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Design and Analysis of AC Induction Motors with Integrated Gear Trains

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Keywords : AC induction motor, gear train, integrated device, finite element analysis

ABSTRACT

This work presents a design procedure to integrate the configurations of motors and gear transmission systems with defined graph representations systematically. And, an AC induction motor and a gear train are applied as an example. The existing AC induction motor and the gear transmission are studied to conclude the characteristics of topological structure. By following the design procedure, the synthesized novel configurations of integrated gear motors are 1 with a three-link and 6 with a four-link gear train. The strength of the gear is analyzed and the capability for the transmission purpose is verified. The flux linkage, the induced voltages and the current are analyzed, and this verifies the effects of gear profiles. The torque is reduced by 8.96%, and the torque ripple is reduced by 14.23%. In addition, the torque density is increased by 1.75%. This shows that the integrated device provide more stable and efficiency output torque then the existing design.

INTRODUCTION

A machine system can be divided into three main sub-systems, namely the power source, the transmission, and the working machine to transform the power into mechanical energy to achieve the desired functions. The electric motors and gear mechanisms are wildly used as power sources and transmissions, respectively; however they are designed separately. Traditionally, in order to combine the motors and gear trains, the couplings and other power transmission elements are used. And, the disadvantages of such design are longer power transmitting path, incompact space, and extra elements.

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In recent years, several designs with integrated gear motors, gear dynamos, and plenary gear trains with concentric motors are proposed (Kinoshita et al., 2000; Minegishi et al., 2002; Choe, 1982; Johnson et al., 1982; Jimena, 1982). The integrated concepts are applied to vehicles and ships to achieve the idle free and regenerative braking function (Davis et al., 2003; Fahimi et al., 2004). Suzuki et al. (1995) presented that the integrated motor and steering assemblies can reduce the engine output loss and the arrangement space. By applying the Yan's creative mechanism methodology (Yan, 1998; Yan et al. 2006) can synthesis all feasible integrated design concepts. In addition, Yan et al. (2006) presented that the gear profiles integrated on the pole shoes of BLDC motors can reduce the cogging torque and torque ripple.

The purpose of this paper is to present a design procedure to synthesis all possible integrated devices with AC induction motors and gear trains. The graph representations of gear members, motor members, the rotor/stator, and types of armature and air-gap are presented. Three-link and four-link gear trains are used as an example to illustrate this process step by step. And, an existing AC induction motor is used for the gear train design. The effects of gear profiles on transmission capability and magnetic characteristics are analyzed by applying the finite-element analysis (FEA). Finally, a feasible integrated device is built.

GRAPH REPRESENTATIONS

The use of graphs on the mechanism synthesis can simplify the complex structures of mechanisms and present the topological structures and kinematic characteristics clearly. Table 1 shows the representations of members in gear trains.

Graph representations of electric motors can simplify the integrated design procedure. The main components of an electric motor are the stator and the rotor. They can be treated as two members with constant relative velocity to keep the motor rotate. Theoretically, the rotor and the stator can be assigned as moving members. And, the graph representations of motors are shown in Table 2.

For some cases with two motors work as the inputs, i.e., the design has two degrees of freedom, and the stators are on the same link. And, there are two situations, the rotors are coaxial and nonaxiality, as shown in Table 3.

Moreover, considering the combinations of the types of rotor/stator, and the types of armature and air-gap, the graph representations are shown in Table 4.

Table 1. Representations of members in gear trains [10].

Representation	Member
– – –	Gear pair
——	Revolute pair
◬	Revolute pair (triangle)
◬	Revolute pair (quadrangle)
○	Moving link
◎	Fixed link
– – ▸○	Moving internal gear
– – –○	Moving external gear
– – ▸◎	Fixed internal gear
– – –◎	Fixed external gear

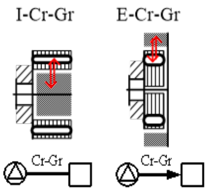
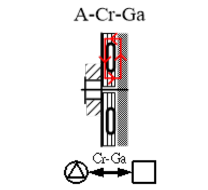
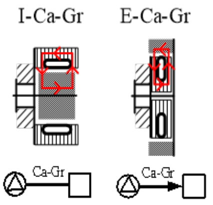
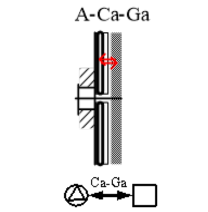
Table 2. Representations of members in motors [10].

