

# 考虑不平衡磁拉力的双馈异步风力发电机 轴承外圈故障动力学建模

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## Dynamic Modeling of Doubly-Fed Wind Turbine Bearing Outer Ring Fault Considering Unbalanced Magnetic Pull

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**Abstract:** Bearing faults can cause changes in the air gap of doubly-fed wind turbines, generating unbalanced magnetic pull (UMP). In order to accurately reveal the bearing fault vibration characteristics of doubly-fed wind turbines, a study on dynamic modeling of the outer ring fault of the bearing considering the UMP is carried out. Firstly, a bearing outer ring fault model is constructed based on the Hertz contact theory. Then, the air gap magnetic flux density of the generator rotor under normal and bearing fault conditions is derived, and the UMP acting on the generator rotor is obtained. Finally, the Runge-Kutta method is used to solve the model and the vibration response of the bearing fault is obtained. Experimental comparison analysis shows that the proposed dynamic model can effectively reveal the double impact phenomenon of the vibration signal of doubly-fed wind turbines with bearing faults, and the UMP excitation can affect the modulation characteristics of the vibration signal of wind turbine bearings outer ring faults. A new theoretical references is provided for fault diagnosis of wind turbine bearings.

**Key words:** unbalanced magnetic pull; dynamic modeling; wind turbine; bearing; fault diagnosis

**摘 要:** 轴承故障会引起双馈异步风力发电机转子气隙

变化,产生不平衡磁拉力(UMP)。为准确揭示双馈异步风力发电机轴承故障振动特性,开展了考虑 UMP 的双馈异步风力发电机轴承外圈故障动力学建模研究。首先,基于赫兹接触理论构建了轴承外圈故障模型;然后,推导了正常和轴承故障下发电机转子的气隙磁密,得到了发电机转子受到的 UMP 解析式;最后,采用 Runge-Kutta 法对模型进行求解,得到了轴承故障振动响应。试验分析表明:所提动力学模型能够有效揭示双馈异步风力发电机轴承故障振动信号的双冲击现象,UMP 激励会影响风力发电机轴承外圈故障振动信号的调制特性。为风力发电机轴承故障诊断提供了新的理论参考。

**关键词:** 不平衡磁拉力; 动力学建模; 风力发电机; 轴承; 故障诊断

## 0 引言

双馈感应发电机(Doubly-Fed Induction Generator, DFIG)具有结构简单、可靠性高及制造成本低等优点,是风力发电机组的主流机型<sup>[1]</sup>。滚动轴承作为风力发电机的关键支撑部件,长期服役于恶劣环境和变载工况下,容易出现元件局部损伤,从而影响机组的正常运行<sup>[2]</sup>。建立正确、符合实际工况的双馈异步风力发电机轴承动力学模型,通过动力学研究揭示其故障振动机理,可为故障诊断提供理论参考。

集中参数法是构建动力学模型,揭示轴承振动特性的常用方法。Jones A B<sup>[3]</sup>考虑到轴系和

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支撑结构的弹性变形,提出了故障轴承拟静力学分析方法。Rubini R 等<sup>[4]</sup>通过简化单一故障模型对轴承振动信号进行研究,分析了故障轴承的振动特性。McFadden P D 和 Smith J D<sup>[5]</sup>将故障激励描述为一系列瞬态脉冲,用于模拟轴承在单点或多点缺陷情况下产生的振动。Jain P H 等<sup>[6]</sup>考虑轴承径向间隙和滚动体个数的影响,建立了二自由度模型。刘静等<sup>[7]</sup>提出了一种取决于缺陷尺寸的分段函数来描述故障接触激励。胡爱军等<sup>[8]</sup>考虑了滚动体与缺陷的相对几何关系,给出了接触力中刚度和形变的修正函数。罗茂林等<sup>[9-10]</sup>考虑了时变接触激励并建立了轴承双冲击动力学模型。

