FEM Based Multi-Criterion Design and Implementation of a PM Synchronous Wind Generator by Fully Coupled Co-Simulation

Cemil OCAK[1], Durmuş UYGUN[2], İlhan TARIMER[3]
[1]*Vocational College of Technical Sciences, Gazi University, Ankara, 06374, Turkey*
[2]*Department of Research and Development, Aegean Dynamics Inc. Co., İzmir, 35390, Turkey*
[3]*Department of Information Systems Engineering, Muğla University, 48000, Turkey*
cemilocak@gazi.edu.tr

***Abstract*—This study deals with analyzing, designing and fabricating of a 1 kW PM synchronous generator for gearless and direct drive off-grid wind turbines. Performance characteristics of this generator have been calculated analytically in collaboration with dynamic transient coupled-field analysis. All specifications of the PMSG have been investigated and optimized by using finite element method and parametric multi-criterion design approach. At the end of research, a prototype has been fabricated based on the optimized dimensions. Furthermore, the analytical calculations present along with experimental studies carried out for different shaft speeds and load levels. The comparative experimental studies have verified effectiveness of the optimized designing and dynamic co-simulations.**

***Index Terms*—design optimization, electromagnetic analysis, finite element analysis, permanent magnet machines, wind energy generation.**

I. INTRODUCTION

Variable-speed permanent magnet synchronous generators (PMSGs) are ideal candidates for gearless and direct drive off-grid apparatus due to having high efficiency, smaller size, and brushless construction. It is known that PMSGs have importance in the last two decades [1-4]. In the literature, several studies were exposed to PMSGs having different rotor structures [5-8]. The number of poles in a normally designed inner-rotor PMSG is low [9]. Higher number of poles and higher diameter are required for the generator to achieve rated frequency at low shaft speed [10]. An optimum solution for an economical design should be offered considering power density, cost and efficiency factors [5]. An outer-rotor structure offers a unique solution to meet all these requirements.

When to design a small and gearless generator for a part of low speed wind apparatus, the machine's specifications should be determined as outer-rotor structure, stationary wound stator, located in the center, since outer-rotor structure is able to carry more magnets than inner-rotor structure, and this rotor type allows designing a multi-pole PM generator. Therefore, the study focuses on designing, optimization and experiments of an outer-runner, multipole, radial-flux PM synchronous machine. Besides, features of high efficiency and low torque ripples are taken into account in designing the low-speed generator. In addition, size of the generator should not be high and the overall cost should be lower as possible as. Because of the fact that most of the generator losses occur both stator and the rotor, hence loss minimization methods should be taken into consideration. Cogging torque can prevent the wind turbine generator to start at low speeds and should be reduced to acceptable values by skewing or optimizing the stator or rotor geometry [8]. Based on the cooling method and output power of the PM generator, current density varies between 3.5 to 10 A/mm^2. Lower range current density defined due to rated power of the generator is low in this study. Along with that, specific loadings and flux per pole values of the generator should be carefully defined while sizing machine dimensions regarding to operational condition and load types.

This work tries to reveal a low-speed, direct drive outer-rotor structured PM generator and performs analysis of fully coupled magnetic field co-simulation of the generator. The generator is designed and optimized based on the analysis of operating conditions and requirements. Optimized and non-optimized generators are compared in terms of physical and operational parameters. In pursuit of analytical design, optimized machine and parametric design approach is verified by 2D and 3D transient co-simulation technique via Ansys Maxwell and Simplorer. Various output parameters for different wind speed rates and varying load conditions have been calculated and evaluated for the PMSG. The analytical studies are presented with experimental studies carried out for different load and generator speeds.