Representation	Member
▬	Revolute pair
□	Rotor
⟁	Stator
⟁—□	Fixed and moving members
□—□	Relative moving members

Table 3. Representations of members with two inputs [10].

Representation	Member
□⟁□	Coaxial
□⟁□	Nonaxiality

Table 4. Representations of armature direction and air-gap direction [10].

Armature direction	Air-gap direction	
	Radial	Axial
Radial		
Axial		
		

1. CONCEPTUAL DESIGN

The purpose of this study is to synthesis all possible integrated devices with AC induction motors and gear trains to meet the design specifications, requirements, and constraints. Figure 1 presents the design procedure to synthesis feasible new designs systematically. In this procedure, Yan's creative mechanism design methodology is applied and modified [9, 10], and, three-links and four-links gear mechanisms are chosen to go for conceptual design.

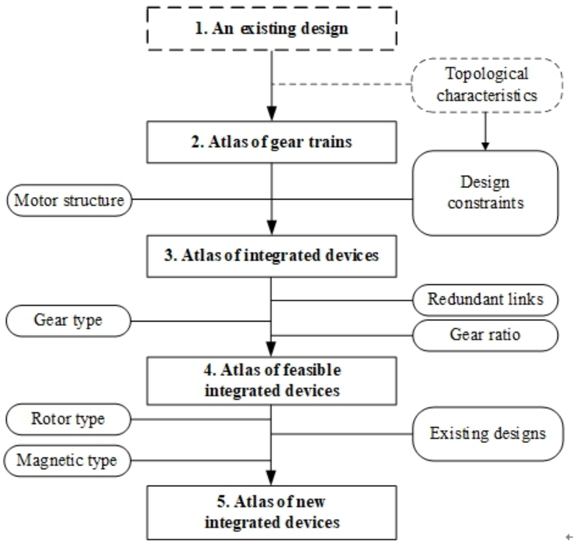


Fig. 1. Design procedure

Step1: Analyze existing design

First of all, designers can choose an existing design arbitrarily to analyze to topological characteristics and conclude the design constraints. If there is no existing design, designers can go direct to step 2 for a totally new design subject to design constraints concluded from required topological characteristics. In this study, the design constraints are concluded as follows:

C1. The output link must not be the fixed link.

C2. The fixed link and the output link must be connected by revolute pair or polygonal revolute pair.

C3. The stator and the rotor must not be assigned to the fixed link and the output link at the same time.

C4. The stator and the rotor must be connected by a revolute pair or polygonal revolute pair.

C5. The stator should be assigned as fixed link.

C6. Only internal rotors are used.

C7. The number of teeth should be integer multiple of the number of slots. The teeth root should be removed as the slot openings to wind the coil windings for automatic manufacturing purpose.

C8. The radius of the addendum/dedendum circle of the gear profiles should be the same as or close to the radius of the rotor/stator to keep the radius of the air-gap.

C9. The widely used AGMA standard 20° pressure angle involute spur gear profile is used.

C10. The commonly used JIS B 1701 gear modulus is selected.

Step2: Atlas of feasible gear trains

In this step, all the atlas of gear trains that meet the design constraints are synthesis. Firstly, label each member and assign the fixed link and output link of gear trains. To synthesis all possible atlas of gear trains, the fixed link and output link need to be assigned in the first step. Based on constraints C1 and C2, there is only 1 graph meets the design constraints for three-link gear train and 3 graphs for four-link gear train as shown in Figure 2. After labeling each member and assigning the fixed link and output link, there are 2 atlases of feasible three-link gear trains as shown in Figure 3.

