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The Study of Hybrid Permanent Magnets in Synchronous Generators for Hydroelectric Application

Emir Poskovic
Energy Department
Politecnico di Torino
Torino, Italia
emir.poskovic@polito.it

Alex Lucco Borlera
R&D Department
SicmeOrange1 s.r.l.
Torino, Italia
alucco@orange1.eu

Luca Ferraris
Energy Department
Politecnico di Torino
Torino, Italia
luca.ferraris@polito.it

Silvio Vaschetto
Energy Department
Politecnico di Torino
Torino, Italia
silvio.vaschetto@polito.it

Alberto Tenconi
Energy Department
Politecnico di Torino
Torino, Italia
alberto.tenconi@polito.it

***Abstract*— The voltage regulation for permanent magnet synchronous generators shows several complexities, especially if the system is connected directly online. Hybrid magnets represent a particular solution to resolve this drawback. The dedicated coils are used to control the magnetic flux of magnets and permit voltage adjustments. Different generators with hybridization equipment have been studied for a small hydroelectric plant. Some solutions show promising results.**

Keywords*— *Hybrid Permanent Magnets, Synchronous Generators, Hydroelectric

I. Introduction

The production of electrical energy from renewable and green sources is an important goal in various countries [1]. Different factors affect the production process: resource management and supply, type of plant, regulatory policy, etc. In the case of hydropower, the plants have different sizes and power capacities, starting from the traditional water wheel to arrive at modern turbines such as Pelton, Francis, and Kaplan. Also, recently, the Archimedes Screw has been developed to exploit the minor falls of the water to produce electrical energy. Every cited turbine obtains its maximum in determined conditions that depend on the waterfall height, water flow and morphological structure of the basin.

The hydroelectric system is constituted of turbines, generators, and transmission components. The most common generators are synchronous electrical machines, but for small hydro plants (< 10 MW) are used induction generators (IG) and permanent magnet synchronous generators (PMSG) [2-4]. The generator can be directly connected by the shaft to the turbine or through the use of the gearbox. Also, using the inverter allows more power adjustment [5], but at the same time, the costs and maintenance increase.

For small hydro, the use of permanent magnets permits to design the generator with high poles and mainly does not require the excitation current supply [6]. The machine is without the brushes and could work without the gearbox. On the other hand, the cost of permanent magnets and complicated voltage regulation are the main disadvantages of these generators. Also, the power factor and reactive power are not easily regulated. The permitted voltage regulation is around ±10% of the rated voltage for the directly connected system. Power electronic conversion allows the regulation of voltage and reactive power but adds another cost for the hydroelectric system. A possible solution is to use hybrid permanent magnets (HPM) [7-11].

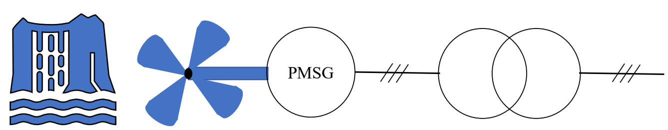

Fig. 1 – Hydroelectric system with the permanent magnet synchronous generators connected directly online

The magnet hybridization activity can be obtained in two different modes: with the combination of strong and weak permanent magnets or through the use of specific coils around the magnets. In the case of hybrid permanent magnets, the strong magnets are sintered or bonded NdFeB and SmCo, while the weak magnets are ALNiCo or hybrid magnetic composites (HMC) [12], [13]. Also, obtaining a unique magnet, a multilayer magnet, with both magnetic forces is possible by means of a specific moulding process [14]. The described solution with the hybrid permanent magnets is trendy for increasing the torque density in the flux-weakening range, especially in variable flux machines. The magnets can be arranged in serial or parallel configurations concerning the magnetic flux direction produced by magnets. On the other hand, highly complex driver control must be implemented, and the power electronic converter must be used. This solution is not employable for generators directly connected to the grid.