II. ANALYTICAL DESIGN OF THE PMSG

Fengxiang explained design techniques of high, medium and low speed direct-driven wind power PM generators and discussed development tendency of design and technology of PM wind generators in his paper [20]. Sizing studies are of great importance to machine design to provide the highest efficiency at the lowest cost. In addition, thermal characteristic of the machine and the operation speed should be carefully taken into account for these studies. In order to start the design of an outer-rotor structured PM generator, it can be initiated with the sizing equation [11-13, 21];

$$C_0 = K_f \alpha_i K_{w1} \pi^2 A_1 B_g \tag{1}$$

where: C_0 − output coefficient; B_g − specific magnetic loading; A_1 − electrical loading; α_i − magnetic flux density; K_{w1}, K_f − winding factor and form factor respectively. Output coefficient is also can be defined as air-gap apparent

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power S_{gap}:

$$C_0 = \frac{60 S_{gap}}{D_{is}{}^2 L n_1} \tag{2}$$

S_{gap} − function of core length and inner stator diameter and it can also be defined by specific electrical and magnetic loadings, winding and form factor:

$$S_{gap} = K_f \alpha_i K_{w1} \pi^2 D_{is}{}^2 L \frac{n_1}{60} A_1 B_g \tag{3}$$

where: n_1 − shaft speed of the generator in rpm; D_{is} − main dimension of the generator; L − core length of the generator are expressed in (4):

$$D_{is} = \sqrt[3]{\frac{D_{is}{}^2 L 2p}{\pi\lambda}}\ , \qquad L = \frac{D_{is}{}^2 L}{D_{is}{}^2} \tag{4}$$

By taking stator slot dimensions into consideration, outer stator diameter can be expressed as follows [14]:

$$D_o = D_{is} + 2(h_s + h_{cs}) \tag{5}$$

where: D_o − outer stator diameter; h_{cs} −stator yoke height; h_s − slot depth. Another significant parameter is the ratio of core length to inner stator diameter [15, 22]:

$$\lambda = \frac{L}{\tau} = \frac{2L_{p1}}{\pi D_{is}}; \quad 0.6 < \lambda < 3.0 \tag{6}$$

The ratio of core length to inner stator diameter for synchronous generator can also be expressed as L/D − and given in the (7) below:

$$X = \frac{L}{D} = \frac{\pi}{4p}\sqrt{p} \ \ and \ X = \frac{L}{D} = 1 - 3 \tag{7}$$

Outer to inner stator diameter can be calculated by:

$$\lambda_o = \frac{D_o}{D_{is}} = f\left(h_s h_{cs} L_{pm} D_{is} p N_s\right) \tag{8}$$

where: L_{pm} − length of the core; N_s − number of phase turns; p − number of poles.

Outer to inner stator diameter value can be defined regarding to pole numbers as 1.65 to 1.69 for 2 poles, 1.24-1.26 for more than 10 poles. In case of generator operation; output power can be calculated as:

$$P_o = 3 U_s I_s \cos\phi \tag{9}$$

As a ratio between output and input of the generator, the efficiency can be expressed as:

$$\eta = \frac{P_o}{P_i} x 100\% \tag{10}$$

Based on these assumptions and design constraints; main design parameters of the low speed, direct-drive, PM synchronous generator is given as shown in Table I.

TABLE I. DESIGN PARAMETERS FOR THE PMSG

Design Parameter	Value	Design Parameter	Value
Rated power	1 kW	Number of phases	3
Rate speed	600 rpm	Magnet type	N40SH
Load line voltage	24 V	Stator steel	50W800
Maximum output power	1.4 kW	Rotor steel	ST37
Number of poles	10	Magnet mounting	Surface

III. MULTI-CRITERION DESIGN OPTIMIZATION

To optimize an electrical machine needs several features such as operational characteristics and low cost [16, 17]. There are also variables or parameters such as number of pole, phase or slot which need to be pre-determined.

Krotsch and Piepenbreier have proposed a hybrid multi-objective optimization algorithm and an approximation method to dimension and shape optimization of a permanent magnet synchronous motor in their paper [23]. Pinilla and Martinez have proposed a methodology to optimize a machine design considering uncertainty of magnets cost in their study [24]. Optimization process is to provide a suitable design that meets all the requirements with optimum values. On the other side, there are many contingencies for defining an objective function. Using the (11) for a PMSG, main idea of the multi criterion optimization can be clarified.

$$\vec{X} := \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} \rightarrow \begin{pmatrix} f_1(x_1,\ldots x_n) \\ f_2(x_1,\ldots x_n) \\ \vdots \\ f_m(x_1,\ldots x_n) \end{pmatrix} =: \begin{matrix} Q_1 \\ Q_2 \\ \vdots \\ Q_m \end{matrix} =: \vec{Q} \tag{11}$$

where: Q − the evaluation criteria; x_1, x_2… x_n − feature vectors respectively. It is a fact that the case becomes even more complicated when more than one evaluation criterion is available. However, by using multi criterion design optimization combined with exact constraints, it is possible to compute more than one parameter with more than one varying criteria, thus leading less computation time with more complex formulations.

