Analytical Modelling of Harmonics in an Exciterless Synchronous Generator

Abstract—The replacement of the brushless exciter in the synchronous generator has long been desired as a method to increase power density. There are many topologies available that allow the excitation system of a synchronous generator to be combined with the main magnetic circuit, but these topologies have previously only been demonstrated on low power machines. This paper develops an analytical model of an existing exciterless machine topology, and uses it to produce an optimized winding configuration to convert an existing, brushless exciter based, generator design to exciterless. Harmonic performance is a key requirement for medium power designs, with strict restrictions placed on manufacturers by grid standards worldwide. Therefore, the focus of the analytical model is to accurately predict the harmonic content of the machine at no-load, including the overall output voltage shape. This is validated experimentally against a prototype machine, and the feasibility of the exciterless topology, for medium power and above applications, is discussed.

Keywords—synchronous generator, wound-field, exciterless, excitation system

I. INTRODUCTION

The typical wound field synchronous generator (WFSG) has the field winding placed on the rotor. This presents a challenge to the machine designer in the choice of excitation system (ES) to supply current to this winding. The most common options are slip rings, i.e. a static ES, to provide a direct rotating connection, or the brushless exciter, an additional synchronous machine that generates an AC output that is rectified before supplying the main field [1]. The advantages and disadvantages of each method are given in Table I. In general, for medium power machines the need to achieve low cost and high reliability, coupled with relatively high excitation demands, results in the brushless exciter as the chosen option. This is thanks to its maintenance free design and leverage of the prime mover leading to a significant reduction in power electronics requirements. Slip rings are more common on both low power and high power machines where, for low power machines the converter costs are low, and for high power machines the response time benefits of a static excitation system are critical.

There has been significant research effort into the design of a brushless ES that combines its magnetic circuit with that of the main machine, allowing for improved power density, reduced manufacturing complexity, and ultimately reduced cost [2]. Of these methods, one of particular interest to the medium power designer is that first presented in [3]. While only demonstrated on a 3-kVA machine, the method has a simplified rotor winding structure that is suited for salient pole machines. Most other topologies contain separate excitation and field windings, requiring a round rotor machine [4], [5]. In addition, this method does not significantly restrict the design freedom of the main phase winding, unlike alternative methods in which both excitation and output current flow in a single armature winding [6]. Nor does it require a power converter capable of processing the whole output power to inject harmonics for excitation [7].

This paper provides a deeper look at this method, in the context of the medium power synchronous generator, and in doing so develops and validates an analytical model of the machine. This model is used to convert an existing 72.5-kVA synchronous generator design to excitierless through optimization of the stator winding design. Experimental results are given and used to assess the feasibility of this method for medium power applications.

II. TOPOLOGY AND OPERATION

The method presented in [3] makes use of an additional DC winding added to the stator producing a 2-pole field in the machine. Each pole winding on the rotor is individually rectified by a parallel diode, such that the voltage induced by the 2-pole field during rotation, causes a positive pulsating current. The strong mutual inductance between the pole windings ensures that a constant 4-pole flux is produced in the air gap, relative to the rotor. This flux couples with the 4-pole armature winding inducing the output voltage. A schematic of the main circuits involved in a SG implementing such a method is shown in Fig. 1.

![Fig. 1. Schematic of the excitierless machine winding topology](image330x83to526x240)

TABLE I

| Method                      | Advantage       | Disadvantages               |
|-----------------------------|-----------------|------------------------------|
| Static excitation with slip rings | Simple construction, Low cost, Fast response | Regular maintenance, Carbon dust produced, Voltage/Current limited |
| Rotating excitation using AC exciter | Energy supplied by prime mover, No maintenance | Wound machine component, Excitation coupled to rotation |

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In previously shown examples the rotor diodes are mounted to the shaft and the DC excitation winding is placed in an additional winding layer. Alternative winding configurations for the stator have been shown in which the DC excitation current is made to flow in the armature winding, though this introduces further restrictions on the winding design and layout [8].

III. TEST CASE MACHINE

The topology has previously only been demonstrated on low power machines of 3-kVA and below. To understand the scalability of the topology a typical medium power generator of 72.5-kVA has been chosen as the basis for this analysis. The specification of the machine is given in Table II. This machine is typically fitted with a brushless exciter that extends the axial length of the machine by 30%, reducing the overall power density of the genset. The exciter sits directly in the inlet path partially obstructing airflow, as shown in Fig. 2, and contributing to some pre-heating of the air. An exciterless solution is therefore desirable to overcome the power density reduction and potentially improve airflow allowing for a greater power output to be achieved.

