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► To cite this version:

Hang Zhao, Chunhua Liu, Zaixin Song, Wusen Wang, Thierry Lubin. A Dual-Modulator Magnetic-Geared Machine for Tidal Power Generation. IEEE Transactions on Magnetics, 2020, 10.1109/TMAG.2020.3003788 . hal-02880407

HAL Id: hal-02880407

<https://hal.science/hal-02880407>

Submitted on 25 Jun 2020

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A Dual-Modulator Magnetic-Geared Machine for Tidal Power Generation

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In this paper, a new dual-modulator magnetic-geared machine (DM-MGM) is proposed for tidal power generation with the virtue of high torque output at low speed. Firstly, the requirement of DM-MGM for tidal power generation is derived. Then, the flux modulation principle and flux-enhancing effect of the extra modulator of the proposed DM-MGM are elaborated. After that, a finite element analysis and genetic algorithm combined (FEA-GA) method is utilized to solve a multi-objective optimization problem for the DM-MGM design. The electromagnetic performances of the optimized DM-MGM with different pole-pair combinations are quantitatively compared via FEA. The results show the effectiveness of proposed machine, which is suitable to be applied in tidal power generation scenario.

Index Terms—Tidal power generation, magnetic-geared machine, PM machine, modulator, finite element analysis.

I. INTRODUCTION

Renewable energy sources have attracted more and more attention as the global environment deteriorating [1, 2]. Among various renewable energies, tidal energy enjoys the virtue of its predictability and easy access [3]. Besides, the tidal energy can be utilized for power generation to provide electricity for offshore islands [4]. However, the electric machine connected to the turbine for tidal power generation is difficult to be designed: electric machines are always designed to acquire high efficiency when operating under rated speed and power, the rated rotating speed of the turbines for tidal power generation is low [5]. A common method to solve the speed match problem between the turbine and the electric machine is to install a mechanical gearbox, which reduces the efficiency inevitably.

Flux-modulation machines are a novel breed of electric machines that utilize magnetic-gearing effect to alter the magnetic field distribution on the air gap [6], thus, the pole-pair number of the stator is no longer required to be equal to that of rotor [7]. Hence, the flux-modulation machine can naturally reduce the rotating speed of the rotor by increasing the pole-pair number of PMs on the rotor, serving as a perfect candidate to be used in tidal power generation [8]. What's more, by eliminating the mechanical gearbox, the system efficiency can be improved and the vibration and noise can be reduced [9, 10]. Indeed, flux-modulation machines have become a hot spot in recent years, and various topologies have been proposed. In [11], a novel magnetic-geared machine is firstly proposed for direct-drive wind power generation, but it has two rotating components which increases wear and tear. A novel Vernier machine with split teeth structure is proposed in [12], but the on-load back electromotive force (EMF) has a

severe distortion due to the saturation of split teeth structure, making it infeasible for tidal power generation. A Vernier machine with spoke-type PMs is proposed in [13], whose back EMF is greatly improved by adding a flux barrier. A dual-stator Vernier machine spoke-type PMs is invented in [14], the air-gap flux density is greatly boosted by adding an extra flux path outside the spoke-type PMs.

In this paper, a dual-modulator magnetic-geared machine (DM-MGM) is proposed for tidal power generation. By adding an extra modulator outside the rotor, the air-gap magnetic flux density can be greatly enhanced. The operation principle is analysed in Section II. Then, in Section III, an optimization is conducted for DM-MGM for a better power generation capability. Finally, the electromagnetic performances of the proposed DM-MGM is simulated by using finite-element analysis (FEA) in Section IV.

II. SYSTEM CONFIGURATION

A. Tidal Power Generation System

Fig. 1. Proposed tidal power generation system.

