Minimising Unbalanced Magnetic Pull in Doubly Fed Induction Generators

Citation for published version:
Chuan, HW & Shek, J 2019, 'Minimising Unbalanced Magnetic Pull in Doubly Fed Induction Generators', *Journal of Engineering*, vol. 2019, no. 17, pp. 4008 - 4011. https://doi.org/10.1049/joe.2018.8088

Digital Object Identifier (DOI):
10.1049/joe.2018.8088

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Journal of Engineering

Minimising Unbalanced Magnetic Pull in Doubly Fed Induction Generators

H. Chuan, J.Shek

Institute for Energy Systems, School of Engineering, The University of Edinburgh, United Kingdom,
Email: H.Chuan@ed.ac.uk

Keywords: Unbalanced Magnetic Pull, Doubly Fed Induction Generator, FEA

Abstract

The Doubly Fed Induction Generator (DFIG) has become increasingly popular in wind energy generation because of the lower power electronics converter rating required. However, the small airgap of a DFIG causes it to be vulnerable to slight misalignment of the rotor which may cause a large unbalanced magnetic pull (UMP) to be exerted on the bearing. The reliability of the generator is important to reduce revenue loss; this is especially the case for generators in offshore wind turbines where minimising the cost of energy is crucial in completing with more established forms of electricity generation. This paper had proposed the usage of stator damper windings to reduce the UMP. An example of a 4-pole DFIG with static eccentricity is shown where Finite Element Analysis (FEA) is used to verify the UMP for cases with and without damper windings. Finally, additional losses due to rotor eccentricity are discussed.

1 Introduction

Global warming and climate change has brought awareness on the importance of reducing carbon emissions. Switching from conventional fossil fuel-based electrical power generation to renewable energy can effectively reduce carbon emissions. Therefore, this move had been widely implemented by many countries. 26.2% of the electricity in the United Kingdom was generated by renewable energy sources in 2016 [1]. Wind energy generation is the most popular type renewable energy generation because of its maturity in technology. From the Wind Global Energy Council, wind turbines have been installed in more than 80 countries; more than 29 countries have installed more than 1000MW of wind turbines [2].

In recent years, offshore wind turbines had gained higher popularity because it could solve the lack of spaces and environmental issues that onshore wind generation suffered. Furthermore, offshore wind farms also offered a more steady wind speed and lower turbulence intensity if compared to onshore wind farms [3,4]. The total capacity of global offshore wind generation has increased more than 300% over the last five years from 4.1GW to 14GW. The UK has the largest share of offshore wind turbines occupying 36% of the world's total installed capacity [2]. However, the biggest risk for offshore renewable energy generation is its long downtime when failures occur because the accessibility for maintenance is limited [5]. This long downtime associated with offshore wind generation can lead to significant revenue loss [6]. Therefore, the reliability of wind turbines is important, especially offshore wind turbines.

The two main types of generator used in offshore wind turbine are squirrel cage induction generator (SCIG) and DFIG. As reported in [7], both types of induction generators have more than 90% of the overall share in generators for offshore wind farms. SCIG is more popular for a fixed speed wind turbine due to its simplicity. Meanwhile, DFIG is a better solution for a variable speed wind turbine because of the reduction of power rating in power electronics converter. Furthermore, DFIG can also solve the reactive power consumption problem that induction machines always encountered. Hence, using DFIG in wind energy generation has received increasing popularity [8].

According to [9], the percentage failure of components in induction machines are: bearing related (40%), stator related (38%), rotor related (10%) and others (12%). It shows that bearing failure has the highest percentage failure. As UMP exerts additional loading on the bearing, UMP is one of the factors that can cause bearing failure. UMP caused by the rotor eccentricity is going to be discussed in this paper. In addition, the installation of damper windings in DFIGs is further proposed in this paper.