上述学者致力于研究轴承本身的非线性冲击,而发电机轴承在运行中还会受到转子不平衡磁拉力(Unbalanced Magnetic Pull, UMP)的影响。UMP 主要是由气隙偏心导致,转子安装偏心(静偏心)和质量偏心(动偏心)是形成气隙偏心的主要原因<sup>[11]</sup>。赖文海等<sup>[12]</sup>基于理论解析和有限元法,分析计算了转子偏心电磁力和挠度,推导了永磁同步电机 UMP 的解析表达式。赵道利等<sup>[13]</sup>利用能量法推导了气隙偏心 UMP,并将其表示成电磁刚度的形式,通过动力学方程分析了 UMP 对滚动转子-轴承系统碰摩特性的影响。唐贵基等<sup>[14]</sup>计算分析了动偏心、静偏心及复合偏心对汽轮发电机转子振动特性的影响并结合有限元仿真进行验证。郭少杰等<sup>[15]</sup>研究了 UMP 和轴承力对三相异步电机非线性振动的磁固耦合效应。张敖等<sup>[16]</sup>综合考虑陀螺效应、非线性轴承力和 UMP,建立了永磁同步电机偏置转子轴承系统耦合模型。以上文献主要研究转子动、静偏心引起的 UMP,而 Blodt M 等<sup>[17]</sup>研究发现,轴承缺陷会引起转子径向运动导致气隙周期性偏心。王晨等<sup>[18]</sup>在此基础上提出了一种通过定子电流估算轴承缺陷尺寸的新方法。

综上可知,不平衡磁拉力对风力发电机轴承振动特性的影响机制尚不清楚。因此本文以双馈异步风力发电机轴承为研究对象,通过分析轴承故障对转子气隙的影响,建立考虑 UMP 的 DFIG 轴承动力学模型。结合仿真与动态模拟试验研究不平衡磁拉力影响下双馈异步风力发电机轴承外圈故障的振动特性。本

研究可为风力发电机轴承外圈故障诊断提供新的理论参考。

## 1 动力学模型建立

### 1.1 整体系统模型

本文采用集中参数法对双馈异步风力发电机轴承-转子系统进行建模。转子轴承系统简化模型如图 1 所示,转子模型采用 Jeffcott 模型,包含一个刚度为  $k$  的无质量转轴,转轴中间是质量为  $m_1$  的转盘,转盘的偏心距为  $e$ ,转盘阻尼为  $c_1$ ,转盘角速度为  $\omega$ ,转子转轴两端采用滚动轴承支撑。 $O_1(x_1, y_1)$  为转子的形心,  $O_2(x_2, y_2)$  为轴承的形心,轴承的质量为  $m_2$ ,轴承阻尼为  $c_2$ 。模型考虑了轴承的 Hertz 接触力  $F^{\text{Hertz}}$  以及电机转子所受的不平衡磁拉力  $F^{\text{ump}}$ 。系统整体动力学方程如式 (1) 所示:

$$\begin{cases} m_1 \ddot{x}_1 + c_1 \dot{x}_1 + k(x_1 - x_2) = F_{x_1}^{\text{ump}} + m_1 e \omega^2 \cos(\omega t) \\ m_1 \ddot{y}_1 + c_1 \dot{y}_1 + k(y_1 - y_2) = F_{y_1}^{\text{ump}} - m_1 g + m_1 e \omega^2 \sin(\omega t) \\ m_2 \ddot{x}_2 + c_2 \dot{x}_2 + k(x_2 - x_1)/2 = F_{x_2}^{\text{Hertz}} \\ m_2 \ddot{y}_2 + c_2 \dot{y}_2 + k(y_2 - y_1)/2 = F_{y_2}^{\text{Hertz}} - m_2 g \end{cases} \quad (1)$$