TABLE II

| Parameter     | Specification                  |
|---------------|--------------------------------|
| Rotor         | Salient, 4-pole, tapered shoe   |
| Stator        | 48-slot, 7.5° skew across core length |
| Armature      | 3-phase double layer, 2/3rd short pitch |
| Core Length   | 240 mm                         |
| Rated Power   | 72.5-kVA                       |
| Rated Speed   | 1500 rpm (50Hz)                |

IV. EXCITERLESS MODELING

Previous works have focused on FE modelling of the exciterless topology [11], as it is able to provide an accurate simulation of the complex interactions between the many windings in the machine. That is not to say that this method is ideal – the large winding inductances result in long transient times meaning that a significant simulation must be carried out to reach steady state. Additionally, the requirement to model the diode commutation increases the complexity of the model and computation time, whilst ruling out many parallel simulation methods.
One of the key achievements of this work is the production of an analytical model of the topology which greatly reduces simulation time. Thereby allowing the designer more freedom to experiment with winding configurations and, in the case of this work, produce an optimized machine design through an iterative process.

The modelling method considers each winding as a circuit shown in Fig. 6, in which the winding is in a series loop with its equivalent resistance, $R$, and a load resistance, $R_L$. Optionally a voltage source can be included in the series loop, as in the case of the excitation winding. This is modelled mathematically as (1) in which the inductance is an 8x8 matrix, corresponding to the 8 windings in the machine, containing both the self and mutual inductances for each winding, and $V$ and $i$ are vectors containing the terminal voltage and current (respectively) for each winding loop.

$$V = Ri + \frac{d}{dt}Li$$  \hspace{1cm} (1)

In this work the inductance matrix has been populated using a modified FE model of the production machine that matches the new winding structure. This allows for rapid calculation of accurate inductance waveforms, carried out for a nominal single turn design. These waveforms can then be scaled to match the winding turn counts of a design. The waveforms are captured for a single mechanical cycle of the machine.

Equation (1) is rearranged to the form shown in (2) which is solved using Simulink, using the model of Fig. 7. The electromagnetic voltage component has been split into two components: 1) the voltage due to varying current (the transformer action), and 2) the voltage due to varying inductance with respect to the position $\theta$ of rotor vs. stator (the machine action). The differential form is pre-computed from the FE inductance waveforms and both are stored as lookup tables in the model.

$$V = Ri + L \frac{\partial i}{\partial t} + i \frac{\partial L}{\partial \theta} \omega$$  \hspace{1cm} (2)

The rotor diodes are modelled by modifying the pole winding load resistance in response to the calculated current. An ideal diode response is modelled, as shown in Fig. 8, by presenting a short circuit to positive current and an open circuit to negative currents. The implementation of Fig. 8 achieves this by ensuring only negative currents produce a voltage response.

The core saturation curve is critical to the performance of the machine. This has been modelled analytically, for no-load operation, by a scaling factor lookup, applied to the inductance matrices, controlled by the instantaneous average pole current. This is driven by saturation data from the benchmark production machine as they share the same magnetic circuit. An additional scaling factor based on the excitation current is also applied to account for saturation by this winding.

**V. OPTIMIZATION PROCESS**

The aim of the optimization process is to achieve the maximum possible power output while staying within the constraints of the current design. To this end the optimized variables are the number of turns for the armature ($N_{ph}$) and excitation ($N_{ex}$) windings, and the number of parallel conductors for the armature winding ($/p_{ph}$). The rotor winding and lamination design have been maintained, along with the conductor current density and wire diameter, this is to simplify future manufacturing.

An iterative process, outlined in Fig. 9, has been applied to optimize the turn combination. The machine is simulated using the analytical model at the maximum excitation current given the winding current density. Based on performance, copper area is reallocated between the excitation and phase windings, ensuring maximum utilization of the winding copper.