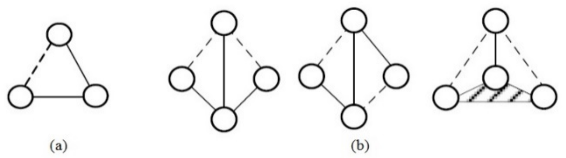


Fig. 2. Graphs of (a) three-link and (b) four-link

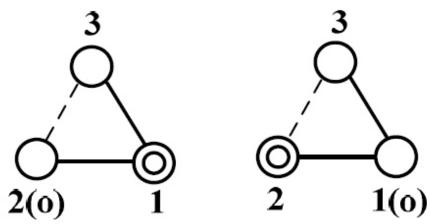


Fig. 3. Atlas of feasible three-link gear trains

Step3: Atlas of integrated devices

This step starts with assigning the rotor and the stator of the motor to get the atlas of integrated design that meets the design requirements and constraints.

Based on the characteristics of AC motors, the design constraints of the assignment of rotor and stator are C3 and C4. An AC induction motor is an asynchronous motor, and the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. The rotor and the stator have a constant relative velocity to keep the motor rotate. Theoretically, the rotor and the stator can be assigned as moving members, and then the output angular velocity will be defined by their relative velocity. To avoid the unpredictable affect and simplified design complexity, the constraint C5 need to be considered. There is only one result for the three-link gear train that meets the design constraints, as shown in Figure 4.

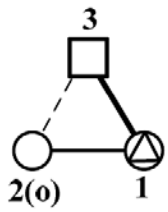


Fig. 4. Atlas of feasible three-link integrated device

Step4: Atlas of feasible integrated devices

In this step, all the atlas of integrated design are analyzed to remove the redundant links. And, the internal gears are assigned to analyze the gear ratio. By, removing all the incompatible integrated devices, the atlas of feasible integrated devices is obtained. For the three-link gear trains, there is only one fundamental loop with three members. And, there is no redundant links in three-link gear trains.

Step5: Atlas of new integrated devices

By assigning the type of rotor and the type of armature, along with removing the existing design, the atlas of new integrated devices is obtained. In this study, most AC induction motors are using internal rotors, and this yields the constraint C6.

By following the design procedure, the three-link gear mechanism result one feasible new design concept as shown in Figure 5 (a), and the four-link gear mechanism can have six feasible new design concepts as shown in Figure 5 (b)-(g).

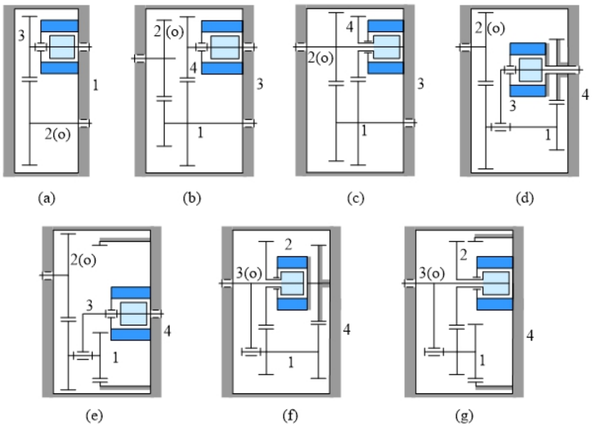


Fig. 5. Atlases of feasible integrated AC induction motor with three-link and for-link gear trains

GEAR TRAIN DESIGN

To integrate the gear profile on the above design concepts, the design constraints C7-C10 are considered for the manufacture purposes. In this study, the rotor radius of AC induction motor is 43.2mm. The gear profile with module 0.5 and 88 teeth meets the design constraints. Figure 6. shows the cross-section of the design concept in Fig. 5(b). Figure 7. shows the 3D model of the gear train, and the required reduction ratio is 6.8. Figure 8. shows the 3D model of the integrated device.

By applying the finite-element analysis, the strength of gear profiles can be evaluated to ensure the transmission capabilities. The parameters of the gear train are listed in Table 5, and the loading results of the gear train are shown in Table 6. The results of the FEA are shown in Figure 9. The maximum stress of the gear is 98.32 MPa, and the yielding stress is 312 MPa. The strength of the gear is thus capable for the transmission purpose.

