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ELECTROMECHANICAL IMPACT OF POLES ON THE PERFORMANCE OF DOUBLE STATOR MACHINE

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Abstract

The electromechanical effect of rotor pole numbers on machine output parameters such as flux linkage, induced-voltage, torque, power and demagnetization of a double stator permanent magnet machine is presented in this study. The investigation is carried out through the application of MAXWELL-2D finite element software. The study revealed that the machine topology that has 11 rotor poles would have higher flux linkage, induced-electromotive force, torque and power amplitudes compared with other analyzed machine types. Nevertheless, the machine type that has 14-rotor poles would have the largest output torque, if the machine types are subjected to the same amount of permanent magnet material or volume. Also, the 14-pole machine type has the widest-speed coverage, an excellent quality for traction and vehicle applications. Similarly, the results revealed that the compared machine topologies have good capability against demagnetization effects. The largest shaft torque produced in the 10-pole, 11-pole, 13-pole and 14-pole machine types is 1.37 Nm, 2.44 Nm, 2.28 Nm and 1.47 Nm, respectively.

1.0 INTRODUCTION

The electromagnetic performances of electrical machines are heavily dependent among other factors on its number of rotor poles [1]. Thus, the effects of these pole numbers on the output performance of permanent magnet machine are carefully considered and compared in this present investigation. Although, the stator teeth or slot number is vital in determining the capabilities of a given electric machine, particularly the fault-tolerance potentials, as shown in [2]; however, the scope of the current investigation is limited to the impacts of rotor pole numbers alone. The great and joint impact of both the stator and rotor pole numbers as well as the significant influence of machine geometry on the resulting machine's winding factor values and its subsequent effect on the overall electromagnetic performance of a typical flux-modulating machine is presented in [3]. Additionally, both the usable and unwanted machine characteristics are influenced by the machine's rotor geometry, as presented [4], with experimental proof.

Similarly, the gear ratios, transmission torques, efficiencies and even the unattractive machine variables like the no-load torque of flux-modulated permanent magnet (FMPM) machines are very sensitive to its pole pairs, as demonstrated in [5] and

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[6]. It is worth noting that the compared machine in this present investigation is also an FMPM machine, due to the machine's ability to modulate the generated magnetic fields in the entire system using the modulating steel ring, i.e. the cup-shaped rotor structure, for effective torque production. Further, the studies in [7] have re-confirmed that the influences of these performance indices could be enormous on the machines' overall electromagnetic performance, including the resultant power and average torque of the device. Nevertheless, the predictions in [7] are conducted mainly with numerical modelling methods, which may lack some level of precisions compared to the implemented finite element analysis (FEA) approach, in this current investigation.

Furthermore, most of the machine's performance metrics could be affected considerably, either positively or otherwise by controlling its rotor pole numbers, as confirmed in [8]. More so, the studies in [9] revealed that the generated magneto-motive force of permanent magnet machine (PMM) could be classified according to its magnetization arrangement, by considering the machine's pole number formation using its available harmonic elements. Meanwhile, the effectiveness of this classification would basically depend also upon its adopted winding type; that is, either the distributed or single-toothed winding style. Saliency ratio which is dependent upon the direct-axis and quadrature-axis components of a machine is vital in determining the machine's output values; however, enhanced output performance could be attained by introducing static capacitive element in the system, because this capacitive arrangement has a way of increasing the electric loading potential of the machine [10]. Machine axis-component theory is a concept that converts multiphase variables to its two-axis equivalents, using relevant mathematical transformation expressions. A machine's electromagnetic torque is invariably related to its saliency ratio worth, as demonstrated by [11]. Moreover, structural variables of any given electric machine have considerable effect on its output performances [12]. Thus, great attention should be given to these variables at the early design stage of the machine, for better output performance.

Performance metrics such as flux linkage, induced-electromotive force, demagnetization characteristics, torque and power values of a two-stator machine are investigated and compared, with special reference to the effect of its rotor pole numbers, for potential direct–drive uses. The background study is presented in Section 1. Machine description and the employed method are presented in Section 2. The results and its discussions are provided in Section 3. The investigation is concluded in Section 4.