![Simulink analytical model of the machine](image)

**Fig. 7. Simulink analytical model of the machine**

![Analytical implementation of the rotor diodes](image)

**Fig. 8. Analytical implementation of the rotor diodes**

![Flowchart showing the iterative design process used to optimize winding turns](image)

**Fig. 9. Flowchart showing the iterative design process used to optimize winding turns**
The final optimized design resulted in a significant output power reduction. This is primarily due to the desire to maintain the field winding design resulting in underutilized copper area. Whist likely that greater performance could be achieved by also modifying the turn count of this winding, the increased magnetic loading would still result in less output power than that of the production machine.

VI. prototype construction

A prototype stator was wound with the winding specification, given in Table III, produced by the optimization process. There are two challenges when constructing this machine type: 1) the significant end winding length of the excitation winding – see Fig. 10, and 2) reduced fill factor due to additional lining papers. While neither of these are critical to the construction of the machine both should be key considerations for the designer.

| TABLE III | WINDING SPECIFICATION OF THE PROTOTYPE MACHINE |
|-----------|-----------------------------------------------|
| Winding   | Specification                                  |
| Field     | 84 turns per pole                              |
| Armature  | 3-phase, 2/3rds pitch                          |
|           | 4 coil groups per phase                        |
|           | 4 coils per group                              |
|           | 5 turns per coil                               |
|           | 2 winding layers                               |
| Excitation| 24 coils                                       |
|           | 30 turns per coil                              |
|           | 1 winding layer                                |

Fig. 10 - Photo of the excitation end windings during construction of the machine.

Fig. 11 - Photo of the machine rotor showing the absent damper bars.

On the rotor the existing pole windings were separated and terminated to shaft mounted diodes. The damper bars have not been fitted during manufacture leaving slots in the rotor core, Fig. 11.

VII. EXPERIMENTAL RESULTS

The prototype machine has been coupled to a DC motor as a prime mover for testing. A photo of the test rig is given in Fig. 12. Slip rings are used to bring out one of the four rotor diode connections for current monitoring. Experimental validation has been carried out by capturing the OCC along with the output harmonics and waveform at rated voltage.

Fig. 12. Photo of the test rig used to drive the prototype machine.

Fig. 13 compares the OCC with those obtained by FE simulation and the analytical model. Good matching is observed and while there is no direct comparison to be made with the production machine (as a lower excitation current is required) the trend is as expected.

Fig. 13. Comparison of the OCC of the prototype machine analytical, vs FE, vs experimental

Harmonic performance is a key requirement for medium power WFSGs as there are strict limits imposed for grid connection applications. Fig. 14 compares key no-load harmonics at rated output for the prototype and production machines. In general, the harmonic performance of the prototype is worse than that of the production machine although still with an acceptable total harmonic distortion of 2.17%.
A focus of this work has been the development of an analytical machine model to allow faster simulation of this complex winding geometry. The rated no-load output voltage waveform shape is compared in Fig. 15 and shows good matching, albeit with some more significant high frequency harmonics present in the analytical output. This is reflected in the comparison of key harmonics in Fig. 16, which shows good matching given the small harmonic magnitude. Significant deviation is shown on the 23rd harmonic though this is related to the slot openings and skewing, therefore affected by manufacturing tolerances of the prototype.

Fig. 14. No-load harmonic results of the prototype machine against those of the production machine

Fig. 15. Voltage waveform shape comparison for the prototype machine of experimental and analytical results

Fig. 16. Comparison of prototype machine no-load harmonics, experimental vs analytical model

VIII. CONCLUSION

This work has presented the modelling, simulation, and experimental validation of an exciterless medium power synchronous machine. The focus has been on both the analytical modelling process and investigating the feasibility of this exciterless method for medium power and above generators.

It has been shown that although the method functions, when adhering to an existing machine design, there are many challenges that the designer faces. Firstly, there is a significant cost to pay in terms of output power reduction. This could partially be overcome by allowing more design flexibility (for example in the main field winding) but ultimately will always be limited by the additional magnetic loading. Secondly the new winding structure reduces manufacturability and potentially cooling by increasing the end-winding fill.

No-load harmonic performance, whilst worse than the production machine, has been shown to be within acceptable THD (<3%) with no individual harmonics exceeding limits imposed by IEEE-519 and EN50160. That said, the significance of high frequency harmonics in the machine may be of concern for some applications as these will result in a high telephone influence factor (TIF). In addition, the analytical modelling method provides good matching of these harmonics. This could be further improved by implementing a more advanced method to account for magnetic saturation, as this has a critical effect on the operation of this exciterless topology.

