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Analysis of Fractional-Slot Axial-Flux PM Machines by 3-D FE Simulation

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***Abstract* — As the concept of hybrid electric vehicles and more electric aircraft are extending nowadays, achieving the desired performance along with decreasing the weight can be of the highest importance for the companies to save the fuel and decrease the costs. Axial-flux PM brushless-dc machines with concentrated windings provide high efficiency, compact construction, and high torque-density and are subsequently excellent choices to be used in direct-driven applications. As pole and slot combination has dominant effect on machine performance, this paper investigates effect of similar pole and slot numbers on machine's performance by three-dimensional finite-element (3-D FE) analysis. Air-gap flux density, back-electromotive force (back-EMF), cogging torque, winding inductance, and unbalanced torque exerted on bearings of two 3.4 kW axial-flux PM brushless-dc machines are obtained using 3-D FE method. It provides useful results to be considered in design of brushless-dc machines.**

Keywords* — *Axial Flux Permanent Magnet, Brushless Dc, Yokeless Segmented Stator, Cogging Torque, Unbalanced Torque, 3-D Finite Element

I. Introduction

World today is approaching toward applications with high reliability [1], high efficiency, and high power density while achieving low weight and low fuel consumption. For example, as the concept of hybrid electric vehicles and more electric aircraft are extending nowadays, achieving the desired performance along with decreasing the weight can be of the highest importance for the companies to save the fuel and decrease the costs [2]-[4].

Recently, axial-flux PM machine technology is developing [5]-[9]. Axial-flux PM brushless-dc machines with concentrated windings provide high efficiency, high power-density, ease of winding, compact construction; and are excellent choices to be used in direct-driven applications as in more electric aircrafts, electric vehicles and wind turbines [10]-[12], but when used in micro grids, the control selection mode should be taken care of to higher the chance of islanding detection [13].

There are different topologies for Axial-flux PM machines [14]. An Axial-flux PM machine with double-rotor, single-stator, yokeless, and segmented stator designed for electric vehicles [15-17], as shown in Fig. 1, is chosen for this study. Woolmer *et al* [16] analyzed the topology with sinusoidal back-EMF, and Jafarishiadeh *et al* [17] investigated this topology for brushless-dc operation, i.e. trapezoidal back-EMF. Also Jafarishiadeh *et al* [3] showed similar pole and slot combination is better choice with respect to torque-density and fault tolerance compared to conventional pole and slot combination. The machine has a single stator that is sandwiched between two surface-mounted PM rotor discs. Segmented stator with parallel slot-opening is employed so that high filling factor can be achieved.

Fig. 1. Axial-flux PM machine with segmented stator topology [16]

As mentioned before, high efficiency should be of highest importance for the companies to improve the performance and decrease the cost [18-20]. This increasing in the performance can lead to reduce the harmonics induced to the network which helps to reduce the final customer’s cost [21- 22]. In order to achieve high efficiency and decrease the cost by saving the fuel, it is important to decrease the total weight. Axial-flux PM brushless-dc machines with concentrated windings are candidate choices for direct-driven applications. One of the important steps in machine design is choosing number of pole and slot, which determines machine performance. The conventional ratio of number of slots to number of poles in PM brushless-dc machine, which yields to an easy simple winding configuration, is 3:2 [23], such as 15-slot/10-pole machine. This results in a low pitch factor and hence low winding factor and low torque. In the case of using similar slot number and pole number, higher pitch factor can be achieved which results in higher winding factor and hence higher flux linkage and output torque. So as the merit of an axial-flux PM brushless-dc machine is especially its high torque-density for applications with limited space, machines with similar slot number and pole number could be an excellent choice for these applications. This paper investigates axial-flux PM brushless-dc machines with similar number of slots and number of poles; i.e. combinations in which number of pole and number of slot differ by 1 or 2. Equal number of pole and number of slot is not practical. So two 10-pole axial-flux PM brushless-dc machines with similar slot and pole combination are considered: 9-slot/10-pole machine and 12-slot/10-pole