The proposed tidal power generation system (TPGS) is shown in Fig. 1. The turbine is installed in a culvert located in the bay, the blades rotates when tides occur. The turbine drives the rotors of DM-MGM directly, where the gearbox is eliminated. The generated electricity will flow to the power grid through power electronic devices. Assuming the water

Manuscript received March 26, 2020; revised June 13, 2020; accepted June 15, 2020. Date of publication Month **, 2020; date of current version Month **, 2020. *Corresponding author: Chunhua Liu (e-mail: chunliu@cityu.edu.hk)

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velocity v in the culvert in a general TPGS is 3 m/s [15], the radius R of the culvert is 1 m. The tip-speed ratio (TSR) of the turbine blades is defined as:

$$TSR = \frac{\omega R}{v} \quad (1)$$

where ω is the angular speed of the blades. To maximize the power obtained from the water flow, the value of TSR can be set in a range from 5~8 [16].

As for the electric machine connected to the turbine, the frequency of generated electricity f can be formulated as:

$$f = \frac{pN}{60} \quad (2)$$

where p is the pole-pair number of the electric machine, and N is the rotating speed of the shaft, which can be obtained by:

$$N = \frac{\omega}{2\pi} \cdot 60 \quad (3)$$

To minimize the iron loss of the electric machine and the switching losses of power electronic devices, the frequency f should be around 50 Hz. By combining (1)~(3), the optimized pole-pair number p of the electric machine ranges from 13 to 20. If conventional synchronous machine is applied in this scenario, the power density is limited due to a relative high pole-pair number. However, by utilizing the magnetic-gearing effect, the pole-pair number of MGM can be reduced and the power density can be improved. Thus, MGM will be more suitable to be applied in TPGS.

B. Design Rules and Operation Principle

The proposed machine for the TPGS is shown in Fig. 2. Compared to existing spoke-type magnetic-gear machine (SMGM), the DM-MGM has an extra modulator at the outside of rotor to enhance the magnetic flux density on the air gap. The rotor of DM-MGM is composed of evenly distributed tangential-magnetized permanent magnets (PMs) and soft-magnetic material. The tangential-magnetized PMs has the advantage of flux-focus effect. The stator is at the innermost part. The design rules of DM-MGM follows that of magnetic gear. The only difference is that the DM-MGM adopts stator windings to replace the rotating PMs.

Fig. 2. Machine topologies (a) SMGM; (b) DM-MGM.

The distribution magnetic flux density B at the air gap can be qualitatively analysed by using magnetic permeance function, namely:

$$B = F \cdot \Lambda \quad (4)$$

where F is the magnetic motive force (MMF), and Λ is the air-gap permeance. The MMF generated by spoke-type PM is shown in Fig. 3, where the initial angle middle of one N-pole PM at the rotor is set as the origin. Thus, F satisfies: $F(\theta) = -F(\theta)$ and $F(\theta) = -F(\theta + \pi/P_r)$. Thus, the Fourier series of

$F(\theta)$ only has odd cosinoidal component, and it can be written as:

$$F(\theta, t) = \sum_{n=1,3,5,\dots}^{\infty} F_n \cos nP_r(\theta - N_r t) \quad (5)$$

The air-gap permeance distribution of the modulator pieces is shown in Fig. 4. Only the fundamental harmonic is considered, then the Fourier series of $\Lambda(\theta)$ can be written as:

$$\Lambda(\theta) \approx \Lambda_0 + \Lambda_1 \cos Q(\theta + \theta_s) \quad (6)$$

Hence, the radial component of the magnetic flux density can be expressed as:

$$B_r = \sum_{n=1,3,5,\dots}^{\infty} \Lambda_0 F_n \cos nP_r(\theta - N_r t) + \frac{1}{2} \sum_{i=1,3,5,\dots}^{\infty} \Lambda_i F_n \cos((nP_r + Q)\theta - nP_r N_r t + Q\theta_s) + \frac{1}{2} \sum_{i=1,3,5,\dots}^{\infty} \Lambda_i F_n \cos((nP_r - Q)\theta - nP_r N_r t - Q\theta_s) \quad (7)$$

It can be seen that after modulation, there mainly exist three different harmonic in the air gap. With the increase of n , the amplitude of F_n decreases. Thus, to generate a maximum steady electromagnetic torque, the pole-pair number of stator winding P_s , pole-pair number of rotor P_r and the inner modulator slot number Q must satisfy [17]:

$$P_s = |P_r \pm Q| \quad (8)$$

In TPGS, a smaller pole-pair number of stator winding can obtain a more sinusoidal back EMF, thus the smaller P_s is adopted:

$$P_s = Q - P_r \quad (9)$$

The extra modulator also serves to modulate the magnetic field to obtain the P_s^{th} order harmonic, thus its slot number equals to that of inner modulator, namely Q .