In parametric approach, a geometric or electrical value defined as a variable instead of a constant value. The minimum-maximum range and solution steps are also defined regarding to degree of precision required. Lower steps result with higher computation time as expected. To find an optimal generator size, electrical and electromagnetic parameters, optimization problem should be focused on the analytical model of the machine. Therefore, defining proper parameters which respond the requirement of optimization goals serves a very important purpose. Magnet height, stator outer diameter and flux densities, slot opening, core length, and rotor outer diameter parameters are defined to be optimized as given below;

$$OptFunction = \left\{ \begin{matrix} \min\left[P_{loss}\left(D_o, L, B_{S0}, t_{mag}\right)\right] \\ x_{\min} \le x \le x_{\max}, x = D_o, L, B_{s0}, t_{mag} \\ f_{(x)} \end{matrix} \right\} \tag{12}$$

The generator variables and the constraints are given in Table II–III.

TABLE II. MINIMUM AND MAXIMUM VALUES OF VARIABLES

Design Parameter	Minimum	Maximum
Rotor outer diameter	175 mm	185 mm
Core and magnet length	30 mm	60 mm
Embrace (pole)	0.6	0.9
Rotor yoke	5 mm	10 mm
Stator yoke	10 mm	20 mm
Slot depth	25 mm	35 mm
Slot width	3 mm	5 mm

TABLE III. APPLIED CONSTRAINTS ON PARAMETERS

Parameter	Constraint
Efficiency	≥ 85 %
Specific electric loading	≤ 25 kA/m
Core and magnet length	≤ 60 mm
Stator yoke flux density	≤ 1.2 T
Rotor yoke flux density	≤ 1.8 T
Stator tooth flux density	≤ 1.7 T

Airgap flux density	≥ 0.65 T
THD of induced voltage	≤ 10 %

The given constraints are determined for ensuring the generator running requirements. According to parameters obtained by analytical method, the initial electrical and dimensional values are given in Table IV.

TABLE IV. MAIN PARAMETERS OF THE PMSG

Parameter	Analytical Value
Rated power, P	1 kW
Rated speed, n	600 rpm
Rated torque. T	19.93 Nm
Phase voltage, U_{ph}	24 V
Magnet thickness, l_{PM}	5 mm
Total PM weight, G_{PM}	0.74 kg
Number of slots, Q	36
Number of pole pairs, p	5
Air-gap length, g	1 mm
Stator outer diameter, D_{Sout}	155 mm
Rotor outer diameter, $D_{Rou}t$	180 mm
Stator inner diameter, D_{Sin}	63 mm
Core Length, L	50 mm

By using optimization functions, the results of multi-criterion design optimization are shown in Table V in comparison with the ones derived from non-optimized model.

Regarding to overall performance, most of the important parameters of the fabricated generator have been optimized. There is a small difference in the phase voltage after optimization, which is allowable value.

TABLE V. INITIAL AND OPTIMIZED PARAMETERS OF DESIGNED PMSG

PMSG Parameters	Analytical Calculation Results		
	Initial	Optimized	Improvement
Rated Power	1 kW	1 kW	-
Efficiency	84.3 %	88.9 %	+4.6 %
Phase Voltage	28 V	26.5 V	-1.5 V
Outer Rotor Diameter	180 mm	178 mm	+2 mm
Core Length	50 mm	45 mm	+5 mm
Current Density	5.22 A/mm^2	4.93 A/mm^2	+0.29 A/mm^2
Slot Opening	2mm	2.52mm	-0.52 mm
Airgap Flux Density	0.73 T	0.76 T	+0.03 T
Specific Electric Loading	21581 A/m	19390 A/m	+2191 A/m
Total Loss	186 W	125 W	+61 W
Armature Thermal Load	112.7 A^2/mm^3	100.6 A^2/mm^3	+12.9 A^2/mm^3
Total Net Weight	7.71kg	6.92kg	+0.79kg

Due to thermal characteristics, the slot opening distance value increased by 0.52 mm. Furthermore, the total net weight of the generator is decreased significantly in comparison to non-optimized (initial) generator. Reducing the total net weight of the generator while increasing the efficiency can be defined as a top goal of every optimization process for such a design.

