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Design of small scale, axial flux, permanent magnet wind generator in Vietnam

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Abstract. This paper presents the design of light weight, small scale, disk type, axial flux, permanent magnet (AFPM) generator for wind applications. This article also shows the partial works done under state projects in renewable energy in Vietnam to find out the most suitable, reliable, self – made wind generator types for rural and remote areas. The collaboration project of Hochiminh City University (HCMUT) – Hanoi University of Science and Technology (HUST) – Berlin University of Technology (TU Berlin) resulted in some small scale, axial flux, slow speed, permanent magnet (PM) generators which best suited for Vietnam countryside areas. The researches in rare earth PM from HUST, the electrical machine design knowhow of TU Berlin and the renewable energy research experiences of HCMUT, especially in slow speed wind turbines have shown many promising applications. The small scale, permanent magnet wind generator for remote and rural areas as a cheap source of power supply is necessary in Vietnam. Though there are many large wind farms built in many provinces recently but the needs for telecommunication, family lighting in the heights, mountain, unreachable electric grid communes are still necessary. Further research should be done to match the generator for hydro power stations, diesel coupled internal combustion engine. These prospects are very promising.

1. Overview of Wind Power application in Vietnam

According to Wind energy potential in Vietnam [5], in Vietnam, several wind measurement studies are conducted. Vietnam is considered to have the best wind resources in Southeast Asia, especially in the nearshore/offshore and onshore coastal regions in the south of Vietnam. In these areas yearly average wind speeds of 9 to 10 meters per second are measured. Generally, wind speeds are declining further inland. Noteworthy is that Vietnam is vulnerable to extreme weather events like storms and typhoons, especially in July, August, September and October. The possibility of a typhoon is relatively high in these months, which can have severe consequences for the exploitation of wind farms.
Vietnam has paid attention to renewable energies a long time ago with many projects, especially in solar and wind energy [1].

1.1. Research gaps

The demands for power supply in remote, rural, unreachable power grid areas in Vietnam are high, however there are no wind generators matching the low wind speed profiles of Vietnam provinces. Furthermore, the imported, expensive, high wind starting speed wind generators mostly from China are not suitable for Vietnam applications. The research for the low cost, self - made, reliable wind generator type utilizing in fierce exposed weather conditions needs to be done.

1.2. Small scale wind power in Vietnam

In the year 1992-1995, Research Center for Thermal Equipment and Renewable Energy (RECTERE), Ho Chi Minh city University of Technology (BKU, HCMUT) cooperated with some US research agencies to facilitate the pilot measurement for wind power in Can Gio district, Hochiminh city. Thousands of ferrite magnet wind generators with hundred watts in power have been manufactured and installed in Thieng Lieng Islets, Ho Chi Minh City and islands in Nha Trang city, Khanh Hoa province [1].

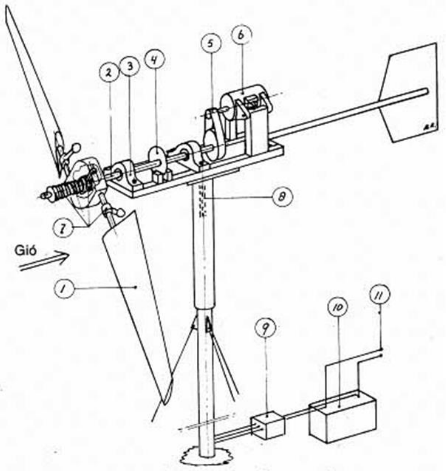


Figure 1. A typical small scale wind generator [1]

1.3. Large wind farm

Vietnam's first high-capacity wind farm, with 30 MW, was inaugurated by the Vietnam Renewable Energy Joint Stock Company (REVN), in the central province of Binh Thuan on April 18.[5] The next two projects—the Phú Quý island hybrid grid with 6 MW and the near-shore Bac Lieu phase 1 with 16 MW—both completed in 2013. No new capacity was added in 2014 or 2015.

