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Research Article

Inherent Difference in Saliency for Generators with Different PM Materials

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The inherent differences between salient and nonsalient electrical machines are evaluated for two permanent magnet generators with different configurations. The neodymium based (NdFeB) permanent magnets (PMs) in a generator are substituted with ferrite magnets and the characteristics of the NdFeB generator and the ferrite generator are compared through FEM simulations. The NdFeB generator is a nonsalient generator, whereas the ferrite machine is a salient-pole generator, with small saliency. The two generators have almost identical properties at rated load operation. However, at overload the behaviour differs between the two generators. The salient-pole, ferrite generator has lower maximum torque than the NdFeB generator and a larger voltage drop at high current. It is concluded that, for applications where overload capability is important, saliency must be considered and the generator design adapted according to the behaviour at overload operation. Furthermore, if the maximum torque is the design criteria, additional PM mass will be required for the salient-pole machine.

1. Introduction

The material most commonly used as permanent magnets (PMs) in electrical machines is neodymium-iron-boron, $Nd_2Fe_{14}B$ (shortened as NdFeB). During the last five years the price for NdFeB has increased and fluctuated extremely. In addition, 97% of all mining currently occurs in China and the export quotas for rare-earth metals from China are politically controlled [1]. Furthermore, the environmental aspects of rare-earth metal are an issue. Therefore, the idea to substitute NdFeB with ferrites has been suggested [2] and tested [3]. Several theoretical comparisons of generators with NdFeB and ferrites for wind power generators have previously been performed [2, 4–6]. In most of these studies [4–6] the better magnetic performance of NdFeB is used as an argument for its advantage. However, when the availability and unstable price development for NdFeB are considered, ferrites are considered superior, especially for applications where the weight increase is of less importance [2]. NdFeB generators have been extensively studied [7, 8]. In wind turbines, variable speed operation is increasingly popular. Therefore, the behaviour of a permanent magnet synchronous generator (PMSG) with NdFeB at variable speed and load has been especially evaluated [9]. When substituting NdFeB with ferrites, very similar characteristics can be found at the nominal operating point [2]. However, the intrinsic difference between these two generator types was not considered in [2]; that is, the difference in saliency which may affect the variable load operation and especially overload behaviour.

A typical NdFeB generator is of round rotor type (also called cylindrical or nonsalient), with magnets surface mounted on a cylindrical iron core. Ferrites have much lower remanence than NdFeB. Therefore, the proposed ferrite generator has tangentially magnetized magnets mounted between magnetic pole shoes reinforcing the field and is thereby a salient-pole machine. The difference in saliency makes these two generator types behave differently at varying speed and load. Therefore, the whole operating range must be considered for a complete comparison between these two generators. In this paper, general machine characteristics are compared for the two generators from [2], over the whole operating range with focus on overload operation.

The NdFeB generator was designed to be used with a vertical axis wind turbine (VAWT) [10–12], even though the comparative study presented here is applicable to other types of PM machines. For this application, a high maximum

Table 1: Properties for different PM materials at 20°C. Data for NdFeB are taken from [2]. Data for ferrites are taken from a supplier (E-magnets UK). Costs are taken from [2] and have been updated by using the current metal price. The Y30 is used in the machine presented here. The Y40 is included for reference.

Property	NdFeB (N40H)	Ferrite (Y30)	Ferrite (Y40)
Remanence, Br (T)	1.29	0.38	0.45
Normal coercivity, Hc, (kA/m)	915	240	342
Intrinsic coercivity, Hci (kA/m)	1353	245	350
Energy product (kJ/m^3)	318	28.3	39.7
Density (kg/m^3)	7700	4700	5000
Energy density (J/kg)	41.3	6.0	7.9
Relative required mass	1	6.9	5.2
PM cost (EUR/kg)	29	1	1
Relative magnetic energy cost per generator	1	0.24	0.18

torque at overload operation is required, since the wind turbine is fully electrically regulated eliminating the need for a pitch-mechanism on the turbine blades [13]. The maximum torque capability of the generator is thereby an important design feature, and one of the objectives of this study was to investigate the difference in torque at overload operation. To ensure high overload capacity the generators were designed with unusually low load angle, which makes the generators quite unique and their overload behaviour especially interesting to evaluate. A low load angle enables the use of a simple, robust passive rectifier. The electrical system of the VAWT consists of a diode rectifier and an IGBT inverter so the generator is operated at unity power factor.