The second solution of hybrid magnets consists of dedicated coils located around the magnets that regulate the magnetic flux produced by permanent magnets [7]. In this way, the voltage is also adjusted for PMSG. Moreover, it is possible to save on the volume of the permanent magnets. Too, the power factor and reactive power can be regulated without inverters. Also, the hybridization coils can operate in series or parallel configurations, and they can be applied in variable flux machines to adjust the torque and power factor in flux-weakening conditions [15], [16]. Their position depends on the type of machine and the final aim of the regulation [17]. The mechanical aspects concerning coils are similar to wound rotor synchronous machines (WRSM) [18], where brushes and slip-rings arrangements provide the external DC supply. On the other hand, the adopted mechanical contacts produce sparking and maintenance problems; from this point of view, the brushless exciter can be used [19-22]. Such a solution consists of adding one or two inverters and a rectifier [23]. Also, the additional winding can be added to generate the sub-harmonic components [24], [25]. In general, in these configurations, the machine is self-excited. However, the machine's cost (presence of inverters) and size increase significantly. Another solution is represented by a rotary transformer [26], [27], which requires a high frequency of operation. Brushless excitation with several inverter stages and rotary transformer are unsuitable for directly connected hydroelectric generators. Therefore, the supply type for the hybridization coils is chosen between brushes and slip rings or simply a brushless exciter with an automatic voltage regulator (AVR) and rectifier.

In the proposed work, the hybridization of permanent magnets by adding the coils has been studied in a small hydropower plant with a direct online connection and without the gearbox. The goal is to regulate the voltage, power factor and reactive power by only varying the current density of the hybridization coils. Other main values, such as power, torque, and harmonic content, have also been examined. Several machine designs with hybrid permanent magnets have been proposed, and only series configurations have been studied. The activity has been coordinated with SicmeOrange1 company.

II. Generator Design

The generator operates at 250 rpm, and rated power is about 278 kW. The machine is studied to work with an immersed Kaplan turbine. Also, the generator is submerged. From this point of view, the designed current density of 4.5 A/mm^2 indicates that a cooling system is unnecessary. Also, the maximum operating temperature is around 80÷90°C, based on the experience and previous activities obtained in SicmeOrange1 company. Therefore, the permanent magnet's demagnetization is not shown due to temperature.

The permanent magnets are sintered NdFeB with a remanence of 1.13 T. The baseline design of the electrical machine is shown in Fig. 2, and principal information is reported in Table I. The baseline configuration is a surface permanent magnet synchronous generator without the hybridization procedure. The number of poles is 24, and the PM arc and pole pitch ratio is 5/6. The PM height is 9.4 mm. The following hybridization configurations start from the baseline, but further modifications will be implemented, maintaining the fixed external geometries (housing, diameters, length) and air gap. Due to a no-disclosure agreement with the company, the main dimensions of the machine cannot be described.

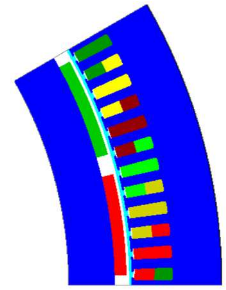

Fig. 2 – Baseline configuration design of PMSG machine

Table I - Design Information of Baseline PMSG Machine

Number of Poles	24
Number of Slots	144
Rated Current	410 A
Rated Power	278 kW
Rated Speed	250 RPM
Rated Torque	11080 Nm
Current Density	4.5 A/mm^2
Max operating temperature	80÷90°C
Air Gap	4 mm

III. Propose Description

The work aims to propose several hybridization arrangements in order to regulate some parameters. Voltage regulation, power factor, and reactive power have been examined, as well as the hybridization effects on torque and power. Also, the rotor geometry and permanent magnet volumes have been changed in some configurations. The hybridization coils will be connected to a voltage regulator through an additional exciter and rectifier.

The investigation was performed using MatLab and finite element analysis (FEA) by Altair Flux. The baseline dimensions and main rated values, like rated current, have been deduced using MatLab analytical elaboration. The performance and hybridization arrangements have been evaluated using the FEA. The models considered only the case in rated condition, fixed rated current, and 50 Hz. No flux weakening operations are performed.

Three hybrid solutions have been studied. The negative and positive current arrangements have been evaluated for each of them. The threshold for a good result has to be more significant than ±5% of the rated voltage. The baseline results have been added to the comparison of each hybridization solution. Some comments concerning fault operation and efficiency have been included in the final discussions.