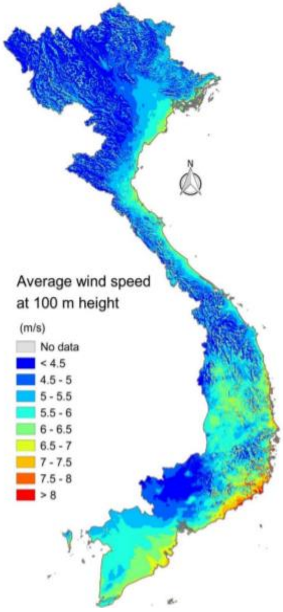


Figure 2. Wind speed at 100 m height in Vietnam [4]

The wind power industry is taking off in 2019 in Vietnam, although not as spectacularly as the solar power industry. By the end of May 31, 2019, 7 wind power plants were in operation, for a national installed capacity of 331 MW.

No.	Name of province	Capacity (MW)	
		2020	2030
1	Bình Thuận	700	1.570
2	Ninh Thuận	220	1.429
3	Sóc Trăng	200	1.470
4	Quảng Trị	110	447
5	Trà Vinh	270	1.608
6	Bến Tre	150	1.520
7	Bạc Liêu	401	2.507
8	Cà Mau	350	3.607
9	Thái Bình	40	70
10	Đăk Lăk	138	1.382
11	Bà Rịa Vũng Tàu	34	107
	Total	2.613	15.717

Figure 3. Provincial Wind Power Development Plans in Vietnam [6]

Up to now, wind power has been deployed enormously in many big wind farms as listed in [3].

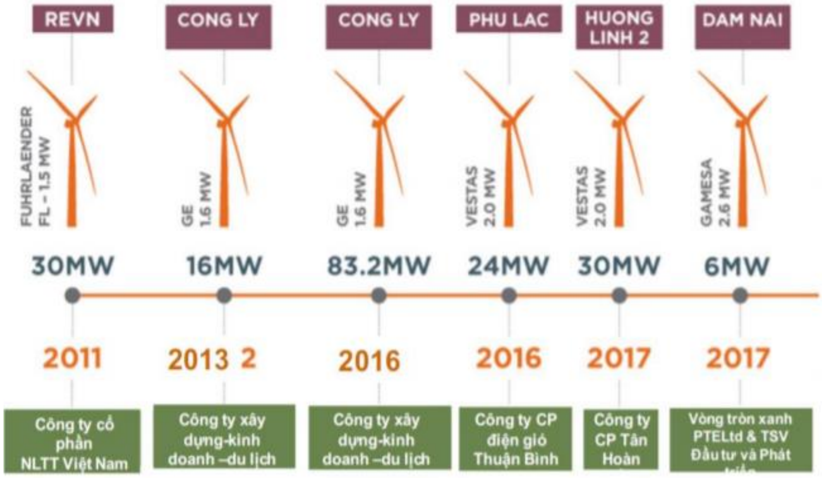


Figure 4. Operational wind farm in Vietnam [6]

2. Overview of Wind Power application

2.1. Advantages and disadvantages of permanent magnet generator (PMG)

The most important component of wind – electric conversion systems is a generator, the development of permanent magnet materials recently pose the potentials of compact, lightweight PMG applications. The advantages and disadvantages of PM excited generators [2,4,7] are listed in table 1.

Table 1. Advantages and disadvantages of PM excited generators

1. **Advantages**	2. **Disadvantages**
High efficiency	Few types of generators from the manufacturers.
No brush losses	Uncontrolled magnetic exciting current.
No external exciter	Controlled via output power
No magnetic exciter losses	Heavily damaged if having armature winding defects.