The saliency of PM machines has previously been discussed and considered concerning motor control [14, 15]. Here, saliency is considered in the area of substituting rare-earth metal based PMs with alternative materials, with the desire of keeping the same electromagnetic properties of the machine. In order to compare machines with different PM material a common reference point is needed. In this paper, it is evaluated whether this is at all possible, by investigating two PM machines with inherently different electromagnetic properties, that is, difference in saliency.

2. Materials and Methods

2.1. Magnetic Materials. Most PMs used in electrical machines today are made of NdFeB. In Table 1 magnetic properties of NdFeB are compared with two different grades of ferrite magnets. New ferrite grades have been developed since the ferrite generator considered here was designed. The presented generator has a ferrite magnet of grade Y30, whereas the new ferrite grade Y40 has a 40% higher energy product. Therefore, a machine with Y40 magnets would have a lighter rotor with less magnet volume.

As seen in Table 1, the required mass for ferrite magnets is much higher than that for NdFeB magnets. However, the cost for the PMs, when substituting NdFeB with ferrite, is only one fourth to one fifth; that is, if the larger mass can be accepted a large cost reduction can be expected.

2.2. Saliency of PM Machines. Saliency is a measure of the reluctance difference between the rotor and the stator around the circumference of the rotor. A generator with tangentially magnetized ferrite magnets placed between magnetically conducting pole shoes is a type of salient-pole machine and has different reluctance and inductance on the pole (direct axis inductance L_d) and between two poles (quadrature axis inductance L_q). A generator with surface-mounted PMs on a cylinder is a type of round rotor, which is defined as a rotor with equal reluctance and inductance all around the rotor ($L_d = L_q$). For a round rotor generator, the power output, P_o, if the inner resistance is omitted, can be found from

$$P_o = \frac{3V_a E_a \sin\delta}{X_s}, \quad (1)$$

where V_a is the terminal phase voltage, E_a is the no-load phase voltage, δ is the load angle, and X_s is the synchronous reactance, which is equal to the direct axis reactance. For a salient-pole machine, omitting the inner resistance, the power is

$$P_o = \frac{3V_a E_a \sin\delta}{X_d} + \frac{3\left(X_d - X_q\right)}{2X_d X_q} V_a^2 \sin(2\delta), \quad (2)$$

where X_d is the direct axis reactance and X_q is the quadrature axis reactance. The second term in (2) is called the reluctance term and it has larger influence if the difference between L_d and L_q is large. The power equations show that the power will vary differently with the loading of the machine depending on the saliency.

For a generator connected to a resistive load or a passive rectifier (diodes) the power factor is unity. For a machine run with unity power factor, the voltage will drop with increasing current. For a round rotor generator with unity power factor and omitted resistance, the output voltage is

$$V_a = E_a \cos\delta, \quad (3)$$

so the voltage drops with increasing load angle. The corresponding voltage drop for the salient-pole machine with unity power factor and omitted resistance is

$$V_a = E_a \cos\delta - I_d\left(X_d - X_q\right)\cos\delta, \quad (4)$$

where I_d is the direct axis current. The voltage drops faster for the salient-pole machine (as long as $(X_d - X_q) > 1$) as is seen when comparing (3) and (4).

Inserting (3) in (1) gives the power output for the round rotor generator with diode rectification:

$$P_{o,\mathrm{diode}} = \frac{3E_a^2 \cos\delta \sin\delta}{X_s} = \frac{3E_a^2 \sin(2\delta)}{2X_s}. \quad (5)$$

Equation (5) shows that, for a diode rectified round rotor generator, the maximum power is half the value and occurs at half the load angle compared to a generator where the output voltage equals the internal voltage, which can be achieved by boosting the generator voltage with an active rectifier. For the latter type of operation, the maximum power occurs at about 90° load angle. For a diode rectified generator, the maximum power occurs around 45° due to the internal voltage drop. Similar behaviour is expected for the salient-pole generator when operated at unity power factor.

2.3. Simulations. The results presented here are from simulations using a two-dimensional model solved with the finite element method (FEM) [16]. Circuit theory, as (1), (2), (3), (4), and (5) are based on, have simplifications and therefore field based simulations are performed to consider all aspects of material and geometry in machine design. The simulation model is a combined field and circuit model solved through time-stepping. The generator characteristics were derived by stationary simulations during an iterative design process and the behaviour at different operating points was found from dynamic time-dependent simulations. The simulation model has been described more thoroughly and verified with experiments for a 12 kW generator and for the 225 kW NdFeB generator in [17] and [12], respectively. In the simulations the generator is connected to a purely resistive load; that is, the power factor is unity.