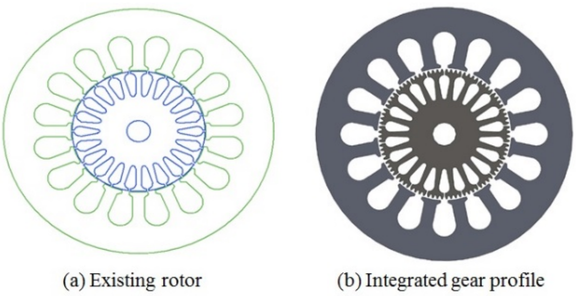


Fig. 6. The cross-section of gear profile integrated on the rotor

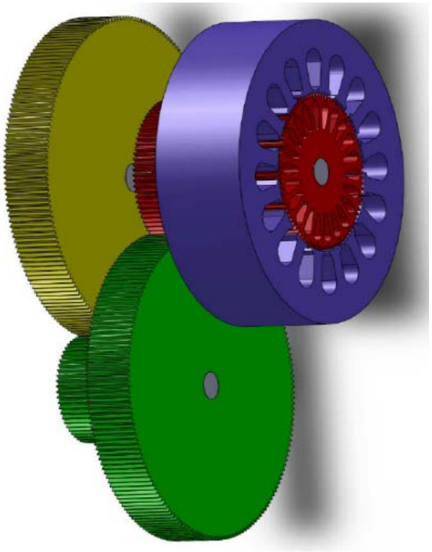


Fig. 7. A feasible gear train design

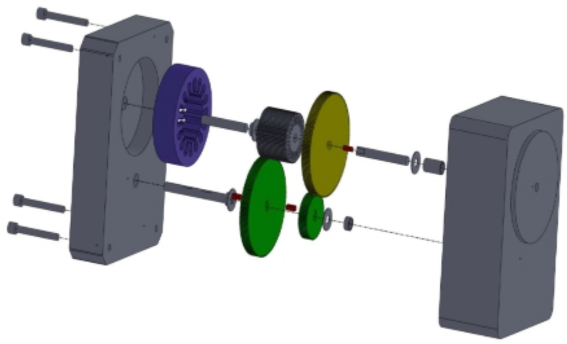


Fig. 8. 3D model of the concept in Fig. 5 (b)

Table 5. Parameters of gear train

Items	Values
Torque (mN-m)	55.3
Rotation speed (rpm)	1600
Number of teeth	88
Module	0.5
Density (kg/m3)	7850
Gear type	Hollow
Outer radius (m)	0.022
Inner radius (m)	0.004
Thickness (m)	0.005
Manufacture error (mm)	0.06
Young’s modulus (GPa)	200
Poisson's ratio	0.3

Table 6. Loading results of gear train

Items	Values
Equivalent elasticity coefficient	5.56x108
Equivalent mass (kg)	5.91x10-3
Theoretical load (N)	2.51
Dynamic load (N)	322.64

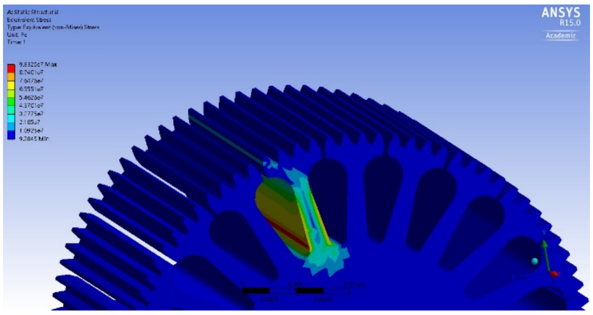


Fig. 9. FEA result of the gear strength

MAGNETIC CHARACTERISTICS OF TEETH INTEGRATED ON THE ROTOR

To integrate an AC induction motor with gear trains, the design strategy is to share a designated part without extra transmitting elements. Gear profiles are integrated on the rotor/stator of an AC induction motor. In order to verify magnetic characteristics of the integrated device to meet the design requirements, it is important to analyze the affection of teeth profile integrated on the rotor/stator. The FEA is applied to assist in numerically calculating of the characteristics of the existing AC induction motor and integrated device. In this study, the ANSOFT/Maxwell 3D field simulator is employed to the field analysis. And, the flux linkages, the induced voltages, the current, and the electromagnetic torque are analyzed to compare the existing design and the integrated devices.