2.0 MACHINE DESCRIPTION AND METHODOLOGY

Figure 1 shows the investigated machine schematic; it is shown that the analyzed machine has two-stator parts, a rotor in ring form and magnets, for its self-excitation. Similarly, its magnetic flux line distributions on open-circuit condition are shown in Figure 2. It is inferred from Figure 2 that the generated flux per pole is inversely proportional to the machines' pole numbers. The analyzed machine has two different stators. In general, two-stator machines have lots of merits over its single stator counterparts, particularly the flux-switching (FS) types [13]; albeit, with some demerits such as high cost of production. Nevertheless, the cost implication could be drastically reduced, if an integrated double stator machine is operated as two independent machines in parallel, as presented in [14]. It is worth mentioning that the compared machine in this present study is a member of the FS machine family. The outer stator radius of the compared machine is 45 mm. It has an active axial length of 25 mm. The employed magnet type is the rare-earth grade of neodymium-iron-boron (Nd–Fe–B) material and having magnetic flux density of 1.2 Tesla.

Similarly, the core sections of the investigated machine are made of silicon steel material. The analyzed machine has armature conductors in its inner and outer stators, though the permanent magnets are located only in the inner stator. Meanwhile, the analyzed machine belongs to both flux-switching permanent magnet machine (FSPMM) and magnetically-geared permanent magnet machine, owing to its dual operating modes. The predicted results are obtained using the MAXWELL–2D finite element analysis (FEA) over an electric period. The electromagnetic torque (T) of a given FSPMM is estimated using Equation (1). Similarly, symmetric electromotive force (EMF) waveforms in FSPMMs could only be realized if Equation (2) is satisfied, such that an even number/integer must ensue from the mathematical expression, as established in [15]. The resulting EMF waveforms of PMMs could be modified and improved through adequate control skills, such as current pulse injection [9]. Thus, the asymmetrical waveforms of the other machine parameters of the analyzed machine types could invariably be influenced by the status of its Equation (2).

$$T = 1.5P_r\left(\psi_d i_q - \psi_q i_d\right) \quad (1)$$

Where, P_r is the number of rotor poles, ψ_d and ψ_q are the inductances in the direct- and quadrature-axis directions, i_d and i_q are the corresponding axis currents [16].

$$\frac{P_s}{HCF(P_s,P_r)} = 2km \quad (2)$$

P_s and P_r is the stator and rotor pole numbers, *HCF* is the highest common multiple between the poles, *m* is the number of phases, and k=1, 2, 3 …

The modulating ring in this work is the rotor, which modulates the magnetic fields of both the magnets and the coil-conductors, for the generation of improved flux linkage and EMF values, using the well-known flux-focusing techniques of spoke-array magnets. Meanwhile, the inner and outer stator coil-conductors are in series with each other, for enhanced overall electromagnetic output.

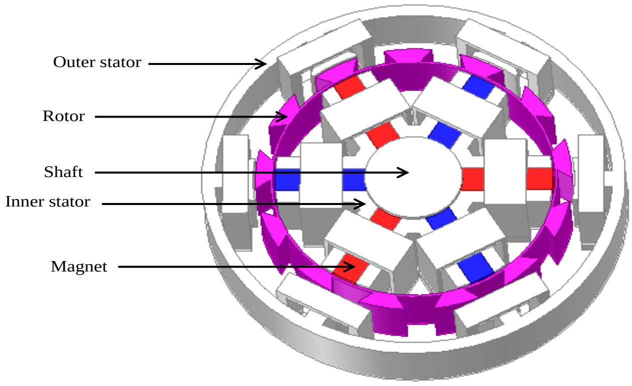

Figure 1: The analyzed machine, 13-pole model [17]