IV. Hybridization of Permanent Magnet Synchronous Generator

A. First solution: hybridization coils around the magnets in the air

Considering the baseline design of the generator, the hybridization coils are placed around and very close to the magnets. The volume of the magnets has been reduced by 16%. However, the ratio is the same between the PM arc and pole pitch. The coils are inserted in the air, and for this reason (heat transfer), the maximum current density applied for the hybridization is 2 A/mm^2. The cross-section of the hybrid coils is 118.73 mm^2. The current is supplied in arrangement with permanent magnet magnetic flux (positive arrangement) and inversely to magnet flux (negative arrangement). Also, the current density condition equal to zero is considered (J=0), where the magnetic flux is not adjusted. The maximum current capacity is 237.47 A. The design of the machine remains very similar to the baseline SG, as illustrated in Fig. 3. In Fig. 4, the comparison among linked voltages at no load condition shows higher values for the baseline machine, and mainly, the voltage regulation is insufficient, where the maximum adjustment interval is 9.56 V. For these reasons, further hybrid PM generator designs have been studied. Furthermore, the harmonic contents of the regulated voltage waveforms are shown in Fig. 5. It is possible to note that the baseline PMSG has more harmonics. However, for a detailed comparison, the total harmonic distortion (THD) has been calculated and reported in Table II. The effect of hybridization on the harmonics is very favourable because the THD is about a third compared to the baseline generator.

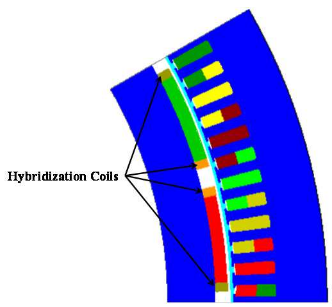

Fig. 3 - Design of HPMSG machine with coils close to magnets in the air gap

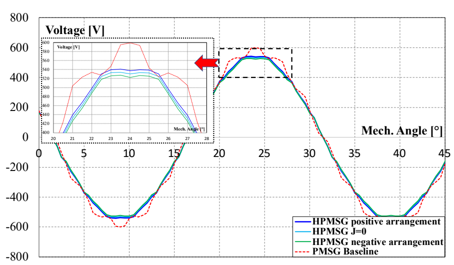

Fig. 4 - Linked voltage comparison between HPMSG and reference PMSG at no load rated condition

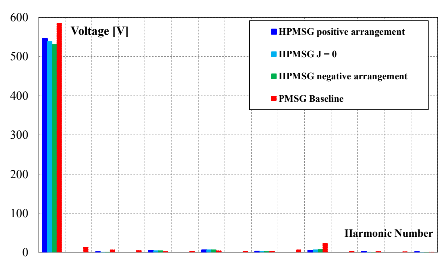

Fig. 5 – Harmonic content comparison between HPMSG and reference PMSG

Table II – THD Values of HPMSG and Baseline PMSG

baseline PMSG	5.28%
positive arrangements	1.81%
J=0	1.96%
Negative arrangements	2.08%

B. *Second solution: hybridization coils around the pole piece*

The following HPMSG design considers the magnet's location when inserted into the pole pieces. The coils for hybridization are placed around the pole pieces/magnet poles. The cross-section is a little reduced, 115.27 mm^2. The maximum current capability is 230.55 A. The air gap is maintained the same, and the magnets are reduced by 18% compared to the reference PMSG machine. The introduction of the pole pieces should optimize the magnetic flux conveyance and provide the location for the damper cage in the case of fault operation. The design of HPMSG with pole pieces is shown in Fig. 6. The voltage regulation has a low increment concerning the interval, 10.77 V, while the voltage value decreases significantly compared to the reference value, as shown in Fig. 7.

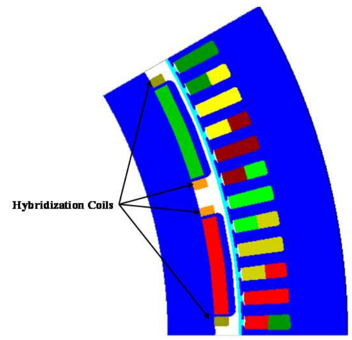

Fig. 6 - Design of HPMSG machine with coils around the pole pieces

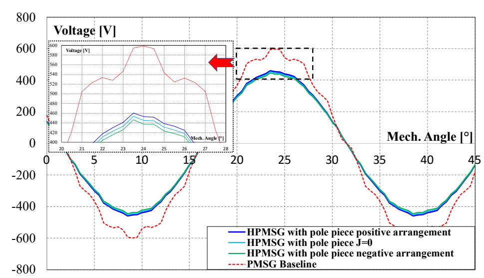

Fig. 7 - Linked voltage comparison between HPMSG with magnet pole and reference PMSG at no load rated condition

The harmonic content analysis is shown in Fig. 8. Again, the baseline has more harmonics, but the first harmonic is very high compared to hybridized ones. The reduction of THD for the hybridized machine is better than the previous solution, as reported in Table III; however, the very low voltage negatively affects this machine.