Table 1. Motor Parameters

Machine Type	*9-slot/10-ploe*	*12-slot/10-ploe*
Number of poles	**10**	**10**
Number of slots	**9**	**12**
Supply voltage, V	50	50
Phase current, A	34	34
Rated rotational speed, rpm	1200	1200
Stator outer radius, mm	95	95
Stator inner radius, mm	55	55
Slot-opening, mm	4	4
Tooth width at average radius, mm	27.41	35.27
pole-arc to pole-pitch ratio	0.7	0.7
Air gap, mm	1.5	1.5
Magnet axial length, mm	5	5
Magnet remanence, T	1.22	1.22
Number of turns per coil	33	25

machine. The investigation is carried to compare air-gap flux density, flux linkage, back-electromotive force (back-EMF), cogging torque, winding inductance, and unbalanced torque exerted on the bearings for the two machines, using three-dimensional finite-element (3-D FE) analysis. The two motor parameters are given in Table I. Fig. 2 (a) and (b) shows 9-slot/10-pole machine and 12-slot/10-pole machine; respectively.

II. Design Considerations

There are different ways to realize a motor with concentrated windings [24, 30]. It is assumed that the design is performed for three-phase motors with balanced windings which have two coils sides in each slot. The angles of the *k*th coil for the concentrated windings are defined as

$$\theta_c(k) = (k-1)\frac{p}{N_s}180^o E \qquad (1)$$
$$for \;\; k = 1, 2, \ldots, N_s$$

where p is the number of poles and N_s is the number of slots. With respect to (1) and for having balanced windings, the 3-phase winding arrangement is $A^/AA^/C^/CC^/B^/BB^/$ for the 9-slot/10-pole machine, while it is $AA^/C^/CBB^/A^/ACC^/B^/B$ for the 12-slot/10-pole machine. The winding factors K_{wn} can be achieved as

$$K_{wn} = \frac{1}{N_{cph}}\sum_{k=1}^{N_{cph}} e^{-jn\theta_c(k)} \qquad (2)$$

where N_{cph} represents number of coils per phase, and n is the order of harmonics.

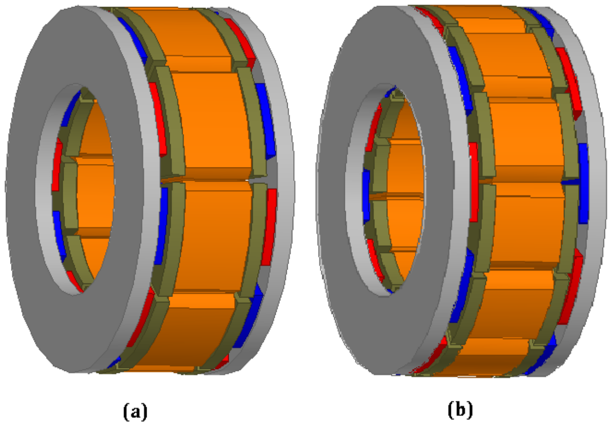

Fig. 2. Similar pole and slot combination. (a) 9-slot/10-ploe axial-flux motor (b) 12-slot/10-pole axial-flux motor

Analytical methods such as finite element have been widely used in order to study the performance of engineering structures. Chakherlou and Yaghoobi developed a finite element model to study the effect of cyclic loading on residual stress relaxation of engineering structures [24]. Finite element is also used by Yaghoobi [25] to determine deflection of 3D plates. This work uses finite element to study and predict the performance of engineering structures If saturation effects, stator and rotor slots, or exact geometric sizes are not neglected, these methods will be very complex. To solve this problem and obtain accurate results, the finite-element method is used which uses a precise analysis of magnetic materials considering geometric details and magnetic nonlinearity. Also, axial-flux PM machines are inherently 3-D machines [3]. It was demonstrated by Masoomi et al. [26] that to get accurate response, the results need to be mesh independent. Therefore, a 3-D FE model was developed using software MAXWELL [27] to study the accurate performance of the machines.