Table 7 shows the parameters of the existing AC induction motor. Based on the parameters, the simulation model can be built to analyze the magnetic characteristics as shown in Figure 10. And, Figure 11 and Figure 12 show the comparison of the induced voltages and the current analysis between the existing AC induction motor and the integrated device. Basically, the affection of the integrated gear teeth on the induced voltages and the current can be ignored.

Figure 13 shows the comparison of the flux linkage between the existing AC induction motor and the integrated device. It shows that the flux linkages have some differences on the peak values, but no affecting to the output values. Basically, the affection of the integrated gear teeth on the flux linkage can be ignored, which meet the design constraints that the magnetic characteristics remain the same.

Table 7. Parameters of the AC induction motor

Items	Symbols	Values
Number of phases	N_{ph}	1
Number of poles	P	4
Number of slots on the rotor	S_r	22
Number of slots on the stator	S_s	16
Air gap length (mm)	g	0.45
Radius of shaft (mm)	R_{shaft}	4
Inner radius of rotor (mm)	R_{ri}	4
Outer radius of rotor (mm)	R_{ro}	21.6
Inner radius of stator (mm)	R_{si}	22.05
Outer radius of stator (mm)	R_{so}	43.9
Skew width of rotor (mm)	W_{tb}	2
Number of conductor per layer	N_c	360
Stack length (mm)	L	16.2
Speed (rpm)	V	1600
Rated output power (W)	W	150
Rated Voltage (V)	V	110
Frequency (Hz)	f	60