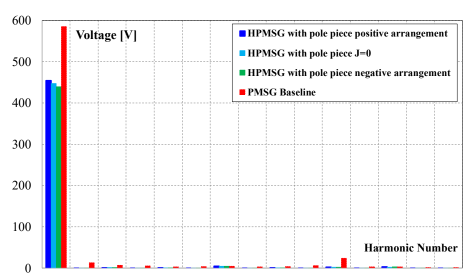

Fig. 8 - Harmonic content comparison between HPMSG with magnet pole and reference PMSG

Table III – THD VALUES OF HPMSG WITH MAGNET POLE AND BASELINE PMSG

baseline PMSG	5.28%
positive arrangements	1.32%
J=0	1.39%
Negative arrangements	1.42%

C. *Third solution: V-type magnet with embedded hybridization coils*

The weak voltage regulation of previous solutions requires a new machine design with little change. The following design concerns the use of V-type embedded magnets. In this context, the hybridization coils are embedded, and the maximum current density for the hybridization is carried to 4 A/mm^2. The increment of current density is due to the interior hybridization coils positioned in the rotor core, where the heat transfer is higher than in previous solutions. The corrs-section of the hybrid coils is 117.55 mm^2. The maximum current capacity is 470.2 A. The air gap is the same as the original PMSG. Two types of V-magnet configurations are proposed: one with a large angular opening (134°), illustrated in Fig. 9, and another with a short angular opening (83°), illustrated in Fig. 10. In the first case, the reduced magnet's volume with respect to the baseline is 14%. On the other hand, the voltage is very low, as shown in Fig. 11, while the regulation is good, 37.19 V.

In the case of the short opening V-type magnet design, the voltage values show good results comparable with the original one, as reported in Fig. 12. This result is due to the maximization of the magnetic flux in the air gap, owing to careful research of the location for hybrid coils. Also, the voltage regulation has promising results with an interval of 24.70 V. On the other hand, the permanent magnets slightly increase their volume by 4% due to the trapezoidal edge shape.

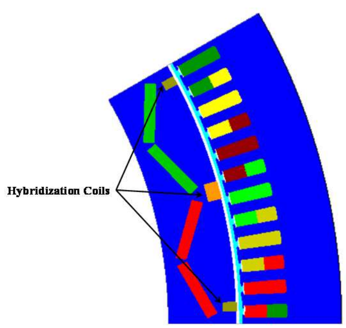

Fig. 9 - Design of HPMSG machine with embedded large opening V-type PM and hybridization coils

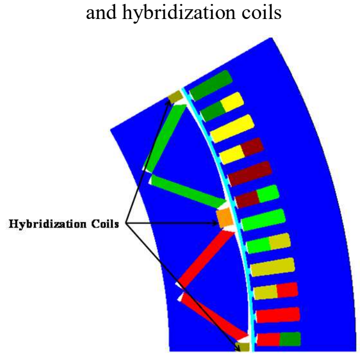

Fig. 10 - Design of HPMSG machine with embedded short opening V-type PM and hybridization coils

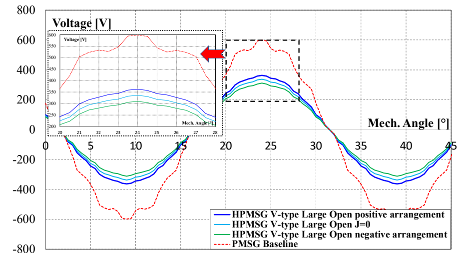

Fig. 11 - Linked voltage comparison between HPMSG with large opening V-type PM and PMSG at no load rated condition

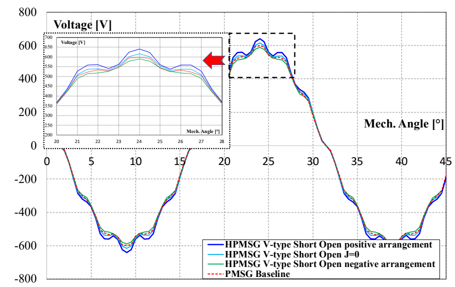

Fig. 12 - Linked voltage comparison between HPMSG with short opening V-type PM and PMSG at no load rated condition

The harmonic content is low for the V-type HPMGS with high angle opening, as reported in Fig. 13. Moreover, the hybrid regulation does not affect the THD value, which remains constant at around 1.46%, as shown in Table IV. On the other hand, the 1st harmonic is very low compared to the baseline PMSG one.