III. Finite-Element Simulation and Results

In axial-flux PM machine the main part of the air-gap flux is in axial direction (*z*-direction). Air-gap flux-density is equal to its axial component near stator poles. The air-gap flux-density distributions for the two machines at the average radius (*r=75 mm*) near stator poles is obtained from 3-D FE analysis, as shown in Fig. 3. The simulation modeling procedure explained in [28, 29] has been used here to account for the electric field distribution in the gap. This model very well covers the electric field and Cogging torque, which is caused by the interaction between PMs and stator teeth, is a pulsating torque which does not yield to a net effective torque, and its reduction is one of goals in slotted PM machine design [31]. Choosing number of slot and number of poles similar to each other, besides producing high torque, will benefit from low cogging torque. Cogging torque waveforms for the two motors were obtained using 3-D FE analysis as shown in Fig. 4. As can be seen, the peak to peak cogging torque of both machines is very low and less than 0.2 Nm. That is because greatest

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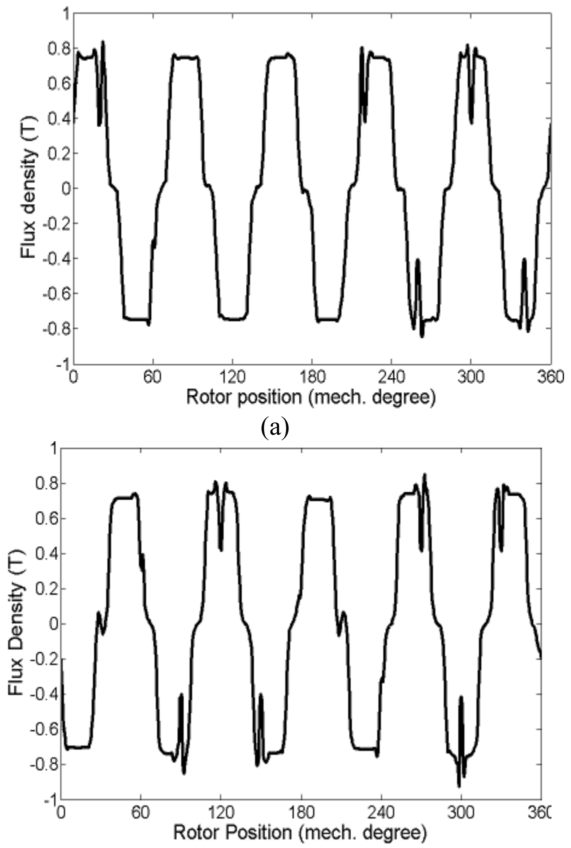
common divisor between pole number and slot number in 9-slot/10-pole machine and 12-slot/10-pole machine is 1 and 2; respectively. Hence cogging torque waveform components produced by the interaction of PMs and stator teeth are rarely in phase to each other. So peak cogging torque of both machines is very low. Fig. 5 (a) shows flux linkage per phase for the motors which is obtained by 3-D FE transient simulation. Phase back-EMF is one of the most important characteristics of the machine and is computed by the no-load change rate of flux linkage through the corresponding coils. In PM brushless-dc machine, phase-back-EMF waveform is desired to be more trapezoidal in order to have less torque ripples. Phase-back-EMF waveforms of 9-slot/10-pole motor and 12-slot/10-pole motor are obtained by using 3-D FE transient evaluation and shown in Fig. 5 (b). It is seen that both machines have a co-sinusoidal back-EMF waveforms, but the 12-slot/10-pole motor has a more trapezoidal back-EMF waveform compared to 9-slot/10-pole motor, which makes it better candidate for brushless-dc operation as it may have less torque ripples.