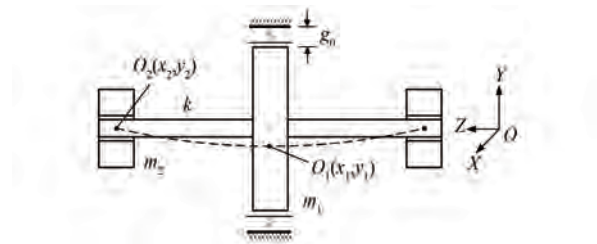


图 1 轴承-转子系统简化模型

Fig. 1 Simplified model of bearing-rotor system

### 1.2 轴承非线性接触力

#### 1.2.1 轴承系统简化

考虑到实际轴承内部受力复杂,为降低模型复杂性,提高计算效率,本文在进行动力学建模前对轴承系统进行简化。如图 2 所示,将滚动体与内外圈之间的接触简化为弹簧-阻尼系统且满足以下假设:

- 1) 轴承外圈固定在轴承座上,轴承内圈与电机转轴之间为过盈配合,二者之间无相对位移;
- 2) 保持架使滚动体沿轴均分布且相邻滚

动体之间距离恒定,相邻滚动体之间无相互作用;

3) 滚动体与轴承内外圈之间无相对滑动且无相对滑动满足 Hertz 接触条件;

4) 接触力仅作用在径向方向上;

5) 滚动体在运动过程中做纯滚动,忽略惯性力、油膜力等其他非线性因素的影响。

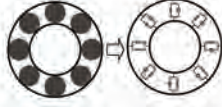


图 2 球轴承弹簧-阻尼系统简化模型

Fig. 2 Simplified model of ball bearing spring-damping system

### 1.2.2 轴承外圈故障模型

轴承几何关系如图 3 所示。参照图 2 及图 3,仅考虑轴承内圈两个方向( $x$  和  $y$  方向)的自由度构建轴承二自由度模型。

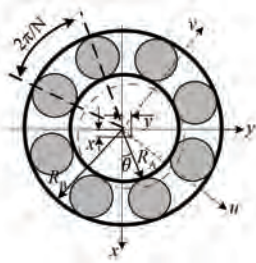


图 3 轴承几何关系示意图

Fig. 3 Schematic diagram of bearing geometric relations

轴承无故障时,假设  $x$  和  $y$  分别为轴承内圈相对于轴承中心在  $x$  和  $y$  方向上的位移量。第  $i$  个滚动体在运动的过程中与轴承内外圈之间的接触形变  $\delta_i$  可由式(2)确定:

$$\delta_i = x_i \cos \theta_i + y_i \sin \theta_i - \zeta \quad (2)$$

式中: $\zeta$  为轴承游隙; $\theta_i$  为第  $i$  个滚动体相对于  $x$  轴的角度位置,如图 3 所示, $\theta_i$  可由式(3)表示:

$$\theta_i = \omega \frac{R_B}{R_A + R_B} t + \frac{2\pi}{N}(i-1), i=1,2,\dots,N \quad (3)$$

式中: $\omega$  为转子角速度; $R_A$  和  $R_B$  分别为轴承内圈和外圈半径; $N$  为滚动体数。

当轴承外圈存在剥落缺陷时,第  $i$  个滚动体经过故障时会产生附加位移  $c_i$ 。如图 4 所示,故障产生的附加位移可以表示为关于时间  $t$ 、滚动体角位置  $\theta_i$ 、缺陷中心角位置  $\varphi_e$  以及缺陷宽度  $w$  的函数:

$$c_i = \begin{cases} l \times \cos \left[ \frac{\text{mod}(\theta_i, 2\pi) - \varphi_e}{w} \times \pi R_B \right], \\ -\frac{w}{2R_B} \leq \text{mod}(\theta_i, 2\pi) - \varphi_e \leq \frac{w}{2R_B} \\ 0, \text{其他} \end{cases} \quad (4)$$