2.4. The Generators. The NdFeB based generator, G1-Nd, was tested and built in 2010 [12]. The ferrite generator, G2-Fe, with a different rotor but exactly the same stator, was designed in 2012 to have similar electromagnetic properties as G1-Nd [2]. The most important generator properties and a comparison at rated operation can be found in Table 2 and in [2]. Figure 1 shows the different geometry of the two generators as well as results from FEM simulations showing the magnetic flux density in the generators.

Table 2: Electromagnetic characteristics for rated speed and power as well as some geometrical characteristics from stationary simulations for the two generators [2].

Characteristics	G1-Nd	G2-Fe
PM grade	N40H	Y30
Active power (kW)	225	225
Load L-L voltage (V) rms	793	793
Current (A) rms	164	164
Electrical frequency (Hz)	9.9	9.9
Rotational speed (r/min)	33	33
Torque (kNm)	65	65
Cogging (% of rated torque)	1.8	1.3
Electrical efficiency (%)	96.6	96.6
Stator copper losses (kW)	5.4	5.4
Stator iron losses (kW)	2.4	2.4
Load angle (°)	9.6	9.3
Power factor	1	1
Airgap force (MN/m^2)	0.18	0.20
Number of poles	36	36
Magnet dimensions (mm)	19 ∗ 120 ∗ 848	100 ∗ 350 ∗ 809
PM weight	536	4789
Total rotor weight, active[a] (t)	1.7	8.5
Total rotor weight (t)	3.3	approx. 10.8
Total generator weight, active[a] (t)	6.5	13.3
Total generator weight (t)	13	approx. 20.5

[a]Active material is material active in the magnetic circuit; see Figure 1.

Table 3: Comparison of overload operation for the two generators.

Characteristics	G1-Nd	G2-Fe
Max. torque (kNm)	200.4	178.0
Load angle at max torque (°)	46.2	44.1
Max. power (kW)	607.5	551.1
Load angle at max. power (°)	43.2	41.4
Voltage drop at 600 A (% of no load voltage)	28	37

3. Results and Discussion

The torque at different load angle for the two machines is compared in Figure 2. At part load operation, the generators have similar behaviour and their rated properties are almost identical, as shown in Table 2. However, at overload operation differences occur. The NdFeB generator has higher overload capacity. The maximum torque for the ferrite machine is only 89% of the maximum torque of the NdFeB machine. The small saliency of the ferrite machine affects the shape of the torque curve and the overload capability even though the differences between the two machines are small; see (1) and (2). Equation (2) shows that the power corresponding to the reluctance torque (the second term) varies with the load angle. For the salient-pole generator considered here, the reluctance term has largest influence at load angles around 20 to 30 degrees and decreases at higher load angles. The reluctance torque will thereby decrease the maximum torque slightly and will make the power curve steeper at low load angles. In order to achieve as high maximum torque as the round rotor machine, the salient-pole machine should have been designed at a lower rated load angle, which would imply using more permanent magnets. However, when designing the machine the objective was to have similar characteristics at rated power.

A comparison of the maximum torque and maximum power for the two machines and at what load angle they occur can be seen in Table 3. The salient-pole machine reaches the maximum values at about two degrees lower load angle than the round rotor machine. The voltage drop at increasing current can be seen in Figure 3 for the two machines. The voltage drops with increasing current since the power factor is unity. The voltage drops faster for the salient-pole machine since the voltage drop depends both on increasing load angle and on increasing direct axis current as discussed in Section 2.2.

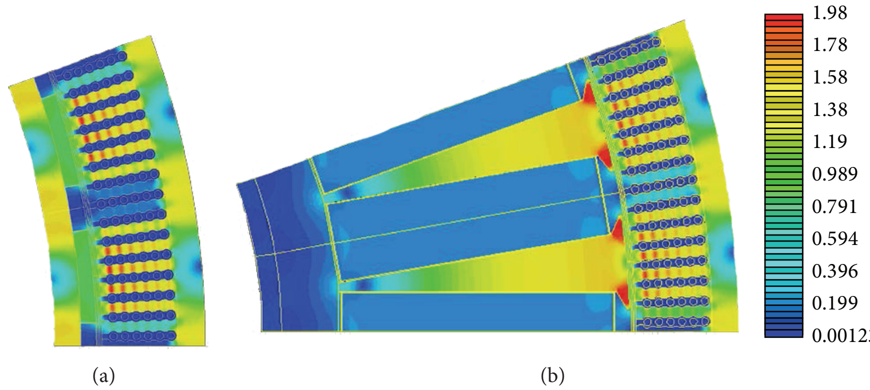

Figure 1: The magnetic flux density (in Tesla) in the two generators. (a) G1-Nd. (b) G2-Fe.