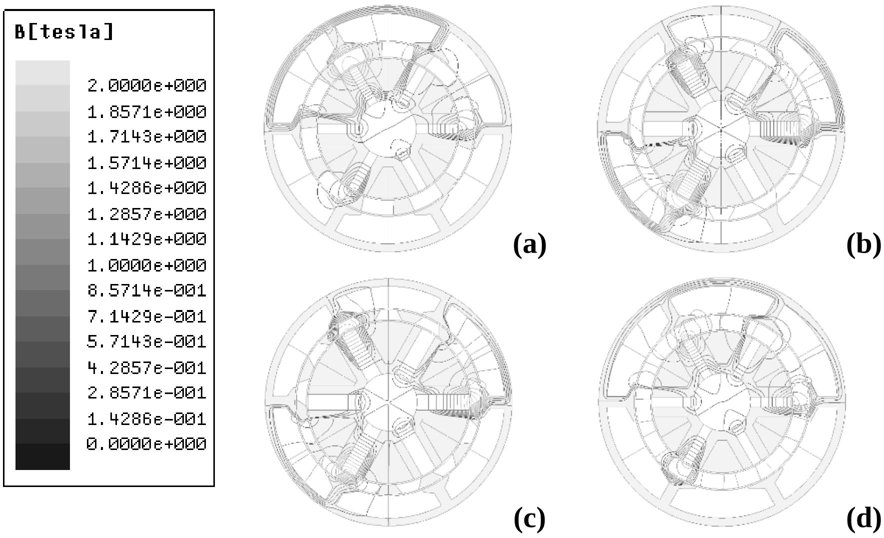

Figure 2: Magnetic flux lines (a) 10-pole (b) 11-pole (c) 13-pole and (d) 14-pole

3.0 RESULTS AND DISCUSION

The phase flux linkage values of the compared machine types are presented in Figure 3(a). It is observed that the flux linkage is independent of the motor's rotational speed. However, the highest fast Fourier transform (FFT) magnitude of the flux linkage is realized from the 11-pole machine, while the least value is recorded in the 14-pole equivalent. Similarly, amplitudes of the induced-electromotive force (EMF) in the compared machines show that the electric loading would affect its resultant values, especially when the machines are saturated, owing to the influence of armature reactions. Overall, the machine types that have odd number of poles would have larger value of induced-EMF, as observed from Figure 3(b).

Also, the electromagnetic torque waveforms of the compared machine types with its resulting harmonic orders are displayed in Figure 4(a) and 4(b), respectively. Again, the most competitive torque is produced by the machine type having 11 poles, followed by its 13-pole counterpart. The presence of the sixth (6^{th}) order torque harmonic component shows an indication of the existence of torque pulsation in the simulated machine, as suggested in [18]. More so, the conspicuous tripling torque harmonics of the compared machines is caused by the consequent effect of its EMF harmonics.

Similarly, it is shown in Figure 5(a) that the resulting average torque in the compared machines would be largest in the machine type that has 11-pole rotor number, while the least case scenario would be seen in the machine type that has 10 rotor poles. It is worth noting that number of torque pulsations in one electric revolution would be dependent upon its stator and rotor number arrangement; it is noted that the 10-pole and 14-pole machine types have three (3) pulsation cycles in one electric period of the simulated machines, while the 11-pole and 13-pole machine types have twice that number of pulsations i.e. six (6) pulsation cycles per electric period.

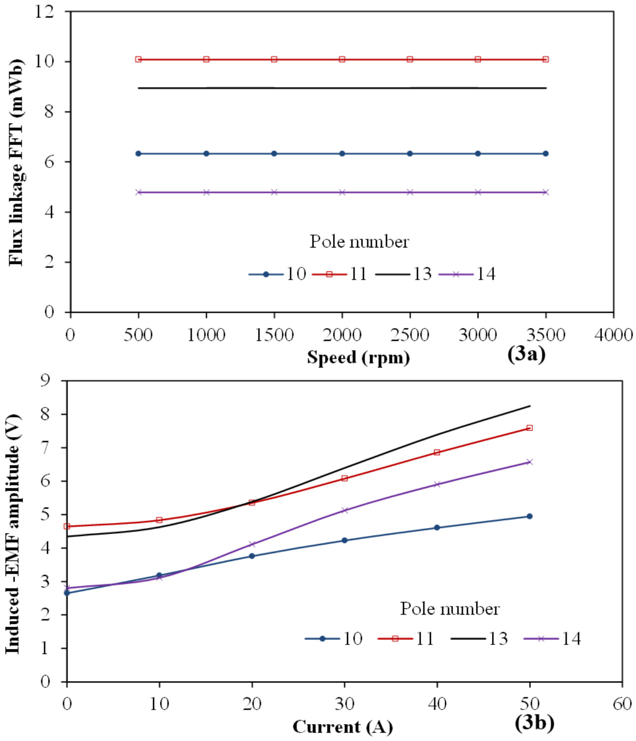

Figure 3: Flux linkage and induced-electromotive force, 400 rpm **(a)** Flux linkage versus speed **(b)** Induced-EMF versus current