式中: $l$  为最大故障深度。假设在轴承工作中滚动体不会接触缺陷底部,最大故障深度  $l$  可由滚动体半径  $R_b$  和缺陷宽度  $w$  确定,即:

$$l = R_b - \sqrt{R_b^2 - (w/2)^2} \quad (5)$$

基于以上分析,轴承外圈故障时,滚动体的接触形变  $\delta_i$  可表示为

$$\delta_i = x_i \cos \theta_i + y_i \sin \theta_i - \zeta - c_i \quad (6)$$

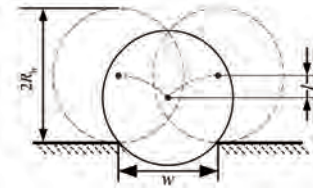


图 4 轴承故障示意图

Fig. 4 Schematic diagram of bearing fault

### 1.2.3 Hertz 接触力

轴承滚动体与外圈之间的接触为点接触,根据 Hertz 接触理论可得第  $i$  个滚动体与滚道之间的弹性恢复力  $F_i$  的表达式为

$$F_i = K_b [\delta_i]_+^{1.5} \quad (7)$$

式中: $K_b$  为轴承等效接触刚度。

当且仅当轴承滚子在受载区,即  $\delta_i > 0$  时才会产生弹性恢复力。考虑到 Hertz 接触力会随着滚动体位置的变化而改变,将 Hertz 接触力分解到水平和竖直方向上:

$$\begin{cases} F_x = \sum_{i=1}^N F_i \cos \theta_i \\ F_y = \sum_{i=1}^N F_i \sin \theta_i \end{cases} \quad (8)$$

### 1.3 气隙偏心及不平衡磁拉力

不平衡磁拉力的存在会影响转子-轴承系统的振动特性。Blodt M<sup>[17]</sup> 描述了轴承在单点故障状态下,电机气隙的变化规律。轴承单点损伤时,滚动体与轴承缺陷的接触会周期性地改变气隙长度。气隙长度的变化会影响气隙磁导,导致 UMP 的变化。

假设发电机不存在动偏心和静偏心, 正常情况下, 电机转子任意角度气隙长度可由平均气隙长度  $g_0$  表示。轴承发生故障时, 剥落缺陷会导致电机气隙产生周期性变化, 如图 5 所示。图中:  $a$  为单次故障冲击时间与电机旋转周期的比值;  $f_0$  为轴承故障特征频率。为了便于计算, 将发电机气隙最小处的角位置记为 0。外圈损伤时, 由于外圈固定, 电机最大偏心位置固定, 此时故障偏心可以视做周期性出现的静偏心。电机气隙可表示为

$$g_o(\theta, t) = g_0 [1 - e_o(t) \cos \theta] \quad (9)$$

式中:  $\theta$  为发电机转轴周向角;  $e_o(t)$  为外圈故障引起的时变相对偏心率;  $t$  为气隙出现的时间间隔, 设  $f_0$  为轴承外圈故障频率, 则  $t = n/f_0, n = 1, 2, 3 \dots$ 。

$e_o(t)$  可由狄拉克函数表示:

$$e_o(t) = e_0 \sum_{k=0}^{+\infty} \delta\left(t - \frac{n}{f_0}\right) \quad (10)$$

式中:  $e_0$  为气隙最大相对偏心度;  $\delta(\cdot)$  为狄拉克函数。

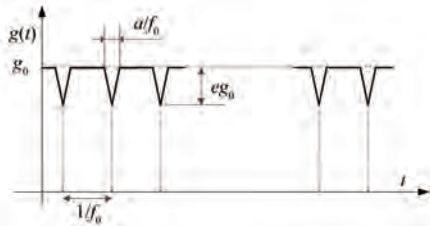


图 5 转子气隙随时间的变化

Fig. 5 Variation of rotor air gap with time

由上述分析可得, 轴承损伤时, 双馈异步电机气隙长度为

$$g(\theta, t) = g_0 [1 - e_o(t) \cos \theta - e_i(t) \cos(\theta + \omega t)] \quad (11)$$