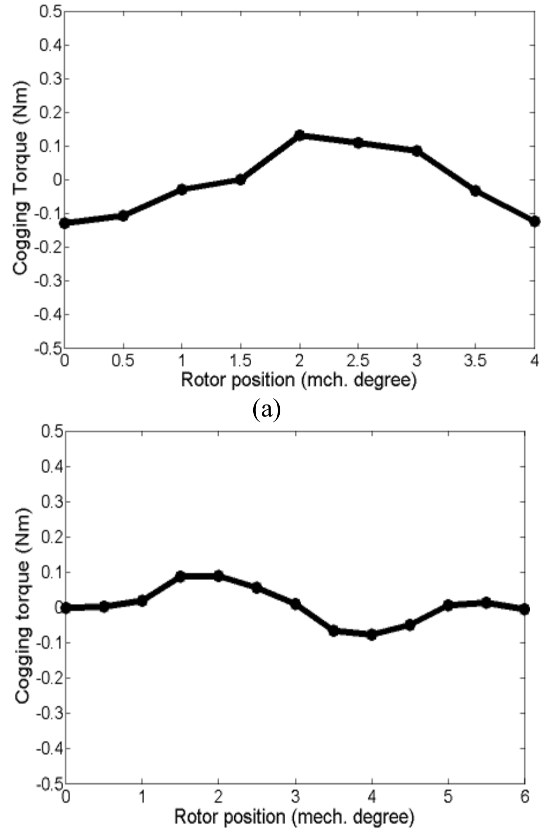
(a)

(b)

Fig. 3. 3-D FE flux density waveforms for (a) 9-slot/10-pole machine (b) 12-slot/10-pole machine

Table II shows self and mutual inductances of the two machines. It is seen that both machines with double-layer concentrated windings have good fault tolerance capability. The 9-slot/10-pole machine has higher self-inductance which can limit short circuit current better than 12-slot/10-pole machine. Also both machines have low mutual-inductance which will isolate phases from each other effectively. So 9-slot/10-pole machine has higher fault tolerance capability compared to 12-slot/10-pole machine.

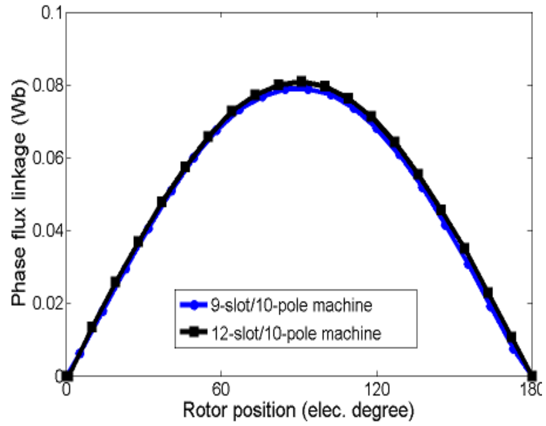
One of the main characteristics of axial-flux PM machines is high attraction axial force between PMs and stator teeth. For the axial-flux PM machines considered for this research, the total axial force exerted on each rotor discs obtained by 3-D FE analysis is from 2000 N to 2300 N, with respect to rotor position. So the bearing lifetime is of concern. It must be noted that in PM machines which number of slot and number of pole differ by 2, the number of slot is even, which results in symmetric disposition of stator slots and coils. But if asymmetric disposition of stator slots and coils exists, as in 9-



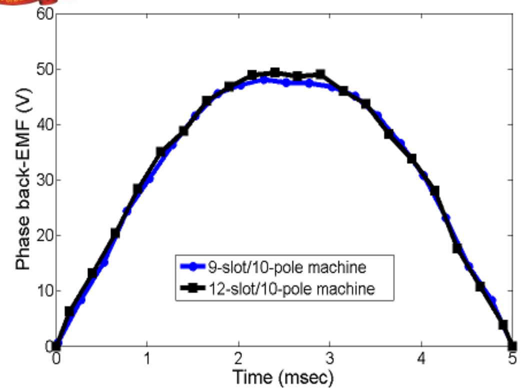
(a)