The stator winding must generate a magnetic field that has the same rotating speed as the magnetic field modulated by the modulator. Hence, its frequency f_n is ruled by:

$$60f_n = P_r N_r \quad (10)$$

where N_r is the rotating speed of rotor.

Fig. 3. MMF distribution of Spoke-type PMs.

Fig. 4. Permeance distribution of modulator pieces.

C. Flux-enhancing Effect of Extra Modulator

The flux line path, as shown in Fig. 5, can illustrate the flux-enhancing effect of the extra modulator. For SMGM, it can be seen that the outer side of the rotor is air, which is of high magnetic resistance; the flux line can only pass through

the modulator piece to construct a loop. However, with the help of extra modulator, the flux line can pass through the extra modulator to construct a loop. Besides, the flux leakage of DM-MGM is much less than that of SMGM, since most flux go through the extra modulator rather than air. Since the magnetic flux density B has linear relation to the flux Φ , B of DM-MGM is larger than that of SMGM.

Fig. 5. Flux line paths of two machines (a) SMGM; (b) DM-MGM.

III. OPTIMIZATION OF DM-MGM

To achieve a better performance when serving as a generator, the geometrical parameters of proposed DM-MGM needs to be optimized. Firstly, different pole-pair combination of DM-MGM can be settled. Generally speaking, the pole-pair number of stator winding P_s , pole-pair number of rotor P_r and the inner modulator slot number Q should be mutually prime to one another to reduce the torque ripple. Assuming the value of P_s is selected as 2, which is reasonable for a small-size generator, then for the integer between 13~20, P_r can only be selected from {13, 15, 17, 19}. Thus, the corresponding machine topologies with different rotor pole pairs and modulator piece number: (a) 13-15; (b) 15-17; (c) 17-19; (d) 19-21 are constructed and compared. All the DM-MGM models in the following sections are constructed and simulated by using the FEA software JMAG.

Fig. 6. Shift angle between the inner modulator and the extra modulator.

A. Shift Angle Optimization of Two Modulators

The axis of the modulator is defined as the middle of a specific modulator piece. Thus, the angle difference between the axis of the inner modulator and the extra modulator is defined as the shift angle φ , as shown in Fig. 6. Due to the symmetry structure of the modulator, the range of φ is $[0, \pi/Q]$, and the shift angle ratio is defined as:

$$\gamma = \frac{\varphi Q}{\pi} \quad (11)$$

The relation between the fundamental harmonic amplitude of back EMF and shift angle ratio is shown in Fig. 7. It can be seen that for different pole-pair combinations, their fundamental harmonic amplitude of back EMF get maximum when $\gamma = 1$. Therefore, the value of φ is set to be π/Q in the later optimization process.

Fig. 7. Shift angle between the inner modulator and the extra modulator.

B. Multi-Objective Optimization

Since the generated power should be further delivered to the power grid, thus the fundamental harmonic of back EMF should be as high enough, while the total harmonic distortion (THD) should be as low as possible to reduce the loss. Hence, three objectives are chosen for optimization, i.e., the fundamental harmonic back EMF V_p , the average electromagnetic torque of rotor T and THD under rated generated power. To simplify the calculation, the THD only consider the harmonic order up to 11th. Thus, it can be expressed as:

$$THD = \frac{\sqrt{V_3^2 + V_5^2 + V_7^2 + V_9^2 + V_{11}^2}}{V_1} \times 100\% \quad (12)$$

Therefore, the optimal design problem is formulated as:

$$\min \{F(\mathbf{x}) = [-T(\mathbf{x}), -V_p(\mathbf{x}), THD(\mathbf{x})]\} \quad (13)$$

where $F(\mathbf{x})$ is a vector of objective functions, $\mathbf{x}$ is a vector of design variables; where $\mathbf{x}$ is given by:

$$\mathbf{x} = \{r_1, r_2, w_t, h, w_s, t_1, t_2, t_3, \alpha\} \quad (14)$$

where the specific variable elements can be referred to TABLE I.