Besides, the effect of cogging torque is considerably significant in low speed direct drive generators. In order to eliminate cogging torque, stator slots are skewed by one slot and slot opening distance is also optimized.

The elimination on one hand increases total length of windings, on the other hand decreases EMF of the machine and effective cross section of a slot. Skewing stator slots or or rotor magnets by equivalent degree of one stator slot shall be enough for less cogging torque. In addition, using a proper slot/pole combination may help lower cogging torque. As a result of analytical calculations, the model can be derived and illustrated as seen in Fig. 1.

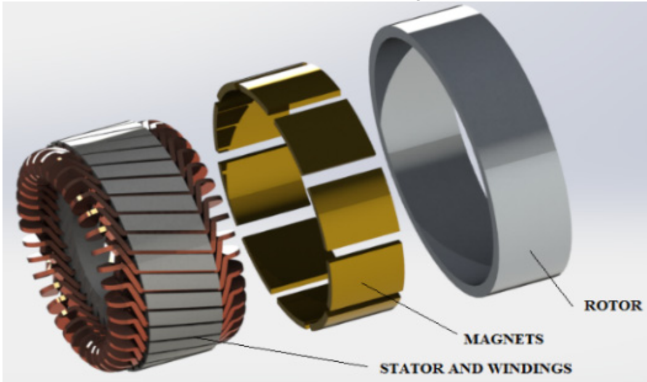

Figure 1. 3D optimized PMSG model

Next to the studies carried out on optimized PMSG, a manufactured prototype is also shown in Fig. 2. Due to being used as a wind turbine generator, rotor is designed to allow blades to be mounted directly on the rotor.

Figure 2. Prototype of the optimized PMSG

These manufactured prototypes are prepared for experimental tests.

IV. COUPLED MODEL AND TRANSIENT FEM STUDY FOR OPTIMIZED PMSG

Finite element analysis is applied to the optimized model to predict performance of the designed PMSG. A torque value in generators or current density/voltage in motors are generally given as the source input. The magnetic field power in an electrical machine can be presented as electromagnetically as follows [18, 19];

$$J = \sigma\left(\vec{E} + v\, x\, \vec{B}\right),\ \vec{B} = \mu_0\left(\vec{H} + \vec{M}\right) \qquad (13)$$

where: B − the magnetic flux density; σ − conductivity, J − current density; μ_0 −permeability of space; M − magnetization vector; v − the velocity of the material.

By taking these electromagnetic properties into account, the optimized PM synchronous generator has been exposed to 2D and 3D time-step simulations for a predefined interval.

One method to apply finite element methods (FEM) is co-simulation approach (indirect coupling) where electromagnetic field and circuit simulator are treated as separate systems in a step by-step process for a predefined time-step with maximum and minimum time intervals. In the simulation, ANSYS Simplorer and Maxwell 2D or 3D interoperated to obtain a fully coupled design solutions. In the study, both 2D and 3D methods have been used to calculate electromagnetic parameters and the outcomes of 3D simulations, magnetic flux density results are illustrated as shown in Fig. 3.