2.2. Torus PMG configuration

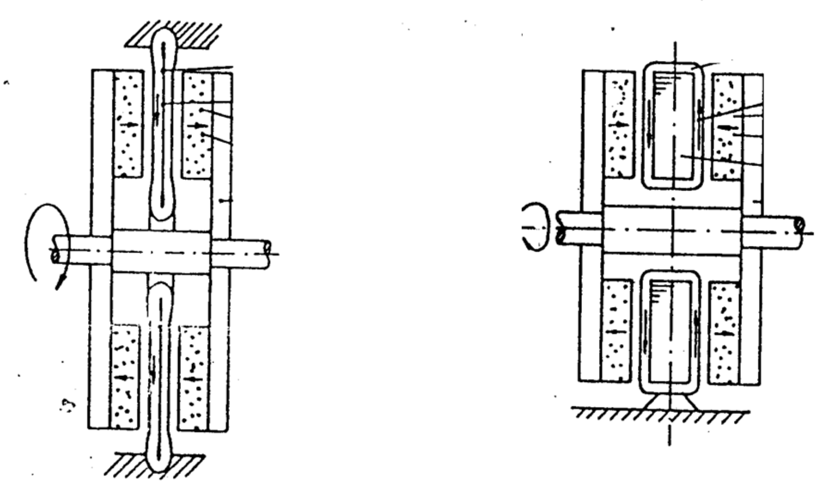


Figure 5. Coreless and Slotless Axial Flux PMG [1]

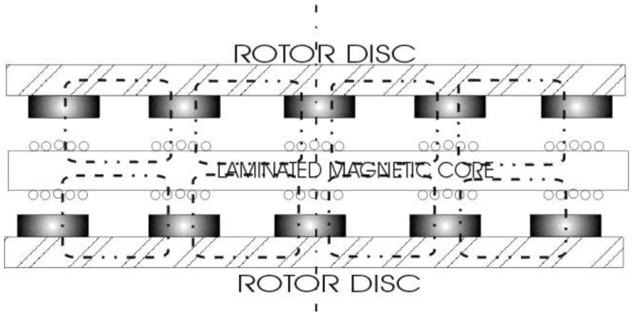
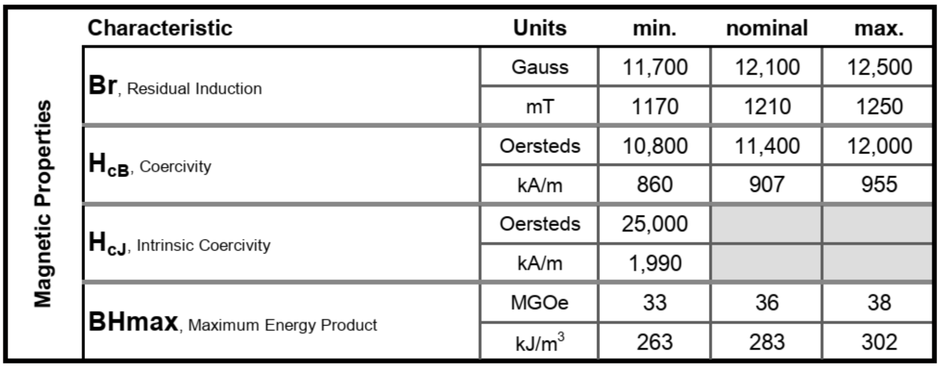


Figure 6. Magnetic Circuit of Axial Flux PMG [1]

2.3. Slottless and slotted toroidal generator

The slottless prototype is made with rectangular rare earth based magnet NdFeB (NeoDelta Magnet) from IBS Magnet, Germany with BxLxh = 20x30x6 (mm), remanence $B_r = 1.2$ T, coercivity $H_c = 930$ kA/m and $(BH)_{max} = 280$ kJ/m^3. The slotted prototype is made with circular anisotropic Barium ferrite magnet from IBS Magnet, Germany with diameter d = 15 mm, remanence $B_r = 0.4$T, coercivity $H_c = 175$ kA/m and $(BH)_{max} = 25.5$ kJ/m^3. The generator's parameters are shown in Figure 7.