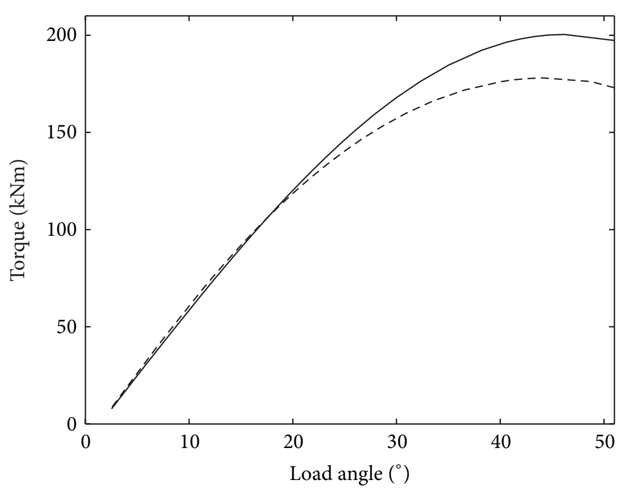

Figure 2: Torque as a function of load angle at rated speed and unity power factor for the round rotor generator G1-Nd (solid line) and the salient-pole generator G2-Fe (dashed line).

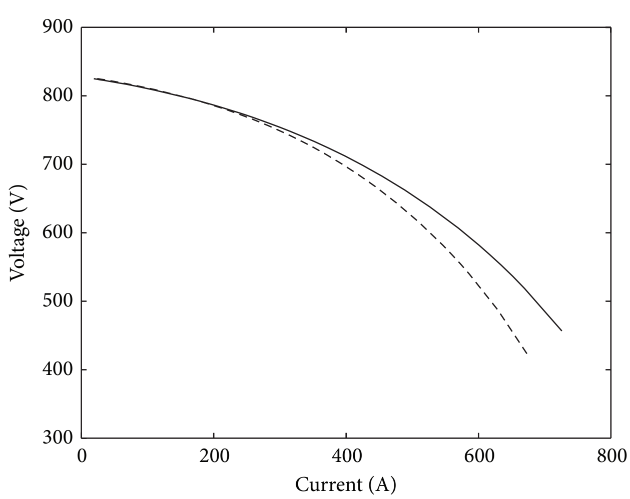

Figure 3: Voltage as a function of current at rated speed and unity power factor for the round rotor generator G1-Nd (solid line) and the salient-pole generator G2-Fe (dashed line).

This study has focused on FEM simulations of field equations which are more accurate than circuit equivalents of generators and since the inductances are difficult to estimate no exact estimation of inductances representing the machines has been done here. The salient-pole machine considered here has a small positive saliency; the saliency ratio L_d/L_q is between 1 and 1.5. A frequency response test in the FEM simulations of G1-Nd gives that L_d equals L_q, as expected for a round rotor, and is 8.1 mH, which is expected to be fairly accurate.

The larger the difference between L_d and L_q is, the more influence the reluctance torque has and the more the maximum torque point is moved to the left of the torque-load angle chart; see Figure 2. When the saliency is quite low, as here, the maxima are not shifted much. In this work, the generators have been designed to have certain rated operation values at, or close to, a particular load angle, in order to ensure a high maximum torque.

When a permanent magnet machine is operated at high current, there is a risk of permanently demagnetizing the permanent magnets. Therefore, the generator should be designed to withstand events such as short circuit currents, which usually are higher than the maximum current considered here. The aim of this study has been to show the differences between the two generators and not to evaluate the risk of permanent demagnetization. However, demagnetization during faults is not expected in any of these machines since the NdFeB magnets have high coercivity and the ferrite magnets are thick (in the direction of magnetization) and are protected by the rotor design.

4. Conclusions

In this paper, it has been shown that two generators with different saliency, designed at the same operational point for rated operation, have different overload characteristics. For machines rated at a low load angle, the difference in behaviour at part load and rated load can be neglected since the behaviour at low load angle is very similar. However, the operation at overload differs. If the maximum torque is the design criteria, the machines are not considered comparable, and a design for the ferrite generator with more magnets and lower rated load angle, as well as lower voltage drop, would have been chosen instead. For a more conventional generator design with a rated load angle at 20 to 30°, the differences would be more apparent and part load behaviour and maximum behaviour load might differ more.