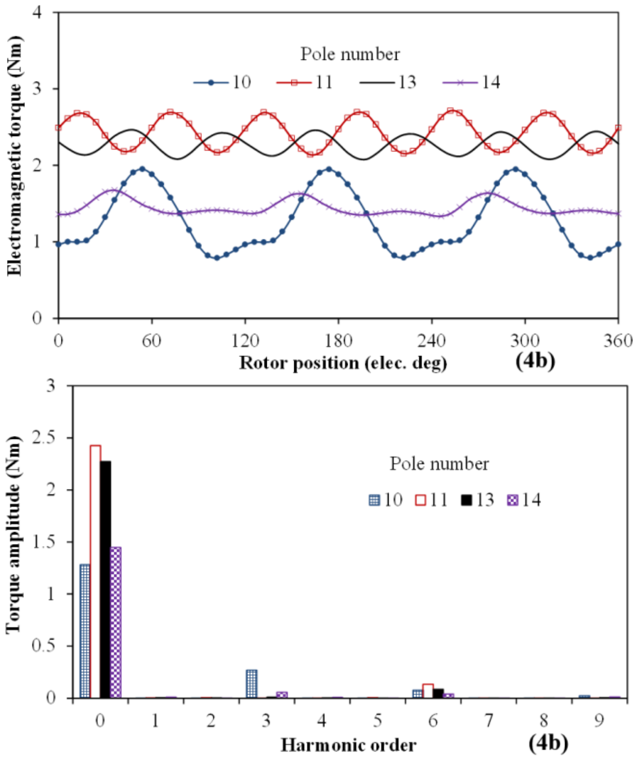

Figure 4: Comparison of electromagnetic torque, 400 rpm at 15 A **(a)** Torque versus rotor position, **(b)** Harmonic spectra

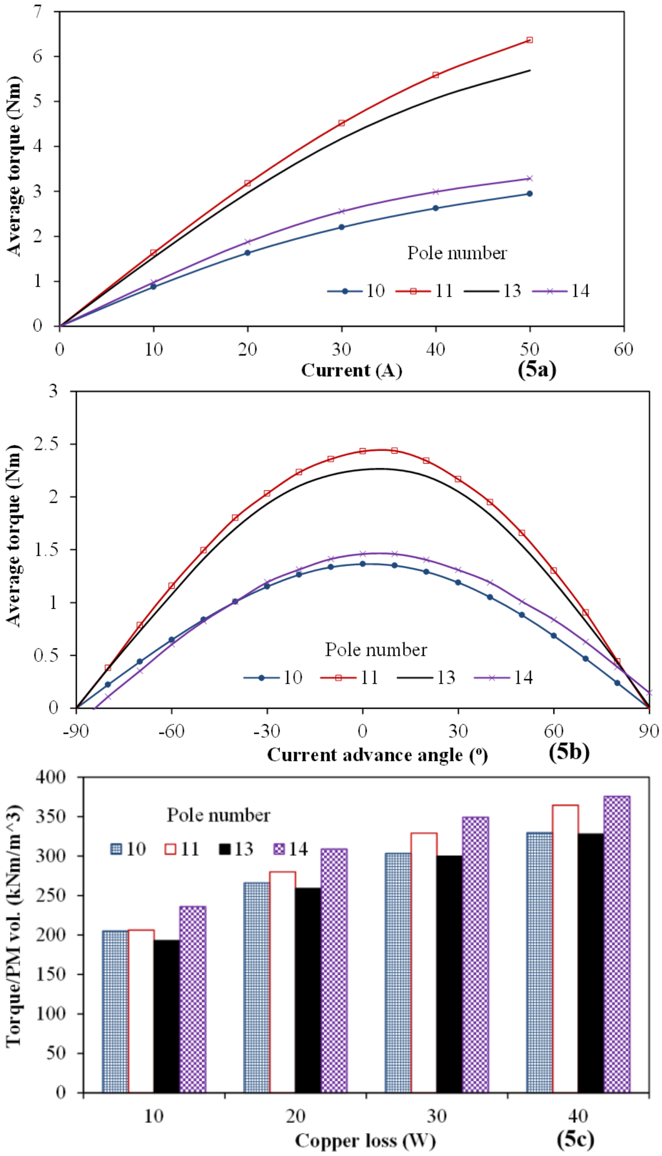

Figure 5: Comparison of average torque, 400 rpm **(a)** Average torque versus current, **(b)** Average torque versus current advance angle and **(c)** Torque per magnet volume