2 Unbalanced Magnetic Pull

UMP is caused by uneven distribution of the magnetic flux around the airgap. One of the reasons that cause the uneven distribution of magnetic flux is rotor eccentricity where the magnetic reluctance around the airgap changes with the airgap length. The generation of UMP has been greatly discussed by many researchers [10,11,12]. In short, the changes of magnetic permeance around the airgap can cause an additional pole pair ± 1 magnetic flux harmonics in the airgap. The interaction between the ± 1 magnetic flux with its original pole pair magnetic flux produces UMP. The UMP calculation is shown in **Error! Reference source not found.**. It is based on the assumption that the rotor eccentricity is low, where $(\varepsilon_s \times B^p)$ is the magnitude of the ± 1 magnetic flux. From (1), the UMP is a function of the degree of eccentricity which causes induction machines to be vulnerable to UMP. As induction machines generally have a small airgap to reduce the magnetising current, a slight misalignment during assembly stage could produce a huge UMP. The UMP from static eccentricity could cause shaft flexing and also dynamic eccentricity [13]. Therefore, the UMP has a snowballing effect that will get worsen with time. It may end up cause contact between the stator and rotor that may damage the whole machine.

$$
\begin{aligned}
UMP = &\frac{\pi r L \varepsilon_s}{2\mu_0}\sum_{p=1}^{\infty} B^{p^2}(1+\cos(2\omega t)) \\
&+\frac{\pi r L \varepsilon_d}{4\mu_0}\sum_{P=1}^{\infty} B^{p^2}(\cos(\omega_r \mathrm{t})+\cos((2\omega-\omega_r)t)) \qquad (1)\\
&+\frac{\pi r L \varepsilon_d}{4\mu_0}\sum_{P=1}^{\infty} B^{p^2}(\cos(\omega_r \mathrm{t})+\cos((2\omega+\omega_r)t))
\end{aligned}
$$

where, r is the radius of the airgap. L is the axial length of the machine. B is the amplitude of the magnetic flux density, p is the pole pair number, ω is the supply frequency, ε_s is the degree of static eccentricity, ε_d is the degree of dynamic eccentricity and ω_r is the rotor rotational speed.

In order to reduce the UMP, the pole pair ± 1 magnetic flux harmonics need to be reduced. Minimising UMP with the usage of parallel winding in the machine is the method that will be discussed in this paper. When there is parallel winding in machines, the pole pair ± 1 magnetic flux could induce an electromagnetic force (EMF) on the windings which produce a counteracting flux to damp the pole pair ± 1 magnetic flux. Parallel windings can be either at the rotor or the stator.

For a SCIM, the cage rotor is naturally parallel connected. In [14], the author has shown that SCIMs can have 80% less UMP than wound rotor induction motors. Subsequently, some researchers also attempted to reduce UMP through having a parallel connected stator winding [15,16]. However, parallel connected stator winding would reduce the stator inductance and more winding turns are needed to prevent magnetic core saturation. Installation of an additional damper winding of pole pair ± 1 of the main winding at the stator is proposed by Dorrell [17]. Dorrell has investigated UMP in both SCIM and wound rotor induction machines. By using the idea from [17], a new set of damper windings are proposed to be used on a DFIG.

3 Damper Windings

The proposed damper windings are individually wound from one stator slot to its opposite stator slot which is 180° apart. This damper winding configuration only allow odd harmonics flux to be induced. Therefore, it is suitable to use in electrical machines with an even number of pole-pairs. EMF cannot be induced by the fundamental magnetic flux in the damper windings. When there is rotor eccentricity, the pole pair ± 1 of the fundamental magnetic flux can be induced in the damper windings. This would allow the counteracting flux from the damper windings to damp the pole pair ± 1 flux. Figure 1 shows the damper winding configuration for a stator with 36 slots.