It can be concluded that, for machines where overload capability is an important property, saliency needs to be considered. In addition, more magnetic material than expected when considering the energy product in Table 1 is needed for a ferrite machine, due to the intrinsic differences in saliency affecting machine properties. The small difference in saliency does not have any large effect on the generator rated operation, but it does have a small effect on the overload capability.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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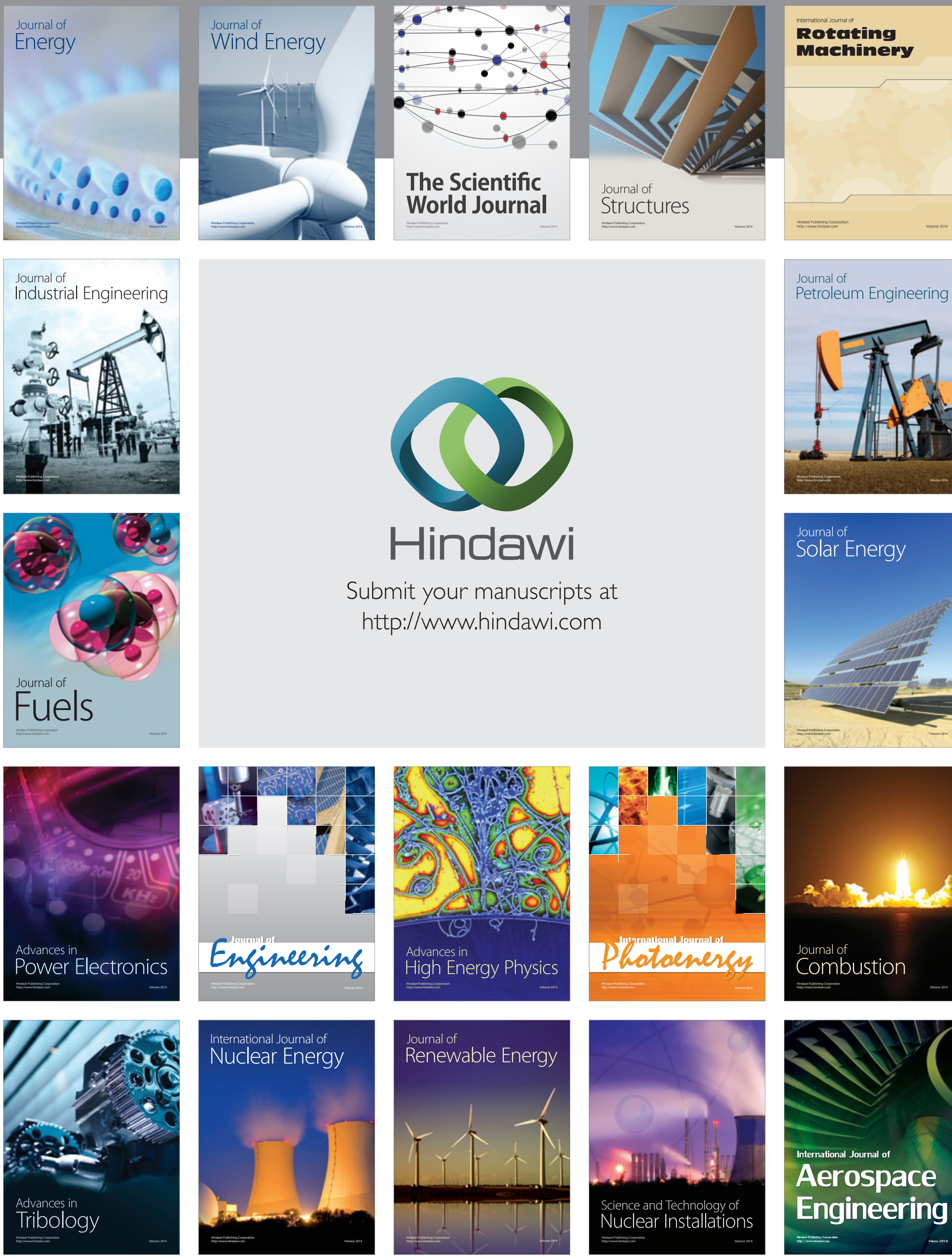
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