exergy value is a variable relating to the environment temperature, which changes with time and space. With the environment temperature (i. e. dynamic-state reference temperature) serving as the reference point, the authors calculated relevant exergy values of the recuperator system of a domestically-made 300 MW subcritical unit, 600 MW and 1 000 MW supercritical unit. On this basis, the exergy efficiencies of the heaters in the recuperator systems were calculated by utilizing the exergy efficiency matrix equation and the influence of the dynamic-state reference temperature on the change in the exergy efficiency of the heater in the recuperator system was also analyzed. With an increase of the reference temperature, the exergy efficiencies of various heaters invariably decrease while the lower the steam extraction pressure, the more the exergy efficiency decreases. The exergy efficiencies of NO. 8 heaters of various units decrease maximally. For No. 8 heaters of various units, when $\triangle T_{jz} = 20$℃, $\triangle \eta$ will be –37.12% (300MW unit), –32.6% (600MW unit), –20.51% (1000 MW unit) respectively. With an increase in the capacity of the units, $\triangle \eta$ assumes a descending tendency. This can offer reference for selecting the dynamic-state reference point of a recuperator system, even a whole unit for exergy analysis. **Key words:** steam turbine unit, recuperator system, dynamic-state reference temperature, exergy efficiency

某600 MW机组低压-发电机联轴节螺栓结构优化分析 = Analysis of the Structural Optimization of Bolts Destined for the Coupling of a 600 MW Unit Low-voltage Generator

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Pu, YUAN Qi (College of Energy Source and Power Engineering, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. – 2012, 27(3). –293 ~ 295

In the light of such problems as abrupt jump of the vibration value and mismatching of the wheel disks caused by any deficiency in design of bolts for the coupling on the rotor of a 600 MW unit low-voltage generator, proposed was an optimized four-boss bolt structure instead of the original three-boss bolt one on the basis of a study of the relationship between the elongation of the bolts and the torque transferred. The three-dimensional non-linear contact finite element method was used to calculate and analyze both bolt structures under different operating conditions. A comparison of the calculated results indicates that the four-boss optimization version can effectively and safely transfer a torque under various operating conditions and ensure safe operation of the unit. **Key words:** coupling, three-boss bolt, four-boss bolt, torque, finite element, low-voltage generator rotor

甲烷三重整制合成气热力学分析 = Thermodynamic Analysis of the Preparation of Syngas Through a Triple-reforming of Methane [刊, 汉] TANG Qiang, YANG Xu-dong, ZHANG Li (Education Ministry Key Laboratory on Low Quality Energy Source Utilization Technologies and Systems, College of Power Engineering, Chongqing University, Chongqing, China, Post Code: 400044) // Journal of Engineering for Thermal Energy & Power. – 2012, 27 (3). –296 ~ 300

TRM (triple-reforming of methane) reaction boasts such merits as a high process energy efficiency, a proper syngas H_2/CO and relatively low carbon deposition of catalysts. A thermodynamic analysis was performed of the preparation of syngas through a triple-reforming of methane by using the equilibrium constant method with the influence of the reaction temperature, pressure and composition of the feed gas on the reforming characteristics being studied. The research results show that when the TRM reaction temperature is above 1073 K, the reaction achieves a very good effectiveness and the temperature rise is conducive to an enhancement of the conversion rate. However, an increase of the pressure is unfavorable to a positive reaction. An increase of the oxygen content will make the conversion rates of methane and carbon dioxide go up to above 95% and down to below 10% respectively while the H_2/CO value will maintain around 1.5. When the steam and carbon dioxide content increase, the conversion rate of methane will increase but that of the carbon dioxide will decrease with the H_2/CO value changing in a range from 1.4 to 2.1. The former will make the H_2/CO value increase while the latter will make it decrease. **Key words:** equilibrium constant, methane, triple reforming, syngas, thermodynamic analysis

高压水扇形喷嘴结构参数对内部流场影响的数值模拟 = Numerical Simulation of the Influence of the Structural Parameters of a High Pressure Water Sector-shaped Nozzle on Its Internal Flow Field [刊, 汉] ZHANG Xin-ming, LUO Qing, HONG Guang, LING Ya (Education Ministry Key Laboratory on Low Quality Energy