The harmonic contributions are the highest for the HPMSG with short opening V-type magnets, as represented by the THD values in Table V. The effect of hybridization is different compared to previous cases; the THD value shows a higher variation, and also, the trend is opposite (direction versus minimum) where the positive arrangement has the worst THD value. The first harmonics are higher than the baseline machine, but the 11th is higher than the reference one, as shown in Fig. 14. In general, for grid connection, several standards require that THD is equal to or less than 5%; therefore, the obtained results could have further slight restrictions. Such a drawback can be resolved with a minor modification of the pole arc.

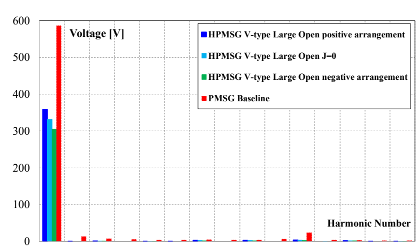

Fig. 13 - Harmonic content comparison between HPMSG with large opening V-type PM and reference PMSG

Table IV – THD VALUES OF HPMSG WITH LARGE OPENING V-TYPE PM AND BASELINE PMSG

baseline PMSG	5.28%
positive arrangements	1.47%
J=0	1.46%
Negative arrangements	1.46%

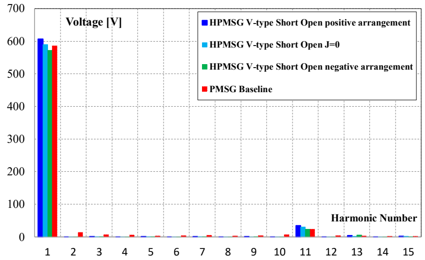

Fig. 14 - Harmonic content comparison between HPMSG with short opening V-type PM and reference PMSG

Table V – THD VALUES OF HPMSG WITH SHORT OPENING V-TYPE PM AND BASELINE PMSG

baseline PMSG	5.28%
positive arrangements	5.67%
J=0	5.19%
Negative arrangements	4.18%

V. RESULTS COMMENTS

A. Voltage adjustment

For a detailed analysis of voltage adjustment, various information are reported in Table VI:

- maximum delta variation of the RMS voltage in the considered current density interval;
- threshold exceeding for ±5% of the rated voltage;
- THD under the 5%.

Table VI – THE MAIN VOLTAGE ADJUSTMENT INFORMATION

	ΔV [V]	**$\Delta V > \pm 5\% V_{rated}$**	**THD<5%**
First sol.	9.56	no	yes
Second sol.	10.77	no	yes
Third sol. I	37.19	yes	yes
Third sol. II	24.70	yes	no

The third solution of HPMSG with a large angle aperture for V-type magnets respects all requirements, but the voltage is very low compared to the baseline PMSG (411.73 V). In this context, the first solution obtains a good result; however, the very low regulation limits its application for hybridization. In the end, using the positive arrangement, the V-type machine with a short opening angle is the best solution for hybridization with the highest voltage, 430.99 V. The slightly high THD can be easily resolved with a small modification of the curvature of the pole arc.

B. Rated Torque and Power

Hereafter, only the first HPMSG and the last V-type short-opening HPMSG will be considered for further results. The torque is greatly affected by hybridization for the V-type HPMSG machine, as can be observed in Fig. 15, where the torque value is higher for positive arrangement compared to the reference one. The first solution design with surface-mounted HPM shows torque values lower than reference one and with modest regulation. The same results are obtained in the case of power, as reported in Fig. 16. Selecting the appropriate hybridization configuration for generators requires careful analysis: if it chooses the adjustment or produced power.