Damping of UMP depends on the rotational speed of the pole pair ± 1 flux because of the reactance of the circuit changes with the magnetic flux frequency. Since the rotational speed of the fundamental magnetising flux of a DFIG is constant, the effect of UMP damping is the same at different rotor rotational speed if the damper windings are installed at the stator. Dorrell has shown that the UMP of SCIMs increase when the rotor rotational speed is close to either its +1 or -1 magnetic flux [17]. The rotational speed with higher UMP depends on the pole pair number of the machine. For example, a 4-pole machine has a higher UMP when running at the slip of +0.33 slip or -0.5 slip. In a fixed speed machine, the slip does not matter as much since it is not the machine operating slip. In addition, the UMP from the higher space harmonics is the dominant flux when running at this rotor slip which makes the UMP from the magnetising flux negligible. As DFIGs are variable speed generators that operate with a large range of rotor slip values, the UMP at certain rotational speed will have a higher UMP if the damper windings are located in the rotor.

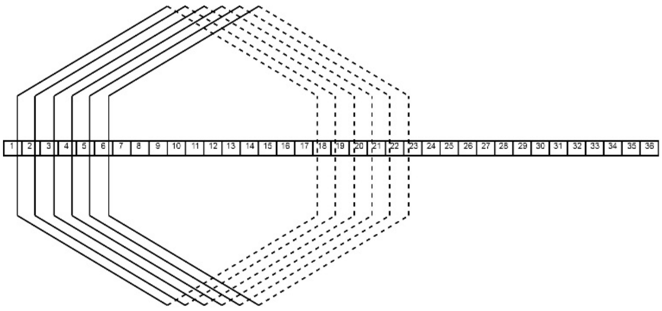

Figure 1: 6 of the damper windings configuration

3.1 Two pole-pair DFIG

A 2-pole pair 7.5kW DFIG with 36 stator slots and 48 rotor slots is used as an example and the supply frequency is set at 50Hz. Each damper winding has 5 turns. As UMP is proportional to the stator and rotor current, the torque of the machine is used as the x-axis parameter. Although the UMP damping effect is the same. The UMP of the DFIG running at super-synchronous speed at +20% (1800RPM) is shown in Figure 2. The machine is set at 20% of static eccentricity. The UMP results are taken at steady state.

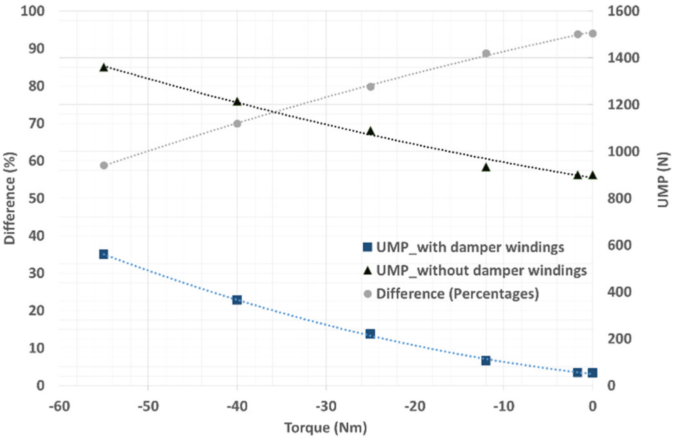

Figure 2: UMP comparison between with and without damper windings

From Figure 2, it is shown that damper windings can greatly reduce the UMP. However, the damper windings cannot damp the zigzag leakage flux or fringing flux because the flux does not induce EMF in the damper winding. Therefore, the effect of UMP damping decreases as the torque increases because higher space harmonics become the dominant flux as the slip increases. The difference in UMP between machines with and without damper windings decreases from 94% (no-load) to 62% (full-load, 48Nm).