式中:  $e_i(t)$  为内圈故障引起的时变相对偏心率。

忽略定子和转子表面的开槽效应, 气隙磁导为

$$\begin{aligned} \lambda(\theta, t) &= \frac{\mu_0}{g(\theta, t)} = \lambda_0 [1 + \delta_o(t) \cos \theta + \delta_o(t) \cos^2 \theta + \\ &\quad \delta_i(t) \cos(\omega t - \theta) + \delta_i(t) \cos^2(\omega t - \theta)] = \\ &\quad \lambda_0 + \lambda_o(t) \cos \theta + \lambda_o(t) \cos^2 \theta + \\ &\quad \lambda_i(t) \cos(\omega t - \theta) + \lambda_i(t) \cos^2(\omega t - \theta) \end{aligned} \quad (12)$$

式中:  $\mu_0$  为真空磁导率;  $\lambda_0$  为气隙磁导常值分量;  $\delta_i(t)$  和  $\delta_o(t)$  分别为内圈和外圈故障引起的时变相对偏心度;  $\lambda_o(t) = \lambda_0 \delta_o(t)$  为静偏心引起的时变磁导分量;  $\lambda_i(t) = \lambda_0 \delta_i(t)$  为动偏心引起的时变磁

导分量。

只考虑基波磁动势时, 磁动势为

$$f(\theta, t) = F_0 \cos(p\theta - \omega_s t + \varphi) \quad (13)$$

气隙偏心下的磁密为

$$\begin{aligned} B(\theta, t) &= f(\theta, t) \lambda(\theta, t) = \\ &F_0 \cos(p\theta - \omega_s t + \varphi) [\lambda_0 + \\ &\quad \lambda_o(t) \cos \theta + \lambda_i(t) \cos(\omega t - \theta)] \end{aligned} \quad (14)$$

式中:  $\varphi$  为基波合成磁势初始相角;  $F_0$  为基波合成磁势幅值;  $p$  为电机极对数, 本文以一台两对极风机为研究对象;  $\omega_s$  为发电机的同步转速, 且  $\omega_s = \omega$ 。

电机单位面积磁拉力可以表示为

$$q(\theta, t) = \frac{[B(\theta, t)]^2}{2\mu_0} \quad (15)$$

对单位面积磁拉力沿圆周方向进行积分得到转子所受的 UMP, 并将其分解到  $x$  和  $y$  方向:

$$\begin{cases} F_X^{\text{ump}} = LR \int_0^{2\pi} q(\theta, t) \cos \theta d\theta \\ F_Y^{\text{ump}} = LR \int_0^{2\pi} q(\theta, t) \sin \theta d\theta \end{cases} \quad (16)$$

式中:  $L$  为转子长度;  $R$  为转子半径。

将式 (14)、式 (15) 代入式 (16) 进行计算可得:

$$\begin{cases} F_X^{\text{ump}} = \frac{2LRF_0^2\pi}{\mu_0} [16\lambda_0\lambda_o(t) + 16\lambda_0\lambda_i(t) \cos(\omega t) + \\ \quad 4\lambda_o^2(t) \cos(2\omega t - 2\varphi) + 4\lambda_i^2(t) \cos(\omega t + 2\varphi) + \\ \quad \lambda_o(t)\lambda_i(t) \cos(2\varphi) + \lambda_o(t)\lambda_i(t) \cos(\omega t - 2\varphi)] \\ F_Y^{\text{ump}} = \frac{2LRF_0^2\pi}{\mu_0} [16\lambda_0\lambda_i(t) \sin(\omega t) + \\ \quad 4\lambda_o^2(t) \sin(2\omega t - 2\varphi) - 4\lambda_o^2(t) \sin(\omega t + 2\varphi) - \\ \quad \lambda_o(t)\lambda_i(t) \sin(2\varphi) + \lambda_o(t)\lambda_i(t) \sin(\omega t - 2\varphi)] \end{cases} \quad (17)$$