Due to the asymmetric EMF waveforms of the compared machines that have 10-and 14-pole numbers; the resulting maximum torque variation with the current advance angle of these categories does not coincide at the zero point, as seen in Figure 5(b). This asymmetry is usually caused by the machine's unwanted voltage and current harmonic components. The mentioned categories of machine naturally have large harmonic elements and thus, the consequent asymmetric outlines. Further, the predicted finite element analysis (FEA) result of Figure 5(c) show that the machine types that is furnished with 14 rotor poles would be most

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promising in terms of output torque, if all the machines are subjected to the same volume of permanent magnet material. Hence, by implication, the 14-pole machine type would also be the most economical machine to be manufactured, considering the high price of magnet materials, occasioned by its market monopoly.

Furthermore, the static torque outlines of the simulated machine types are depicted in Figure 6, at a maximum current rating of 15 A, such that the Phase A current (I_a), Phase B current (I_b) and Phase C current (I_c) are conducted under the simulation condition: I_a=-$2I_b$=-$2I_c$. It is worth mentioning that the machine types that have odd number of rotor poles exhibit symmetrical static torque waveforms over the considered rotor angular positions, unlike their counterparts that have even number of rotor poles. It is also revealed that the resulting magnitudes of the static torques would be a function of the applied load current; thus, the higher the supplied current, then the larger the resulting static torque value, and vice-versa. Meanwhile, the largest static torque profile is obtained in the 11-pole machine topology.

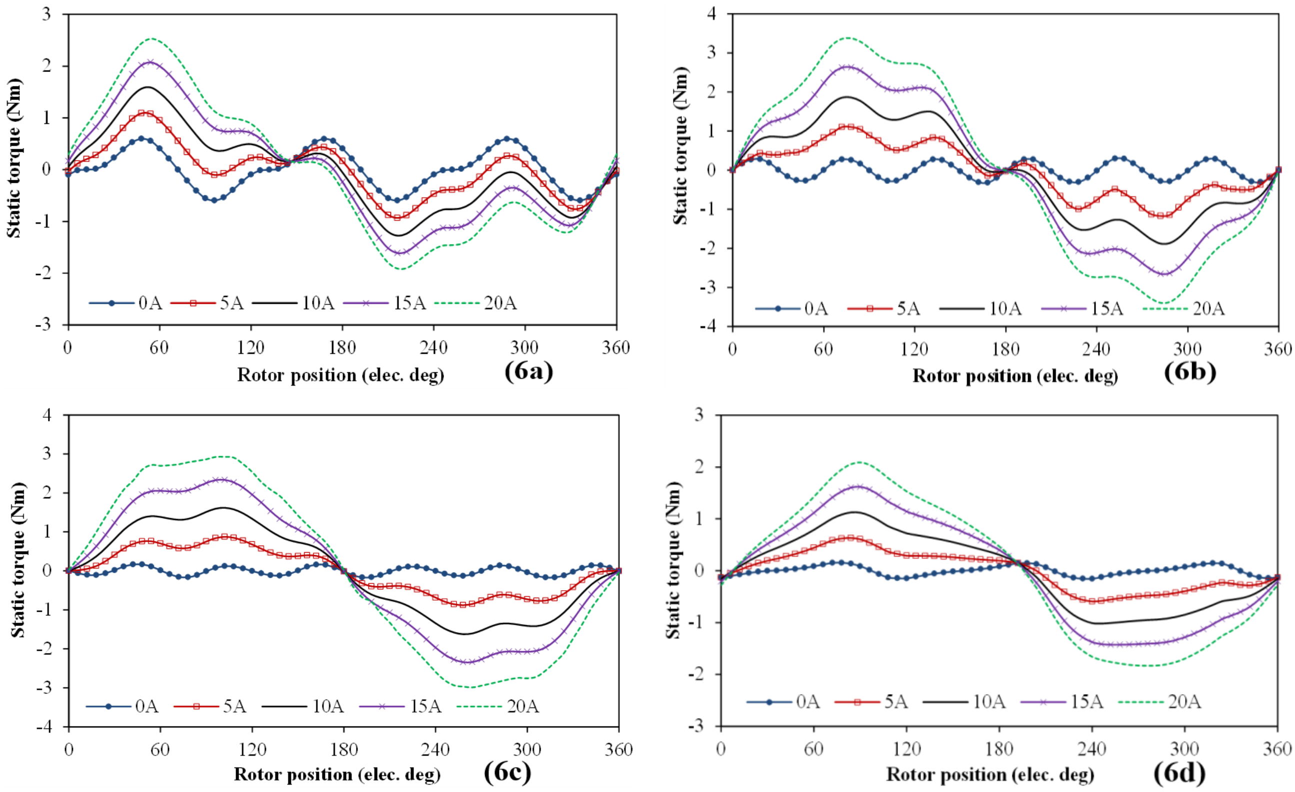
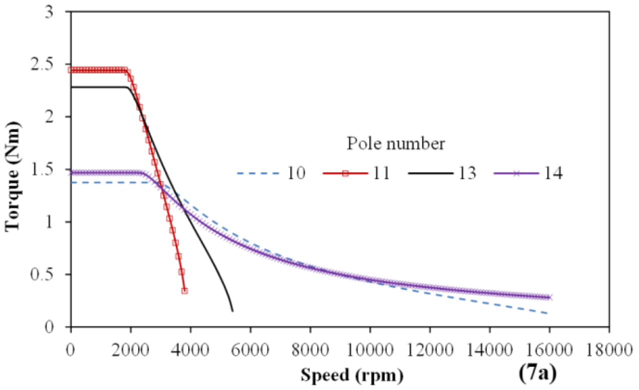