To let the optimization results be comparable to one another, some parameters are set as constant, as shown in TABLE II.

TABLE I
OPTIMIZATION DESIGN VARIABLES

Design Variable	Symbol	Initial value
Stator slot inner radius	r_1	36 mm
Stator slot outer radius	r_2	68 mm
Stator tooth width	w_t	4.6 mm
Stator tooth tip height	h	4 mm
Stator slot opening length	w_s	2.2 mm
Inner modulator thickness	t_1	11 mm
Rotor thickness	t_2	15 mm
Extra modulator tooth thickness	t_3	8 mm
PM pole-arc ratio	α	0.6

TABLE II
OPTIMIZATION DESIGN CONSTANT PARAMETERS

Constant parameters	Symbol	Value
Axial length	L	100 mm
Air gap length	H_a	0.6 mm
Shaft radius	R_s	25 mm
Outer radius of stator	R_o	120 mm
Slot filling factor	β	60%

Constant parameters	Symbol	Value
Current density	D	5 A/mm ²

Besides, constraint functions must be added during optimization to ensure the validness of the machine designs: a lower limit should be set for torque T and a upper limit should be set for THD and the thickness of the yoke of extra modulator should be a positive value. Thus, the constraint functions can be formulated as:

$$T \geq 100 \text{ N} \cdot \text{m} \quad (15)$$

$$\text{THD} \leq 20\% \quad (16)$$

$$r_2 + t_1 + t_2 + t_3 + 3H_a < R_o \quad (17)$$

The convergence criterion is set as:

$$\max \left| \frac{F^{k+1}(\mathbf{x}) - F^k(\mathbf{x})}{F^k(\mathbf{x})} \right| < 0.01 \quad (18)$$

where $F^k(\mathbf{x})$, $F^{k+1}(\mathbf{x})$ means the optimal values of k^{th} and $(k+1)^{\text{th}}$ generation, respectively, and $\max\{y\}$ refers to the value of maximal element of the vector y .

In this paper, a finite-element analysis and multi-objective genetic algorithm combined (FEA-GA) optimization method is utilized to carry out the multi-objective optimization [18],

the maximum generation iteration time is set as 30. The flowchart of proposed FEA-GA method is illustrated in Fig. 8, where the FEA model is constructed and solved in software JMAG, and the GA is conducted in software MATLAB.

Fig. 8. Flowchart of the FEA-GA optimization process.

Fig. 9. Relationship among the average torque, primary harmonic amplitude of on-load back EMF, and THD.

From the optimization result in Fig. 9, it can be seen that the Pareto front of 17-19 is the closet to the Utopia point in the different three planes. Therefore, the DM-MGM with 17-19 pole-pair combination is more suitable to be applied in TPGS. The electromagnetic performances of the optimal case for each pole-pair combination are compared in the following part.

IV. ELECTROMANGETIC ANALYSIS AND COMPARISON

A. Air-Gap Magnetic Flux Density Distribution

Fig. 10 shows the on-load flux line distribution for different pole-pair combinations. It can be clearly seen the flux lines has 4 poles in both stator and the extra modulator for all four topologies. Besides, the flux leakages 15-17 are much larger than other three topologies, which will reduce the power factor.

Fig. 10. Flux lines and flux density distribution for different pole-pair combinations of DM-MGM: (a) 13-15; (b) 15-17; (c) 17-19; (d) 19-21.

B. Back EMF under No-Load Condition and at Rated Power

A criterion to measure whether an electric machine is suitable to generate power and connected to the grid is to evaluate the distortion of its back EMF at rated power. Fig. 11 shows the B-phase back EMF waveforms of DM-MGM at rated power. The THD and fundamental harmonic amplitude of back EMF is shown in TABLE III.