(b)

Fig. 4. 3-D FE cogging torque waveforms for (a) 9-slot/10-pole machine (b) 12-slot/10-pole machine



(a)



(b)

Fig. 5. (a) flux linkage waveforms by 3-D FE transient simulation (b) back-EMF waveforms by 3-D FE transient simulation

Table 2. Comparison of Self and Mutual Inductances

Machine Type	***Self-inductance (mH)***	***Mutual inductance (mH)***
9-slot/10-pole machine	1.77	0.110
12-slot/10-pole machine	1.21	0.106

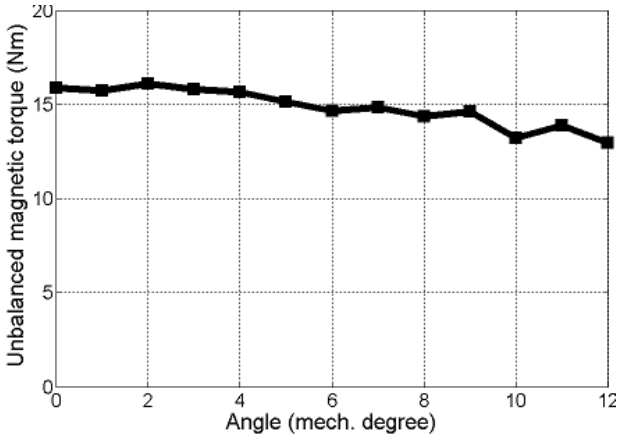


Fig. 6. 3-D FE unbalanced torque exerted on bearing in 9-slot/10-pole machine

slot/10-pole machine winding arrangement, an undesirable unbalanced torque is exerted on bearing. It must be clarified that desirable torque is around *z*-axis (axial-axis) and this undesirable torque exerting on bearings is around a variable axis that is orthogonal to z-axis. So the unbalanced torque will not affect machine's normal performance but applies extra force on rotor bearing and decreases its lifetime.

In 12-slot/10-pole machine the unbalanced torque does not exist due to symmetric winding arrangement. Fig. 6 shows unbalanced magnetic torque exerted on bearing obtained by 3-D-FE analysis in 9-slot/10-pole machine for one switching cycle. It is seen that the amount of this unbalanced torque is very high for such a small machine. This extra unbalanced torque can damage the bearing and shorten the lifetime. It must be noted that apart from high axial forces between PMs and stator teeth, and asymmetric disposition of stator coils, the motors are operated in brushless-dc mode (120^o elec. rectangular phase current waveforms) which intensifies the amount of undesirable unbalanced torque.

IV. Conclusion

Analysis and comparison of axial-flux PM brushless-dc machines having similar slot and pole combination was presented in this paper. The comparison was done for two 10-pole machines with the same dimension and phase current. It is shown that both machines which number of slot and number of pole differ by 1can better fulfill fault tolerance capability. Axial-flux PM brushless-dc machines which number of slot and number of pole differ by 2 have higher torque average along with less torque ripples which makes them more appropriate for applications requiring high torque-density. Also machines which number of slot and number of pole differ by 1 suffer from high extra unbalanced torque exerted on bearing which reduces its lifetime. So axial-flux PM brushless-dc machines which number of slot and number of pole differ by 2 are better choices.

References

[1] M. A. Chitsazan, A. M Trzynadlowski, “State Estimation of Power Systems with Interphase Power Controllers Using the WLS Algorithm”, *Energy Conversion Congress and Exposition (ECCE), 2016 IEEE*, Sep 2016, pp. 1-5.

[2] W. Cao, B. C. Mecrow, G. J. Atkinson, J. W. Bennett, and D. J. Atkinson, "Overview of electric motor technologies used for more electric aircraft (MEA)," *IEEE Trans. Ind. Electron.*, vol. 59, no. 9, Sep. 2012, pp. 3523–3531.