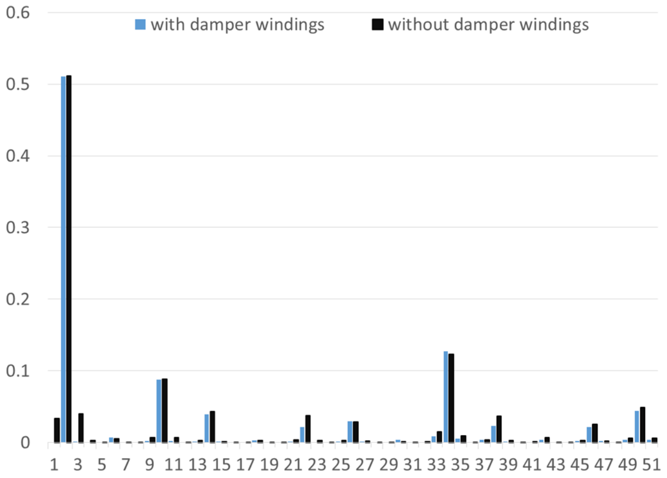

Figure 3: Space harmonics of the airgap flux

The airgap magnetic flux of the DFIG at -9Nm is shown in Figure 3. It is shown that the ±1 magnetic flux sideband (1^{st} and 3^{rd} harmonic) of the fundamental magnetising flux (2^{nd} harmonic) is greatly reduced. As the UMP is linearly proportional to the magnitude of the sideband, the UMP of the machine can be significantly lower.

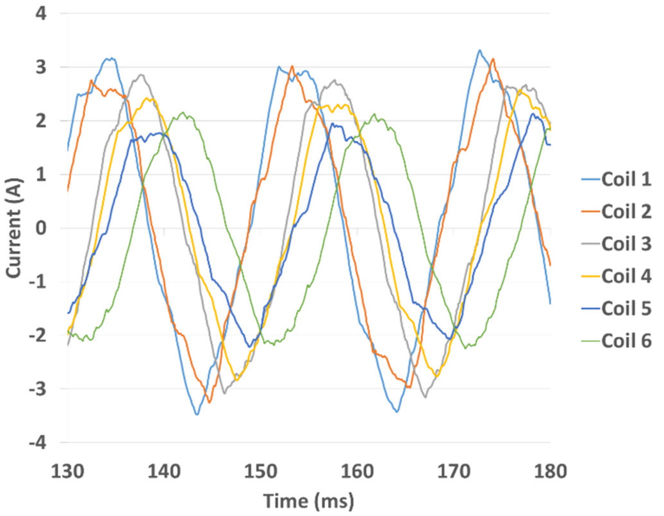

Figure 4: Current in 6 of the damper windings

Figure 4 shows the current in the damper windings. Coil 1 to Coil 6 are 10 degrees apart from each other. Coil 1 is wound from the stator slots that are closest to the narrowest airgap to the stator slots that are closest to the widest airgap. Therefore, there is higher flux difference which causes a greater induced current. Then, the current in the damper winding is smaller when the damper windings position is further away from the narrowest airgap. The magnitude of the current is only affected by the degree of eccentricity if the slight reduction of magnetising flux is neglected when the machine is loaded. For the DFIG with 20% of static eccentricity at 0.01 rotor slip, the copper loss of the damper windings is 1.5W.

4 Power losses due to rotor eccentricity

As the eccentric rotor causes uneven flux distribution around the airgap, this may cause additional power losses in an induction machine with rotor eccentricity. The two main additional losses are iron losses and bearing friction loss. The increment of iron losses is due to the existence of additional harmonics flux in the machine. Meanwhile, bearing friction loss is due to UMP causes additional radial force on the bearing.

Although rotor eccentricity will slightly increase the inductance and this will reduce the magnetising current, this has a minor effect on the copper losses, which is neglected. Furthermore, the additional pole pair magnetic flux could not induce EMF into the series connected stator and rotor winding. Therefore, the influence of rotor eccentricity towards copper losses is neglected.

4.1 Iron Losses

As the iron losses are a quadratic function of the peak magnetic flux density, additional pole pair flux would cause higher iron losses. The hysteresis loss and the eddy current loss formulas are shown in (2) and (3).

$$P_{loss\_H} = \sigma_H B^{\vartheta} f^{\rho} \tag{2}$$

$$P_{loss\_E} = \sigma_E B^2 {l_t}^2 f^2 \tag{3}$$

Where, σ_E is the power loss coefficient for eddy current loss and σ_H is the power loss coefficient for hysteresis loss, l_t is the lamination thickness, f is the frequency. ϑ and ρ are determined by curve fitting of the loss model from the measured data. For low frequency application, ϑ is assumed to be 2. Combining (2) and (3), power loss model is shown in (4).