Figure 7. N35UH permanent magnet properties



	Characteristic	Units	min.	nominal	max.
Magnetic Properties	**Br**, Residual Induction	Gauss	11,700	12,100	12,500
		mT	1170	1210	1250
	H$_{cB}$, Coercivity	Oersteds	10,800	11,400	12,000
		kA/m	860	907	955
	H$_{cJ}$, Intrinsic Coercivity	Oersteds	25,000		
		kA/m	1,990		
	BHmax, Maximum Energy Product	MGOe	33	36	38
		kJ/m^3	263	283	302

Table 2. Slotless and slotted toroidal generators

Machine parameters	Slotless	Slotted
Stator core OD in mm	146	146
Stator core ID in mm	86	86
Core axial thickness in mm	20	20
Winding lavers	6	6
Winding coils	18	18
Phases	3	3
Turns/coil	11	11
Wire diameter in mm	0.7	0.7
Magnet thickness in mm	6	6
Air gap flux density in T	0.5	0.33
Air gap flux in mm	8	3
Length of machine in mm	50	50
Output power at rated speed 500 rpm in Watts	300	130

2.4. Torus PMG calculation

2.4.1. Nomenclature:

- T_e – the electromagnetic torque in [N.m].
- ω_e - the electrical angular speed in [rad/s].
- R_0 – outer radius.
- R_i - inner radius.
- 2p - number of pole pair.
- K_l - flux leakage factor.
- $\emptyset$ - magnetic flux.

2.4.2. Electromagnetic torque

For the axial flux, slottless, permanent magnet generator, the basic parameter can be calculated respectively in the following [2,4].

The output power P [W] can be calculated by a simple formula:

$$P = T_e . \omega_e \tag{1}$$

Or

$$P = T_{\Sigma} . \omega_m \tag{2}$$

One of most important factors, the rated angular speed ω_m of the Torus is determined considering the motive source coupled to the generator. In the case of wind energy application, the rated wind rotor should be chosen how to use the wind energy in the low wind speed.
The electromagnetic torque is determined by following equations:

Due to the double side magnet polarization arrangement, the total electromagnetic torque can be calculated as:

$$T_{\Sigma} = 2T_e$$

$$T_e = K_p \int_{Ri}^{R0} F_i r dr \tag{3}$$

With:
- $\mathrm{K_p}$ – the percentage of armature winding under pole flux
-$F_i = B_{av}.l_i.I_i$ – Lorentz tangential force on current carrying conductor element
- B_{av} - Average flux density in the air gap.
- l_i - Length of a current carrying conductor element in radio direction: $l_i = dr$.
- I_i – Current generated in the conductor element. In polar coordinates: $I_i = J_{av} r d\Theta$.

Then $T_e = K_p \int_0^{2\pi} \int_{Ri}^{R0} B_{av} J_{av} r^2 \mathrm{d}\Theta dr$

Thus: $$T = 2K_p \int_0^{2\pi} \int_{Ri}^{R0} B_{av} J_{av} r^2 d\Theta dr$$

But the current in other parts of the conductor is equal to the current in the conductor at inner radius Ri, therefore, Javr can be replaced by JiRi.

$$T = 2K_p \int_0^{2\pi} \int_{Ri}^{R0} B_{av} J_i R_i r d\Theta dr$$

$$T_{\Sigma} = 2\pi pmn B_{av} J_i R_0^3 (1 - a^2) \tag{4}$$

To maximize the output power, the outer R_0 and the inner R_i radius should satisfied the following equation:

$$\frac{R_0}{R_i} = \sqrt{3} \tag{5}$$

The number of pole pair 2p is determined as:

$$2p = \frac{60f}{n_1} \tag{6}$$

The electric current can be roughly calculated from the Eq.6 as:

$$I = \frac{P}{U}(A) \tag{7}$$

The current density (the electric loading) Ji can be chosen as follows:

- For the long term working mode: $J_i = (2 - 4) A/mm^2$
- For the short repeated term working mode: $J_i = (5 - 12) A/mm^2$
- For the short circuit working mode: $J_i = (2 - 4) A/mm^2$

The permanent magnets can be rare earth based such as NdFeB, Sm_2Co_5, Sm_2Co_{17} or ferrite ones. The segment shape of permanent magnet is assumed (see Fig.1) to generate the constant flux along radii of armature winding core.