Fig. 11. The B-phase back EMF at rated power for different pole-pair combinations.

TABLE III

THD AND FUNDAMENTAL HARMONIC AMPLITUDE

Pole-pair combination	THD/%	Amplitude/V
13-15	19.42	808.6
15-17	14.97	1152.9
17-19	7.38	1302.4
19-21	8.15	1210.3

C. Torque waveforms at Rated Power

The torque waveforms of different pole-pair combinations of DM-MGM at rated power, namely the rated speed, are shown in Fig. 12. The detailed average torques and torque ripples data are shown in TABLE IV. It can be seen that the 17-19 DM-MGM has the largest average torque. Besides, its THD is the lowest among the four structures. Thus, the 17-19 DM-MGM is most suitable for TPGS.

Fig. 12. The torque waforms at rated power for different pole-pair combinations.

TABLE IV

PERFORMANCE COMPARISON

Pole-pair combination	Torque /Nm	Ripple rate /%	Generated power /kW
13-15	249.5	5.15	6.03
15-17	193.1	19.76	4.04
17-19	361.4	10.71	6.68
19-21	354.5	6.61	5.86

D. Comparison between SMGM and DM-MGM

The electromagnetic performances of the optimal 17-19 DM-MGM is compared with that of a 17-19 SMGM. The average torque of the 17-19 SMGM is 190.9 Nm, so the generated power is 3.52 kW, which is only about 53% of the generated power of DM-MGM. The radial component

of inner air-gap magnetic flux density distributions of the DM-MGM and the SMGM and their fast Fourier transform (FFT) are given in Fig. 13. It can be seen that the working harmonic, namely 2th harmonic of the DM-MGM is larger than that of the SMGM. The radial component of outer air-gap magnetic flux density distributions of the DM-MGM and the SMGM and their fast Fourier transform (FFT) are given in Fig. 14. From Fig. 5, there is no modulation slots on the outside of the SMGM, so its 2th harmonic is almost zero. The torque on the rotor of MGM composes of Maxwell tensors on both inner air gap and outer air gap [19]. So, the generated power of DM-MGMs is larger than that of SMGMs.

Fig. 13. (a) Radial component of inner air-gap magnetic flux density distributions of the DM-MGM and the SMGM; (b) Corresponding FFT.

Fig. 14. (a) Radial component of outer air-gap magnetic flux density distributions of the DM-MGM and the SMGM; (b) the corresponding FFT.

E. 3D-Model Validation of Optimal Case

A 3D model of the optimal case, namely 17-19 DM-MGM, is constructed, as shown in Fig. 15. The simulation result is compared with 2D model. It can be seen from Fig. 16 that the back EMF of 3D model decreases a little compared to that of 2D model, i.e., the end effect of proposed DM-MGM can be ignored during design process. In general, the performance difference between 2D and 3D model is negligible unless there exists axial flux path [20].

Fig. 15. 3D model of the optimal case (a) model (b) magnetic flux density distribution.

Fig. 16. Comparison of back EMF waveforms of 3D model and 2D model at rated power.

V. CONCLUSION

In this paper, a new DM-MGM is proposed for tidal power generation. By introducing an extra modulator outside the spoke-type PMs, the magnetic flux density distribution of the desirable harmonic component can be enhanced greatly, thus producing a much larger electromagnetic torque compared to that of SMGMs. The shift angle between the inner modulator and the extra modulator of the proposed machine is optimized. Besides, the FEA-GA method is adopted to optimize the DM-MGMs with different pole-pair combinations. It turns out that the 17-19 combination is most suitable to be installed in the TPGS. The results are validated via FEA.

ACKNOWLEDGMENT

This work was supported by a grant (Project No. 51677159) from NSFC of China, a grant (Project No. JCYJ20180307123918658) from STIC of Shenzhen Municipality, China, a grant (Project No. CityU 21201216) from Research Grants Council of Hong Kong, China, and CityU strategic research grants (Project No. SRG11218317 and SRG11218519) from City University of Hong Kong, Hong Kong SAR, China.

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