Figure 6: Comparison of static torque at 400 rpm, I_a=-$2I_b$=-$2I_c$ **(a)** 10-pole, **(b)** 11-pole, **(c)** 13-pole and **(d)** 14-pole

Figure 7 shows the torque-speed and power-speed outlines of the compared machine types, simulated under a maximum current of 15 A and maximum direct current (DC) voltage of 22.9 V. It is observed that the generated shaft torque and power are largest in the machine topology having 11-rotor poles; however, with short speed range. The machine configuration that has 14 poles has the widest speed coverage, and this particular quality is wanted in traction and vehicle/automobile applications. Hence, the 14-pole machine would exhibit the best flux-weakening capability amongst all the compared machine types i.e. at constant power operating mode. The 10-pole machine configuration also exhibits good flux-weakening ability as shown from Figure 7. However, the speed range of a given permanent magnet machine could be extended by manipulating its axis inductances through appropriate injection of negative or demagnetizing current densities in the machine, as provided in [19]. More so, the demagnetization plots of the compared machines during constant power or flux-weakening situation are presented in Figure 8. In general, it is deduced that the simulated machine topologies would be able to resist partial or full demagnetization influence on its magnets. This good attribute is an inherent worth of flux switching permanent magnet machines [20], to which the analyzed machine belongs to. Nevertheless, high influence of fault conditions such as short-circuit current or extreme overload situation as well as high thermal effects could adversely hike the demagnetization impact of a given permanent magnet machine, as highlighted and deduced from [21] and [22].



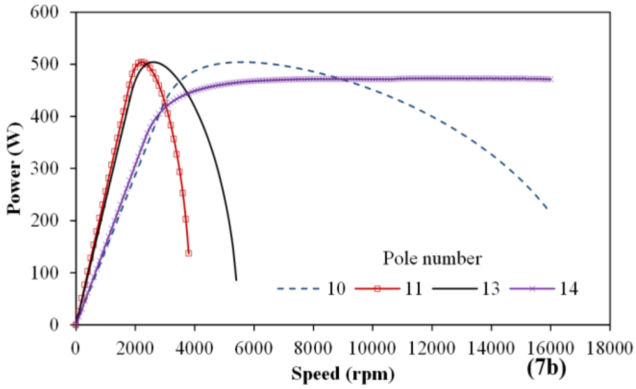


Figure 7: Torque-speed and power-speed comparisons at 15 A **(a)** Torque versus speed **(b)** Power versus speed