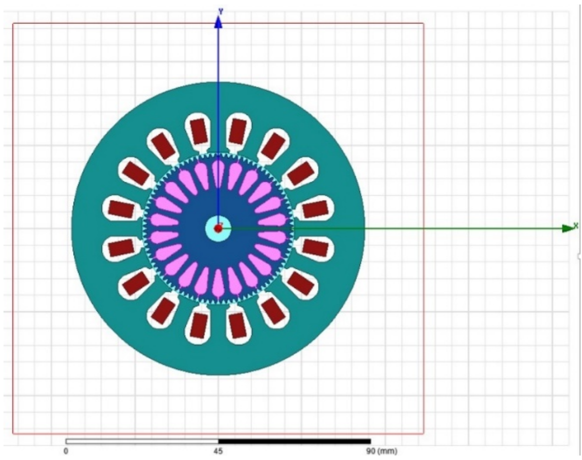


Fig. 10. FEA model of the integrated device

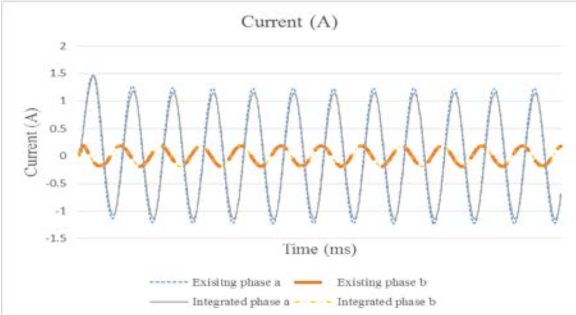


Fig. 11. Comparison of the current

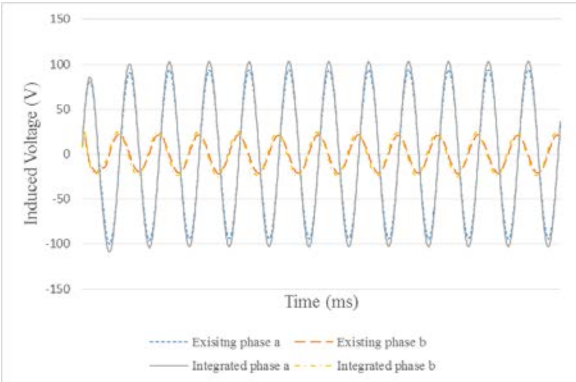


Fig. 12. Comparison of the induced voltage

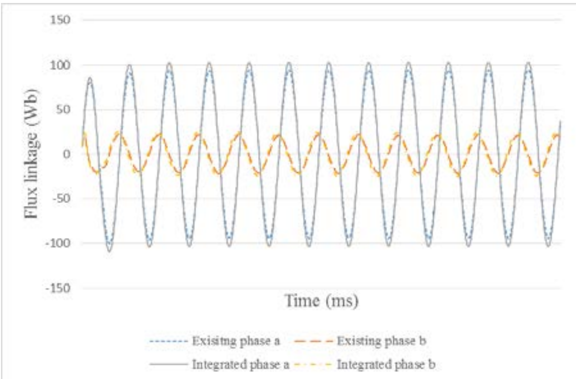


Fig. 13. Comparison of the flux linkages

The electromagnetic torque provides the power source to achieve work. The output performance of the motor is affected by the stability of the electromagnetic torque. In the integrated devices, the gear teeth on the rotor will increase the air gap length, which will reduce the output torque. Fig. 14 and Table 8 show the comparison of the performance between the existing AC induction motor and the integrated device. The average torque is reduced by 8.96% as expected. The torque ripple is reduced by 14.23%, and the torque density which is the output torque per unit volume is increased by 1.75%. The results show that although the average torque is reducing, the integrated device can provide more stable and efficient output torque.

Table 8. Comparison of the output performances

	Average (mN/m)	Ripple (%)	Axial length (mm)	Machine Volume (m3)	Torque density (mN-m/m^3)
Existing design	60.74	197.35	113	6.84x10-4	88801.2
Integrated device	55.3	169.27	101	6.12x10-4	90359.5
Difference (%)	-8.96	-14.23	10.62	10.53	1.75

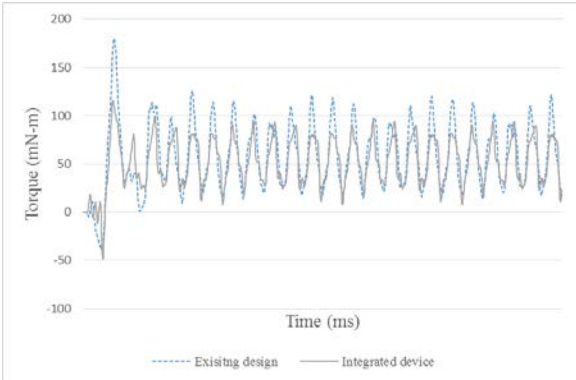


Fig. 14. Comparison of the electromagnetic torque

CONCLUSIONS

In this study, a design procedure is provided to synthesis all feasible concepts that integrate the configurations of motors and gear transmission systems with defined graph representations systematically. An AC induction motor and gear trains are applied as an example. The topological structure characteristics of the existing AC induction motor and gear transmissions are concluded. By following the design procedure, 1 with a three-link and 6 with a four-link gear train of novel configurations of integrated gear motors are synthesized. The 3D model of the designed gear train is developed, and the required reduction ratio is 6.8. The strength of the gear is analyzed in which the maximum stress is 98.32 MPa, and the yielding stress is 312 MPa, and this shows the gear train is capable for the transmission purpose. The integrated gear profiles have no affecting to the flux linkage, the induced voltages, and the current. The torque of the integrated design is reduced by 8.96% with the torque ripple is reduced by 14.23%. The torque density is increased by 1.75% that the integrated device provide more stable and efficient output torque.

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整合齒輪系與交流感應馬達之設計與分析

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摘要

本文提出一種以圖式表示法系統化整合馬達與齒輪傳動機構之設計程序，並以一現有交流感應馬達與齒輪傳動機構做為設計實例。根據現有交流感應馬達與齒輪傳動機構之拓墣構造特性，歸納出整合裝置之設計限制：並根據設計程序，整合出 1 種新型三桿整合裝置，與 6 種新型四桿整合裝置；藉由有限元素分析法，驗證齒輪強度足以負荷其運轉之動態負載，及探討感應馬達之磁交鏈、感應電動勢、及感應電流等電磁特性受齒型的影響，其中，電磁轉矩雖降低 8.96%，但因整合裝置體積緻密，其轉矩密度提高 1.75%，且轉矩漣波降低 14.23%，整合裝置較現有感應馬達可提供更平穩且有效率之輸出轉矩。