从式 (17) 中可以看出, 轴承外圈故障、内圈正常时,  $\lambda_i(t) = 0, \lambda_o(t) \neq 0$ , UMP 中含有转频的二倍频成分, 引起转子二倍频径向振动; 内圈故障、外圈正常时,  $\lambda_i(t) \neq 0, \lambda_o(t) = 0$ , UMP 中含有转频的一倍频成分, 引起转子一倍频径向振动; 内外圈均存在故障时, 转子同时存在一倍频和二倍频径向振动。

## 2 仿真分析

以 SKF6308 深沟球轴承为研究对象进行模



型验证,采用 4 阶 Runge-Kutta 法对模型进行求解,获得轴承的振动响应,其中计算步长为  $1/50\ 000\text{ s}$ ,位移初始值为  $1\times 10^{-7}\text{ m}$ ,初始速度为  $0\text{ m/s}$ ,外载荷  $W_s$  为  $200\text{ N}$ ,模型参数如表 1 所示。

表 1 模型参数

Tab. 1 Model parameters

| 参数名称                                             | 参数值                  |
|--------------------------------------------------|----------------------|
| 内圈直径 $D_i/\text{mm}$                             | 40                   |
| 外圈直径 $D_o/\text{mm}$                             | 90                   |
| 节圆直径 $d_p/\text{mm}$                             | 65                   |
| 滚动体半径 $R_b/\text{mm}$                            | 7.504                |
| 轴承游隙 $\zeta/\mu\text{m}$                         | 8                    |
| 滚动体数 $N$                                         | 8                    |
| 轴承质量 $m_2/\text{kg}$                             | 0.611                |
| 总接触刚度 $k_b/(\text{N}\cdot\text{m}^{-1})$         | $5.41\times 10^{10}$ |
| 阻尼 $c/(\text{N}\cdot\text{s}\cdot\text{m}^{-1})$ | 600                  |
| 转轴刚度 $k/(\text{N}\cdot\text{m}^{-1})$            | $2.52\times 10^8$    |
| 转子质量 $m_1/\text{kg}$                             | 2.6                  |
| 转子偏心距 $e/\text{m}$                               | 0.004                |

根据动力学模型进行仿真得到的信号如图 6 所示。由于初值原因,仿真信号前期有一定的幅值冲击,截取信号稳定段进行分析。从图 6(a)所示的时域图中可以明显的看出以外圈故障特征频率倒数  $1/f_o$  为间隔的冲击,同时还伴随着双冲击现象。如图 7 所示,轴承滚动体在进入和离开故障时会引起振动信号冲击,双冲击的时间间隔  $\Delta t$  与缺陷宽度  $w$  和轴承转速  $\omega$  有关,具体关系式如式(18)所示。通过测量双冲击的时间间隔可实现对轴承缺陷尺寸的定量检测。

$$\Delta t = \frac{w}{\omega R_b} \quad (18)$$

从图 6(b)可以看到其频谱低频段主要成分为外圈故障特征频率  $f_o$  及其倍频、共振频率  $f_m$ ,以及调制产生的谐波分量,同时还有一些微弱的频率成分。如图 6(c)所示,对信号进行包络分析可以看到电机转频和其二倍频。这表明轴承缺陷是引起轴承振动的主要原因,同时 UMP 也会导致轴承产生频率为二倍转频的振动。

### 3 试验验证

采用安徽朝坤测试设备有限公司生产的 10 系列双馈风力发电故障模拟试验台进行试验验证,如图 8 所示。试验在同步转速  $1\ 500\text{ rpm}$  下进行,数据采集器和加速度传感器用于测量垂直接