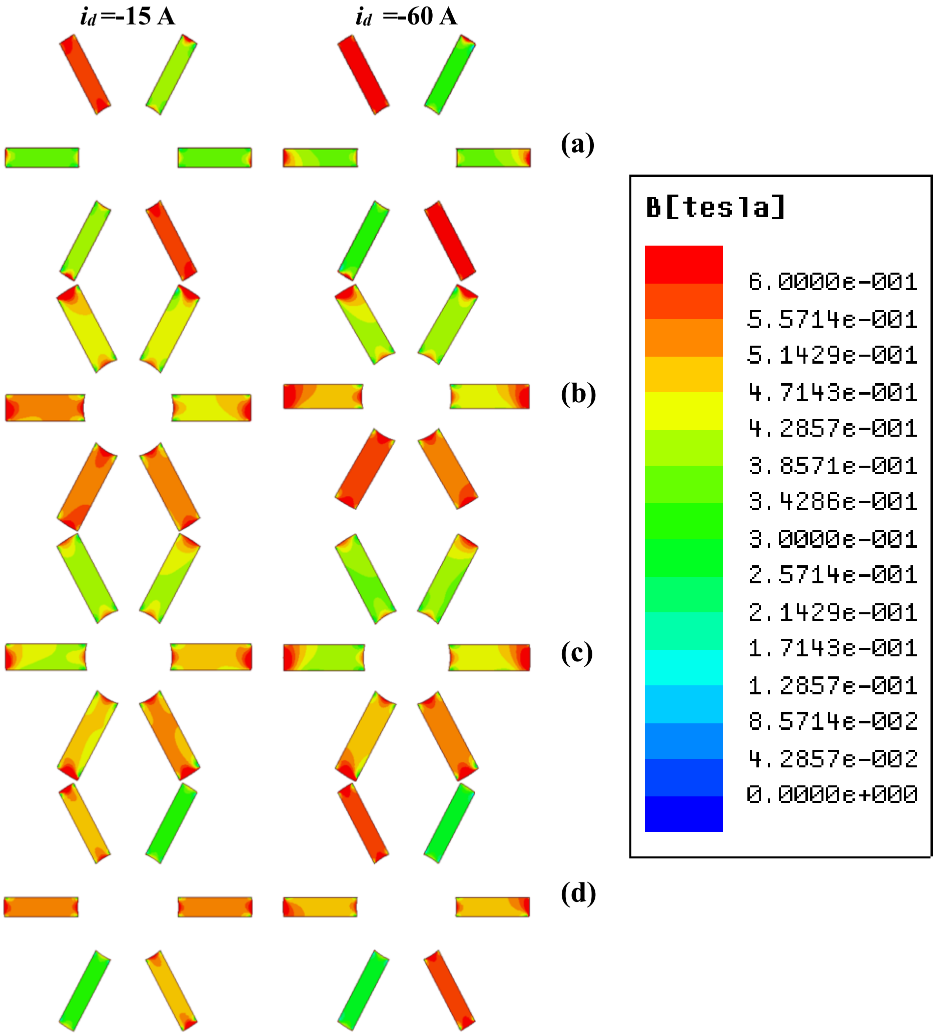


Figure 8: Demagnetization outlines at 4000 rpm **(a)** 10-pole **(b)** 11-pole **(c)** 13-pole and **(d)** 14-pole

4.0 CONCLUSION

The impact of rotor pole number on the output characteristics of a double stator permanent magnet machine is analyzed and presented. It is observed that the machine type having 11 poles, exhibits the most competitive electromagnetic features. Moreover, the machine type having 14-pole number has the best torque per magnet volume or material; and thus, the 14-pole machine type is the most economical to fabricate, considering the magnet usage level per its output torque, in addition to the high market price of magnets. Moreover, the analyzed machine types have good anti-demagnetization abilities. More so, the 14-pole machine has the most excellent flux-weakening capability; thus, it has an edge over others, in terms of extended speed range. The analyzed machine is suitable for direct-drive low-speed machine applications.

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