$$P_{loss\_iron} = B^2\left(\sigma_E {l_t}^2 f^2 + \sigma_H f\right) \tag{4}$$

As the B in (4) is squared, finding the total harmonic distortion (THD) could find the increment of the iron loss due to an eccentric rotor. The THD is higher in an eccentric airgap. (5) shows the THD of the magnetic flux harmonics of a concentric rotor.

$$THD = \sqrt{\frac{1}{2}\varepsilon^2} \tag{5}$$

The total iron loss from an eccentric rotor is shown in (6). It has been demonstrated that the iron loss has an increment of $\frac{1}{2}\varepsilon^2$. For example, 50% of eccentricity would increase the iron loss by 12.5%.

$$P_{loss\_iron\_eccentric} = P_{loss\_iron}\left(1 + \frac{1}{2}\varepsilon^2\right) \tag{6}$$

The iron losses are not evenly distributed across the induction machine. For example, the tooth tips have a higher flux density than the back iron. However, the stator back iron contributes more than 70% of the total stator iron loss [18]. Therefore, FEA is used because it is suitable for estimating electromagnetic problems with a complicated geometry. For Figure 5, the predicted iron loss is based on (6) where the iron loss of a concentric rotor is simulated using FEA.

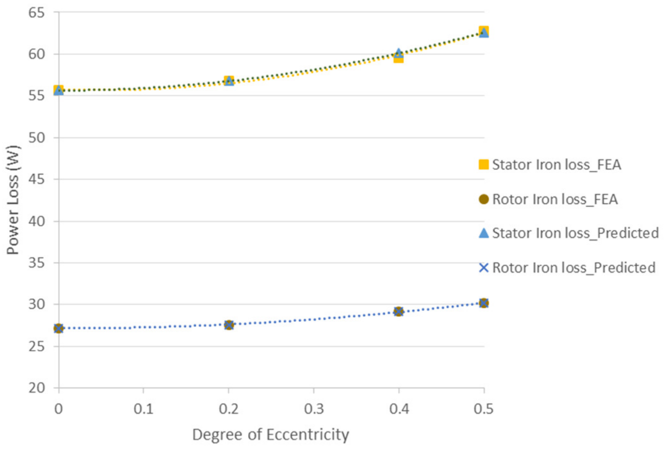

Figure 5: Iron losses with different rotor eccentricity

4.1 Bearing Frictional Loss

The frictional resistance of an object's relative motion creates frictional loss which results in heat generation. In a wind turbine generator, only 0.6% of energy consumption comes from bearing friction loss [19].

$$P_{loss\_friction} = \mu_{fric} r F_{eq} \omega_m \tag{7}$$

The instantaneous power loss due to friction force can be calculated from (7). The μ_{fric} is the friction coefficient, ω_m is the rotation speed of the rotor shaft, F_{eq} is the total force acting on the bearing.

$$F_{eq} = k\left(\overrightarrow{W_r} + \overrightarrow{UMP}\right) \tag{8}$$

Figure 6 shows the influence of UMP towards the bearing loss. It is the bearing friction loss calculation for a ball bearing with a friction coefficient of 0.002 and the diameter of 40mm. Only constant radial force is considered and the axial force is neglected. The weight and the UMP are assumed to be acting in the same direction. The weight of the rotor is 14kg with a rotational speed of 1500 rpm. Figure 6 has shows that the power loss increases as the UMP increases. For a DFIG with 20% static eccentricity, the UMP of the machine is 1.3kN when running at full load. This means that the bearing friction loss increases from 16W to 175W. So, in the 7.5kW DFIG, the UMP will reduce the overall efficiency of the machine by 2.1%.