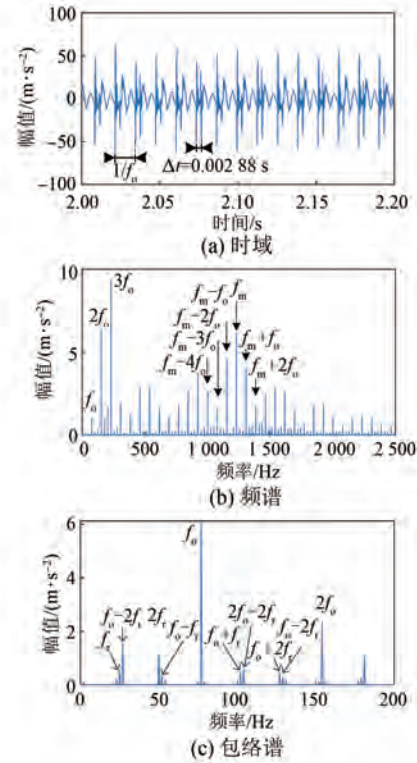


图 6 仿真信号

Fig. 6 Artificial signal

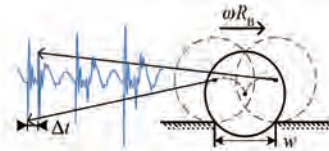


图 7 信号双冲击与滚动体运动对应关系示意图

Fig. 7 Schematic diagram of the correspondence between the double impact of the signal and the motion of the rolling element

向上的系统响应。采样频率选择为  $50\text{ kHz}$ ,测量点设置在发电机轴承端盖上。轴承滚道上存在局部故障,滚道上的凹槽通过线切割产生,以模拟局部故障,如图 9 所示。

通过试验得到的信号如图 10 所示。由图 10(b)所示的包络谱可知外圈故障特征频率  $f_o = 77\text{ Hz}$ ,转频  $f_r = 25\text{ Hz}$ ,二倍转频以及故障频率关于转频和二倍转频的调制,验证了所建立模型的有效性。

为验证所提模型在表征双冲击现象方面的正确性,本文在三种不同转速( $1\ 000\text{ rpm}$ 、 $1\ 500\text{ rpm}$ 和  $1\ 800\text{ rpm}$ )下对模型进行仿真。将仿真、理论计算和试验得到的时间间隔进行对比验证与误差

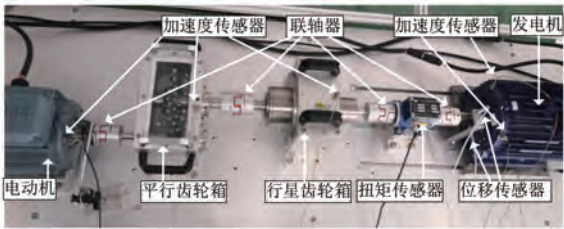


图 8 双馈风力发电故障模拟试验台  
Fig. 8 Doubly-fed wind power generation fault simulation test bench



图 9 测试轴承  
Fig. 9 Test bearing

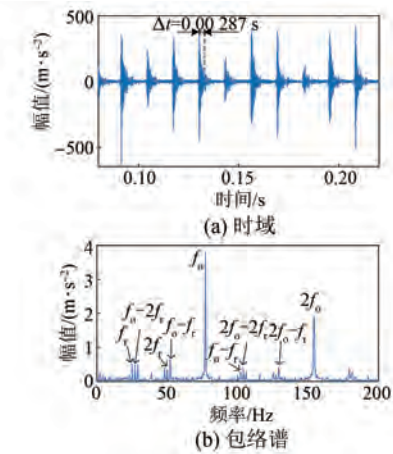


图 10 试验信号  
Fig. 10 Experiment signal

分析,结果如表 2 所示。从表中可以看出,在不同转速下仿真与理论计算的误差均在 1% 以下,试验值与理论值之间的误差不超过 6%,仿真与实测信号的时间间隔值对比均小于 6%。上述对比可验证本文所提模型在揭示轴承外圈故障双冲击特征时的有效性。