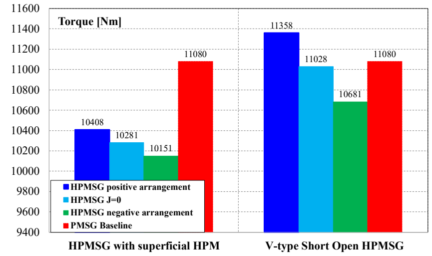

Fig. 15 – Hybridization effect on the rated torque

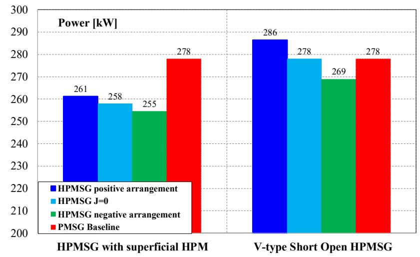

Fig. 16 – Hybridization effect on the rated power

C. Power factor and reactive power adjustment

The possibility of regulating the power factor (PF) with hybridization magnets seems an interesting proposal. For this reason, both proposed generators with hybridization arrangements have been investigated, considering the variation of active power produced. The first solution, with surface-mounted hybrid magnets, shows high power factor values but very low adjustment. Also, with an increment of the produced power, the PF slightly but continually is reduced, as shown in Fig. 17. For the V-type HPMSG machine, the PF show lower values at low produced power; however, with the increment of power, the PF increase very quickly and reach the appropriate values, as illustrated in Fig. 19. Also, the PF regulation is very high, where the best condition is obtained with the negative arrangement of the hybridization procedure. The more favourable design for PF seems to be with surface-mounted HPM because it maintains relative constant and high values. On the other hand, the very promising PF regulation with V-shaped HPMSG allows its application.

The reactive power for the first solution shows limited adjustment, as shown in Fig. 18. Instead, for the V-shaped solution, the reactive power adjustment is promising, as shown in Fig. 20. Furthermore, the values are higher than the first HPMSG design. In this context, the V-shaped hybridized generator can be a promising solution when the electrical grid needs to acquire or provide reactive power [28].

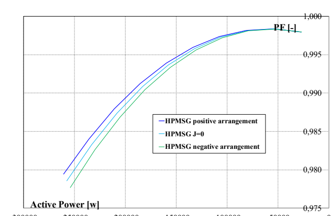

Fig. 17 – Power factor adjustment for HPMSG with surface-mounted HPM

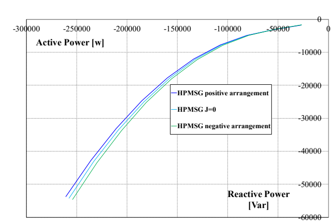

Fig. 18 – Reactive power adjustment for HPMSG with surface-mounted HPM

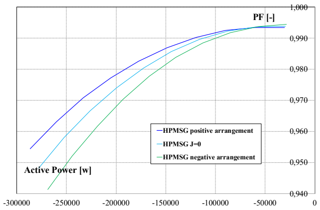

Fig. 19 - Power factor adjustment for V-type short angle open HPMSG

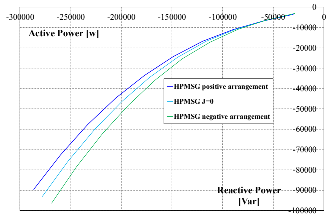

Fig. 20 - Reactive power adjustment for V-type short angle open HPMSG

VI. Final Discussion

Hydroelectric generators commonly include damper cages for several aspects, mainly in fault operations. Hybrid coils, such as a damper cage, can be adopted. However, a detailed study must be performed because serious heat problems could arise. A possible procedure could consist of a fast hybridization circuit opening in the presence of the fault and, consequently, carrying out the start-up management. The saturation of the stator and rotor yoke is controllable. Only some tiny areas close to the air gap in the rotor can show the saturation effect. Instead, in the stator yoke, for both final designs, the magnetic flux density is 0.702 T for V-type HPMSG (3rd.II sol.) and 0.637 T for surface-mounted HPMSG (1st sol.). Both values are not a cause of worry. Compared to WRSM, the principal advantages regard the efficiency and high torque density at rated condition; however, the cost of permanent magnets is a drawback. From this point of view, hybridization could reduce the cost difference between generator types. Also, the control of WRSM is more flexible. However, the conventional WRSM uses brushes and slip-rings to supply the rotor with current, which are a source of issues.

VII. Conclusions

Different design solutions for the hybridization of directly connected PM generators have been proposed. The surface-mounted hybrid magnet solution shows low THD, and constant PF. On the other hand, the V-shaped solution shows very high voltage, torque density, PF and reactive power regulation. The hybridization ratio is appropriate because it does not allow for exceeding 10% of the rated voltage. Also, the hybrid coil heating does not provoke the demagnetization effect for the investigated solutions. A voltage regulator through an additional exciter and rectifier allows studying the prototype's manufacturing. The holder and number of turns for the hybrid coils will be clarified during prototyping. A dedicated study for damper cages will be performed in the future, and the possibility of incrementing the current density for hybridization to raise regulation performance will be explored. In this context, a demagnetization effect will be investigated.

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