The next step in this work is to investigate the transient performance of the machine given the removal of the damper cage. This, coupled with analysis on-load, will provide further validation of the analytical modelling method. Alongside this, work is being carried out looking at an alternative combined magnetic circuit exciterless method in which a winding is fitted in the damper location. This aim is to improve the power output of the machine by allowing for better copper utilization. Additionally, alternative exciterless schemes, based on recent work utilizing wireless power transfer systems for excitation [12], [13], and which do not impact the existing machine design, are being investigated.

REFERENCES

[1] J. Li, ‘Brushless Excitation System’, in Design and Application of Modern Synchronous Generator Excitation Systems, John Wiley & Sons, Ltd, 2019, pp. 215–254.
[2] D. Fallows, S. Nuzzo, and M. Galea, ‘An Evaluation of Exciterless Topologies for Medium Power Wound-Field Synchronous Generators’, presented at the PEMD 2020, Nottingham, UK, Dec. 2020.
[3] S. Nonaka and K. Kesamaru, ‘Brushless three-phase synchronous generator without exciter’, Electrical Engineering in Japan, vol. 105, no. 6, pp. 91–99, 1985, doi: 10.1002/eej.4391050611.
[4] I. R. Smith and P. A. Nisar, ‘Brushless and self-excited 3-phase synchronous machine’, Electrical Engineers, Proceedings of the Institution of, vol. 115, no. 11, pp. 1655–1660, 1968, doi: 10.1049/piee.1968.0288.
[5] K. Inoue, H. Yamashita, E. Nakamae, and T. Fujikawa, ‘Brushless self-excited three-phase synchronous generator without exciter’, Electrical Engineering in Japan, vol. 113, no. 8, pp. 101–115, 1993, doi: 10.1002/eqj.4391130810.
[6] F. Shibata, ‘Electric Machine Arrangements Including Electric Rotating Machines’, 3573578, Apr. 06, 1971.
[7] S. Nonaka and T. Kawaguchi, ‘A new variable-speed AC generator system using a brushless self-excited-type synchronous machine’, IEEE Transactions on Industry Applications, vol. 28, no. 2, pp. 490–496, 1992, doi: 10.1109/28.126760.
[8] T. F. Chan and Y. Lie-Tong, ‘Performance analysis of a brushless and exciterless AC generator’, *Energy Conversion, IEEE Transactions on*, vol. 12, no. 1, pp. 32–37, 1997, doi: 10.1109/60.577277.

[9] D. Fallows, S. Nuzzo, A. Costabeber, and M. Galea, ‘Harmonic reduction methods for electrical generation: a review’, *Transmission Distribution IET Generation*, vol. 12, no. 13, pp. 3107–3113, 2018, doi: 10.1049/iet-gtd.2018.0008.

[10] S. Nuzzo, M. Degano, M. Galea, C. Gerada, N. Brown, and D. Gerada, ‘Improved Damper Cage Design for Salient-Pole Synchronous Generators’, *IEEE Transactions on Industrial Electronics*, vol. PP, no. 99, pp. 1–1, 2016, doi: 10.1109/TIE.2016.2619321.

[11] S. Nonaka, K. Kesamaru, and K. Horita, ‘Analysis of brushless three-phase synchronous generator without exciter’, *Electrical Engineering in Japan*, vol. 113, no. 7, pp. 135–144, 1993, doi: 10.1002/eej.4391130713.

[12] M. Maier, M. Hagi, M. Zimmer, J. Heinrich, and N. Parspour, ‘Design and construction of a novel rotating contactless energy transfer system for an electrical excited synchronous machine’, in *2016 XXII International Conference on Electrical Machines (ICEM)*, Sep. 2016, pp. 709–714, doi: 10.1109/ICELMACH.2016.7732604.

[13] S. Hagen, M. Tisler, J. Dai, I. P. Brown, and D. C. Ludois, ‘Use of the Rotating Rectifier Board as a Capacitive Power Coupler for Brushless Wound Field Synchronous Machines’, *IEEE Journal of Emerging and Selected Topics in Power Electronics*, pp. 1–1, 2020, doi: 10.1109/JESTPE.2020.3039497.