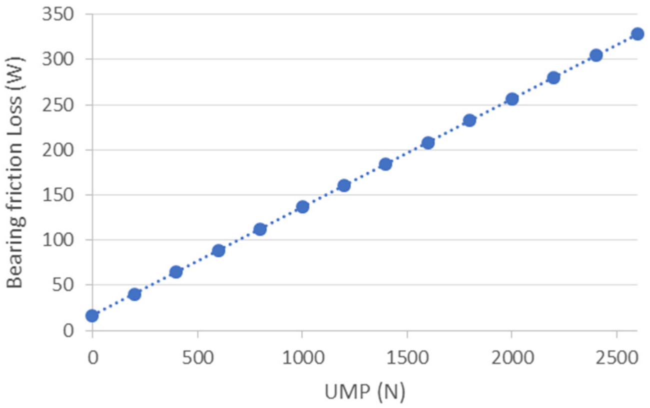

Figure 6: Bearing friction loss for different UMP

4.3 Summary

Figure 7 shows all the losses in the 7.5kW DFIG with 20% of static eccentricity. With the installation of damper windings in a DFIG, the iron losses can be reduced because damper windings produce counteracting flux to damp the pole pair ±1 magnetic flux harmonics. Although there is an additional copper loss from the damper winding, the iron losses can be reduced. When rotor eccentricity occurs and the windage loss is assumed to be constant, the main power loss in a DFIG comes from the bearing friction loss. Therefore, the power losses reduce significantly when the damper windings are used.

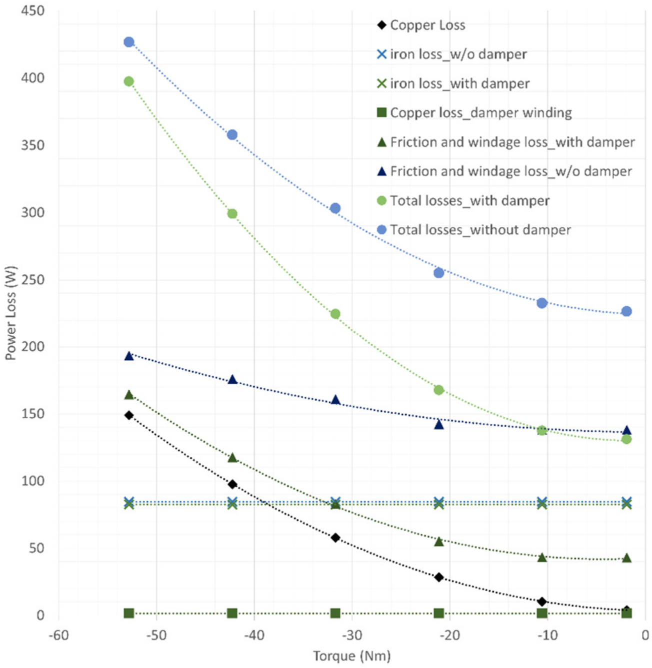

Figure 7: Power losses of a DFIG with 20% static eccentricity

5 Conclusions

UMP is caused by the additional pole-pair ±1 magnetic flux harmonics that is caused by rotor eccentricity. Usage of a set of damper windings in a DFIG is proposed to damp the odd harmonics. Therefore, the proposed damper winding is only suitable for DFIGs with an even pole-pair number. Subsequently, FEA is carried out on a 4-pole DFIG to verify the characteristics of the damper windings. The space harmonics of magnetic flux around the airgap and the current in the damper windings are analysed. Results have shown that UMP is reduced by 94% at no load and 62% at full load. Furthermore, additional power losses caused by the rotor eccentricity are discussed. Bearing frictional loss is the primary loss because UMP may increase the bearing load. By installing a set of damper windings, it not only increases the bearing lifetime but also reduce power losses.

References

[1] Department of Business Energy and Industrial Strategy, Digest of United Kingdom energy statistics 2017, [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/643414/DUKES_2017.pdf [Accessed: 30/10/2017]

[2] Sawyer S, Fried L, Shukla S, Liming Q. Global wind report: annual market update 2016. Technical Report, Global Wind Energy Counci.

[3] M. Stolpe, T. Buhl, B.M. Sumer, S. Kiil, J. Holbøll, and K. Piirainen, 2014. Offshore wind energy developments. In *Dtu International Energy Report 2014*. Technical University of Denmark.