4 结语

本文在考虑双馈异步风力发电机轴承故障引起转子气隙变化的基础上,对 UMP 进行解析推导,构建考虑 UMP 影响的双馈异步风力发电机轴

表 2 双冲击时间间隔对比  
Tab. 2 Comparison of double impact time intervals

| 参数名称      | 转速/(r·min <sup>-1</sup> ) |           |           |
|-----------|---------------------------|-----------|-----------|
|           | 1 000                     | 1 500     | 1 800     |
| 理论时间间隔/s  | 0.004 329                 | 0.002 886 | 0.002 405 |
| 仿真时间间隔/s  | 0.004 32                  | 0.002 88  | 0.002 41  |
| 试验时间间隔/s  | 0.004 08                  | 0.002 86  | 0.002 54  |
| 理论与仿真误差/% | 0.208                     | 0.208     | 0.207 8   |
| 理论与试验误差/% | 5.752                     | 0.901     | 5.613 2   |
| 仿真与试验误差/% | 5.882 4                   | 0.699 3   | 5.118     |

承-转子系统的动力学模型。结合动态模拟试验探究了 UMP 影响下双馈异步风力发电机轴承的振动特性,得到如下结论:

- (1) 双馈异步风力发电机轴承外圈故障会使得转子受到 UMP。UMP 频率成分与轴承特征频率产生调制,在发电机轴承外圈故障频率及其倍频附近出现关于 UMP 频率成分的边频带,这有别于普通旋转机械轴承外圈的故障信号特征。本研究为双馈异步风力发电机轴承故障诊断提供依据。
- (2) 仿真及试验分析结果表明所提的动力学模型可有效表征发电机轴承故障双冲击现象,结合双冲击时间间隔和转速特征可对轴承外圈故障缺陷进行定量分析。

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## Dynamic Modeling of Doubly-Fed Wind Turbine Bearing Outer Ring Fault Considering Unbalanced Magnetic Pull

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**Key words:** unbalanced magnetic pull; dynamic modeling; wind turbine; bearing; fault diagnosis

Wind power is one of the primary sources of renewable energy, and wind power generation plays an increasingly crucial role in electricity production. The doubly-fed induction generator (DFIG), known for its simple structure, high reliability and low manufacturing costs, has gained widespread attention and become a major wind power generation technology. However, as critical components in DFIG systems, rolling bearings are susceptible to adverse environmental conditions and changing operational scenarios. This susceptibility can potentially lead to localized damage, threatening the overall stability and performance of the system. Therefore, to improve the accuracy of bearing fault diagnosis and the reliability of wind turbine generator units, it is essential to establish an accurate DFIG bearing dynamic model suitable for real-world conditions and explore the vibration mechanisms associated with faults.

This paper aims to delve into the impact of DFIG bearing faults on the vibration characteristics of wind turbine generator rotor bearing systems, with particular consideration given to the influence of rotor unbalance magnetic pull (UMP). Firstly, based on Hertz contact theory, the outer race fault model for the bearings is constructed and corrected according to the geometrical relationship between bearing spalling size and rolling element radius.

Subsequently, the effects of unbalance magnetic pull caused by bearing faults is analyzed. It is found that bearing defects induce periodic eccentricity in the rotor. Therefore, the air-gap magnetic flux

density of the motor rotor under both normal and bearing fault conditions is further derived to obtain an analytical expression for UMP.

Finally, a model of the bearing-rotor system of a doubly-fed wind turbine considering the unbalanced magnetic pulling force is constructed. And the Runge-Kutta method is used to solve the model and the vibration response of the bearing fault is obtained.

Through a comprehensive analysis of simulation signals, theoretical calculations, and experimental data, and by comparing the frequency components of the vibration signals and their time-domain characteristics, the following conclusions are drawn:

Outer race faults in motor bearings lead to the generation of UMP in the rotor. Under the influence of UMP, the bearings induce radial vibrations at twice the rotational speed frequency, providing critical clues for the early diagnosis of bearing faults.

The effectiveness of our model has been validated, including the comparison of double-impact time intervals, thus demonstrating the model's efficacy in capturing the phenomenon of double-impact associated with bearing faults. This paves the way for quantitative monitoring of bearing defect sizes.

In summary, this study provides crucial theoretical support for a deeper understanding of the vibration characteristics associated with DFIG bearing faults and their early diagnosis, which is of great significance for improving the reliability and performance of wind turbine generator units, and makes a positive contribution to the field of renewable energy.