[3] I. Niazazari, H. A. Abyaneh, M. J. Farah, F. Safaei, and H. Nafisi, “Voltage profile and power factor improvement in PHEV charging station using a probabilistic model and flywheel,” *In Electrical Power Distribution Networks (EPDC), 2014 19th Conference on*, May. 2014, pp. 100-105.

[4] R. Jalilzadeh Hamidi and H. Livani, “Myopic real-time decentralized charging management of plug-in hybrid electric vehicles,” *EPSR*, vol. 143, 2017, pp. 522-532.

[5] S. Jafarishiadeh, M. Ardebili, A. Nazari Marashi, “Investigation of pole and slot numbers in axial-flux pm bldc motors with single-layer windings for electric vehicles,” 24th *Iranian Conference on Electrical Engineering (ICEE)*, 2016, pp. 1444-1448.

[6] W. Fei, P. C. K. Luk, and T. S. El-Hasan, “Rotor integrity design for a high-speed modular air-cored axial-flux permanent-magnet generator,” *IEEE Trans. Ind. Electron*., vol. 58, no. 9, Sep. 2011, pp. 3848–3858.

[7] H. Vansompel, P. Sergeant, L. Dupre, and A. Van den Bossche, " Axial-flux PM machines with variable air gap," *IEEE Trans. Ind. Electron.*, vol. 61, no. 2, Feb. 2014, pp. 730–737.

[8] S. Jafari-Shiadeh, M. Ardebili, and P. Moamaei, “Three-dimensional finite-element-model investigation of axial-flux PM BLDC machines with similar pole and slot combination for electric vehicles”, *Proceedings of Power and Energy Conference*, Illinois, 2015, pp. 1–4.

[9] R. Di Stefano and F. Marignetti, "Electromagnetic analysis of axial-flux permanent magnet synchronous machines with fractional windings with experimental validation," *IEEE Trans. Ind. Electron*., vol. 59, 2012, pp. 2573-2582.

[10] S. De, M. Rajne, S. Poosapati, C. Patel, and K. Gopakumar, " Low-inductance axial flux BLDC motor drive for more electric aircraft," *IET Power Electronics*, vol. 5, 2012, pp. 124-133.

[11] J. Zhao, D. Cheng, P. Zheng, X. Liu, C. Tong, S. Zhiyi, and Z. Lu, " Field weakening capability investigation of an axial flux permanent-magnet synchronous machine with radially sliding permanent magnets used for electric vehicles," *Journal of*

Applied Physics, vol. 111, issue 7, 2012, pp. 07A719 - 07A719-3.

[12] Y.S. Park, S.M. Jang, J.H. Choi, J.Y. Choi, and D.J. You, " Characteristic analysis on axial flux permanent magnet synchronous generator considering wind turbine characteristics according to wind speed for small-scale power application," *IEEE Trans. Magn*, vol. 48, issue 11, 2012, pp. 2937-2940.

[13] H. Jouybari Moghaddam, S. H. Hosseinian, B. Vahidi, and M. Ghiasi Rad, "Smart Control mode selection for proper operation of synchronous distributed generators", in *2nd Iranian Conference on Smart Grids*, 2012.

[14] M. Aydin, S. Huang and T.A. Lipo, "Axial flux permanent magnet disc machines: a review", *In Conf. Record of SPEEDAM*, May 2004, pp. 61-71.

[15] Seyyedmahdi Jafarishiadeh and Mahraz Amini, "Design and comparison of axial-flux PM BLDC motors for direct drive electric vehicles: conventional or similar slot and pole combination," *International Journal of Engineering Innovation & Research*, Vol. 6, No. 1, Jan. 2017, pp. 15-20.

[16] T. J. Woolmer, and M. D. McCulloch, "Analysis of the yokeless and segmented armature machine," *IEEE International Electric Machines & Drives Conference*, 2007, pp. 704-708.