[4] N. Gatzert, T. Kosub, , Risks and risk management of renewable energy projects: The case of onshore and offshore wind parks, Renewable and Sustainable Energy Reviews, Volume 60, July 2016, pp. 982-998.

[5] M. Shafiee, An optimal group maintenance policy for multi-unit offshore wind turbines located in remote areas," *2014 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, Durham, 2014, pp. 1-6.

[6] M. Shafiee, Maintenance logistics organization for offshore wind energy: Current progress and future perspectives, Renewable Energy, Volume 77, May 2015, pp. 182-193

[7] Z. Zhang, A. Chen, A. Matveev, R. Nilssen, A. Nysveen, High-power Generators for Offshore Wind Turbines, Energy Procedia, Volume 35, 2013, Pages 52-61

[8] A. Zin, M. Pesaran., A. Khairuddin, L. Jahanshaloo, O. Shariati, “An overview on doubly fed induction generators controls and contributions to wind based electricity generation,” In Renewable and Sustainable Energy Reviews, Volume 27, Nov 2013, pp. 692-708.

[9] L. M. Popa, B. B. Jensen, E. Ritchie and I. Boldea, "Condition monitoring of wind generators," *38th IAS Annual Meeting on Conference Record of the Industry Applications Conference,* 2003, pp. 1839-1846 vol.3

[10] D. G. Dorrell and M. F. Hsieh, "Calculation of Radial Forces in Cage Induction Motors at Start—The Effect of Rotor Differential," in *IEEE Transactions on Magnetics*, vol. 46, no. 8, pp. 3029-3032, Aug. 2010

[11] A. Burakov, A. Arkkio, "Comparison of the Unbalanced Magnetic Pull Mitigation by the Parallel Paths in the Stator and Rotor Windings," Magnetics, IEEE Transactions on , vol.43, no.12, pp.4083,4088, Dec. 2007

[12] H. Chuan and J. K. H. Shek, "Reducing Unbalanced Magnetic Pull of an induction machine through active control," *8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016)*, Glasgow, 2016, pp. 1-6.

[13] S. Nandi, T. C. Ilamparithi, S. B. Lee and D. Hyun, "Detection of Eccentricity Faults in Induction Machines Based on Nameplate Parameters," in *IEEE Transactions on Industrial Electronics*, vol. 58, no. 5, pp. 1673-1683, May 2011.

[14] M. Bradford, “Unbalanced Magnetic pull in a 6-pole induction motor,” Proceedings of Institution of Engineers, vol.115, Issue 11, November 1968.

[15] D. G. Dorrell and A. C. Smith, "Calculation of UMP in induction motors with series or parallel winding connections," in *IEEE Transactions on Energy Conversion*, vol. 9, no. 2, pp. 304-310, Jun 1994.

[16] A. Burakov, A. Arkkio, "Comparison of the Unbalanced Magnetic Pull Mitigation by the Parallel Paths in the Stator and Rotor Windings," Magnetics, IEEE Transactions on , vol.43, no.12, pp.4083,4088, Dec. 2007

[17] D.G. Dorrell,; Shek, J.K.H.; Mueller, M.A.; Min-Fu Hsieh, "Damper Windings in Induction Machines for Reduction of Unbalanced Magnetic Pull and Bearing

Wear," Industry Applications, IEEE Transactions on , vol.49, no.5, pp.2206,2216, Sept.-Oct. 2013

[18] D. M. Ionel, M. Popescu, S. J. Dellinger, T. J. E. Miller, R. J. Heideman and M. I. McGilp, "On the variation with flux and frequency of the core loss coefficients in electrical machines," in *IEEE Transactions on Industry Applications*, vol. 42, no. 3, pp. 658-667, May-June 2006

[19] Janssens, Marc, and S. K. F. France. "SKF Energy Efficient deep groove ball bearings for higher driveline efficiency." *Proceedings of the 6th International Conference EEMODS*. Vol. 9. 2009.