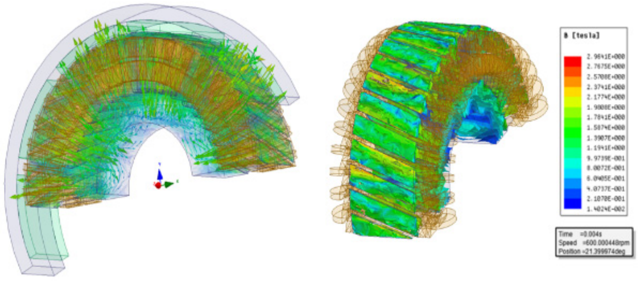

Figure 3. Magnetic flux density distribution by 3D transient analysis

From the 3D simulations, the generator rotates at 600 rpm rated speed, and the variation at 0.04 sec and 21.39° angular position which is calculated as 1.32 T for stator teeth. The generator's outputs are connected to a rectifier which supplies the DC link. 0.018 Ω resistor and 2200 μF capacitor are the DC link components which are connected in series. The model is used to obtain different operational conditions such as changes in wind speed or output load.

In the study, the generator is primarily operated under nominal load resistance of 1.72 Ω and variable velocity source assigned as 600 rpm which is also nominal speed of the generator. In this case, a constant load condition is simulated for the generator which is running at rated speed. Also a proper rectifier block is attached to model to obtain 60 V DC-link voltage. The simulation results for 100 ms transient analysis are shown in Fig. 4 and 5 for generator side and load side respectively.

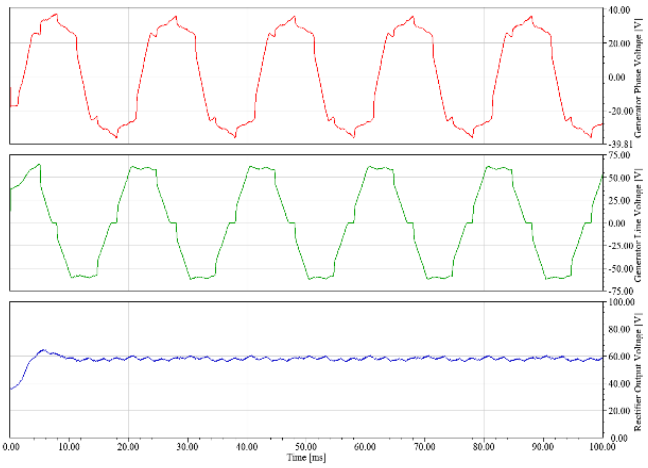

Figure 4. Generator side measurements

At generator side, the simulated and presented significant parameters are generator phase voltage of which RMS value is given as 26.46 V which is in acceptable range for transient studies. The generator line voltage is saved as 45.15 V RMS for the rated condition.

From Fig. 7, the generator is able to generate minimum 30 V line voltages which can be considerably evaluated as acceptable in those cases. There are also some lacks in the simulations where a few voltage trends are observed on the curve which can be due to rapid change in the speed leading some instabilities in generator regime.

It is seen that the designed model produces 1 kW under rated load conditions, and the inverter produces desired voltage level already rectified as 60 V. Beside this rated condition, the generator was also exposed to different conditions in which the rotational speed and the value of load resistance were varied simultaneously.

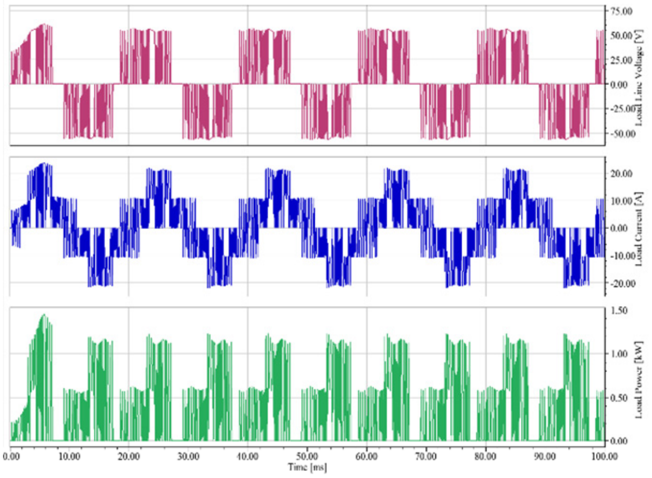

Figure 5. Load side measurements

Variable Speed Condition: In this condition, a constant rated load of 1.72 Ω and a variable velocity source applied to the model. Shaft speed of the generator is changed via variable velocity source to simulate wind speed. The illustration is given in Fig. 6. The generator operates under rated load for 160 ms duration with 0.1 μs time steps.