[17] S. M. Jafari-Shiadeh and M. Ardebili, "Analysis and comparison of axial-flux permanent-magnet brushless-DC machines with fractional-slot concentrated-windings", *Proc. 4th Annu. Int. Power Electron., Drive Syst., Technol. Conf.*, 2013, pp. 72-77.

[18] M. A. Chitsazan, A. M Trzynadlowski, "Harmonic Mitigation in Interphase Power Controllers Using Passive Filter-Based Phase Shifting Transformer", *Energy Conversion Congress and Exposition (ECCE), 2016 IEEE*, Sep. 2016, pp. 1-5.

[19] Mohyeddin Rahmani, "A new residential load management system in presence of variable load and market price," *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering*, Vol. 5, Issue 2, February 2017, pp. 103-108.

[20] Sadeghi-Mobarakeh A, Mohsenian-Rad H. "Strategic selection of capacity and mileage bids in California ISO performance-based regulation market," *InPower and Energy Society General Meeting (PESGM)*, 2016, pp. 1-5.

[21] H. Norouzi, S. Abedi, R. Jamalzadeh, M. Ghiasi Rad, and S. H. Hosseinian, "Modeling and investigation of harmonic losses in optimal power flow and power system locational marginal pricing", *Energy*, vol. 68, 2014, pp. 140–147.

[22] M. Masoomi, Model development and load analysis of an offshore wind turbine, (2014).

[23] D. Ishak, Z. Q. Zhu, D. Howe, "Comparison of PM brushless motors, having either all teeth or alternate teeth wound," *IEEE Trans. Energy Convers*.,vol. 21, no. 1, March 2006.

[24] T. N. Chakherlou, A. Yaghoobi. "Numerical simulation of residual stress relaxation around a cold-expanded fastener hole under longitudinal cyclic loading using different kinematic hardening models." *Fatigue & Fracture of Engineering Materials & Structures*, vol. 33, no. 11, 2010, pp. 740-751.

[25] A. Yaghoobi. "ImplementatIon of nonlInear fInIte element UsIng object–orIented desIgn patterns." *Journal of Mechanical Engineering and Technology (JMET)*, vol 4, no. 1, 2012.

[26] M. Masoomi, S.M. Thompson, N. Shamsaei, L. Bian, "Effects of Inter-Layer Time Interval on Temperature Gradients in Direct Laser Deposited Ti-6Al-4V", *in: 27th Int. Solid Free. Fabr. Symp.*, 2016, pp. 175–184.

[27] D. C. Hanselman, Brushless Permanent- Magnet Motor Design, 2nd ed., McGraw-Hill, Inc, 2006.

[28] P. Gharghabi, P. Dordizadeh B., and K. Niayesh, "Impact of Metal Thickness and Field-Shaper on the Time-Variant Processes during Impulse Electromagnetic Forming in Tubular Geometries," *Journal of the Korean Physical Society*, vol. 59, no. 61, 2011, p. 3560-3566

[29] P. Dordizadeh-Basirabad, P. Gharghabi, and K. Niayesh, "Dynamic Analysis of a fast-acting Circuit breaker (Thompson) Drive Mechanism," *J. Korean Phys. Soc*., vol. 59, no. 6, 2011, p. 3547

[30] M. Dabbaghjamanesh, A. Moeini, M. Ashkaboosi, P. Khazaei, and K. Mirzapalangi. "High performance control of grid connected cascaded H-Bridge active rectifier based on type II-fuzzy logic controller with low frequency modulation technique." *International Journal of Electrical and Computer Engineering (IJECE)* vol. 6, no. 2, 2016, pp. 484-494.

[31] P. Khazaei, S. M. Modares, M. Dabbaghjamanesh, M. Almousa, and A. Moeini. "A high efficiency DC/DC boost converter for photovoltaic applications." *International Journal of Soft Computing and Engineering (IJSCE),* vol. 6, no. 2, 2016, pp. 2231-2307