The flux leakage factor K_l defined based on magnetic flux $\emptyset$ must be optimized. For the surface mounted, segment shape magnet, the flux leakage is determined in Eq.8:

$$K_l = 1 + \frac{2\mu_0 p\alpha H_{magnet} l_{magnet}^2 \left[ln\, ln \left(\frac{R_0}{R_i}\right) + 2\alpha\right]}{\pi(1-K_a)} x \frac{2\left(1+\frac{l_{airgap}}{l_{magnet}}\right)}{B_r\beta(R_0^2 - R_i^2)} \tag{8}$$

$$\frac{\emptyset_{leakage}}{\emptyset_{total}} = \frac{2\mu_0 p H_{magnet} l_{magnet}^2 \left[ln\, ln \left(\frac{R_0}{R_i}\right) + \frac{4\pi K_a}{p}\right] x2\left(1+\frac{l_{airgap}}{l_{magnet}}\right)}{\pi(1-K_a)\frac{2\pi K_a B_r}{p}\left(R_0^2 - R_i^2\right) + 2\mu_0 p H_{magnet} l_{magnet}^2 \left[ln\, ln \left(\frac{R_0}{R_i}\right) + \frac{4\pi K_a}{p}\right] x2\left(1+\frac{l_{airgap}}{l_{magnet}}\right)} \tag{9}$$

The optimum K_a is then obtained when the ratio in Eq.9 achieves minimum value. This happen when $K_a = 0.8$

For the optimum design the following relation between the magnet thickness and the armature winding thickness is of help:

$$P_{copper} = \frac{K\psi}{l_{magnet}^2(l_m - 2t_{core} - 2\Delta - 2l_{nc})} \tag{10}$$

The constant in Eq.9 are found as:

$$K = \frac{2\rho|(R_0 - R_i) + t_{core}|}{d} \text{ and } \psi = \frac{T_\Sigma^2 (l_m - 2t_{core})^2}{\left[2\pi pmnB_r R_0^3 a(1-a^2)\right]^2}$$

With the given torque, a fixed machine length and core length, the copper loss is minimized if the term $K(x) = l_{magnet}^2(l_{machine} - 2t_{core} - 2\Delta - 2l_{magnet})$ is maximized. This happens if $dK(x)/dx = 0$ when $x = l_{nc} = 2t_{winding}$. Then the air gap flux density $B_{airgap} = 2B_r/3$, with given current density J, the torque is maximized when B_{av} maximized, that means $l_{magnet} = l_{airgap}$. The airgap flux density is then $B_r/2$.

The number of winding turn per phase is:

$$n = \frac{T_\Sigma}{2\pi pmnB_{av}J_i R_0^3(1-a^2)} \tag{11}$$

The number of coils per phase is:

$$n_2 = \frac{n}{n_3} \tag{12}$$

The number of winding layer per coil n_1 and coil width b_c is given by:

$$b_c = \frac{nd}{n_1 n_2} \tag{13}$$

The coil width and number of coil can be checked by:

$$3mb_c + K_q \leq 2\pi R_i \qquad (14$$

Where K_q is reserved factor for overall space between coils. K_q can be chosen 10% perimeter at inner radius.

$$b_c \leq \frac{2\pi R_i - K_q}{3m} \qquad (15$$

3. Conclusion

In this article, the prototype of slotted and slottless axial flux permanent magnet generators have been investigated due to its simple configurations and easy manufacturing technology. All calculations for the new proposed AFPM generator are performed, these calculations are necessary for Vietnam to design wind generators at very low cost. These generators promise the potential applications in remote and rural areas in Vietnam. The further studies will be carried out for small hydro power stations and diesel engine coupled generators.

4. Acknowledgement

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