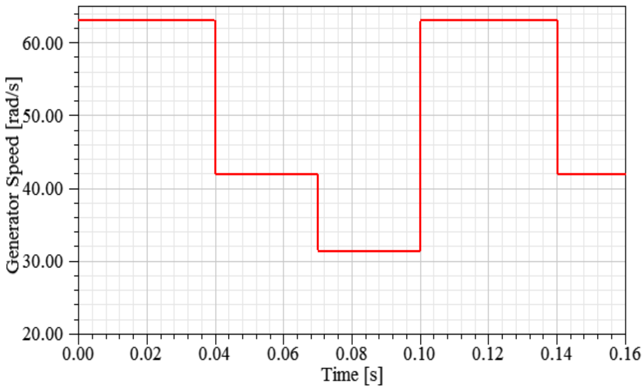

Figure 6. Variable speed condition for 160 ms duration

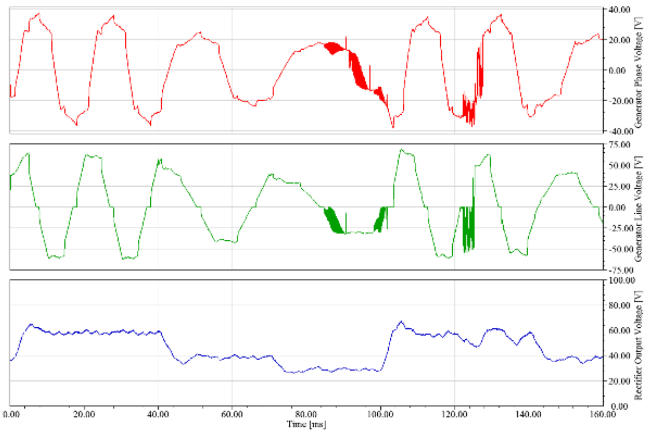

Figure 7. Generator side outputs for variable speed operation

Variable Speed and Load Condition: In contradistinction to first case, both a variable load and a velocity source applied to the model. While variable speed operation of the generator, the load resistance is decreased from rated value to 0.86 Ω which can be determined as double-load. These variations have been summarized in Fig. 8 for both generator speed and load resistance regimes.

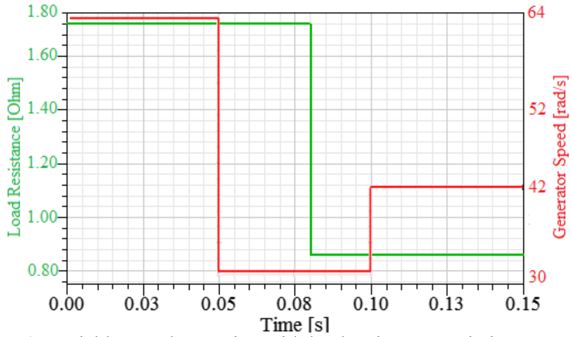

Figure 8. Variable speed operation with load resistance variation

Variable speed operation results combined with load resistance variation for both generator and sload side measurements shown in Fig. 9 and 10 are derived.

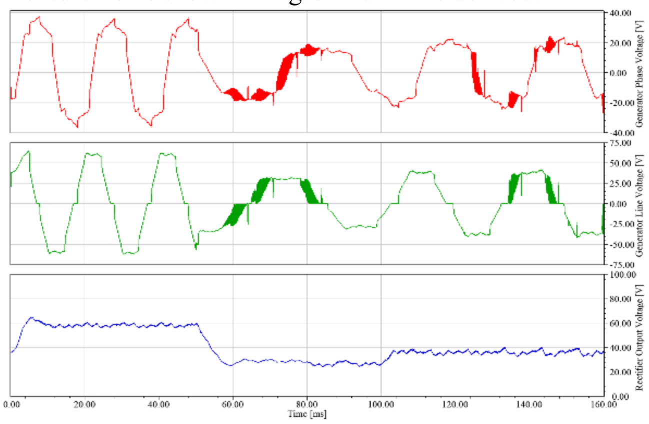

Figure 9. Generator side results

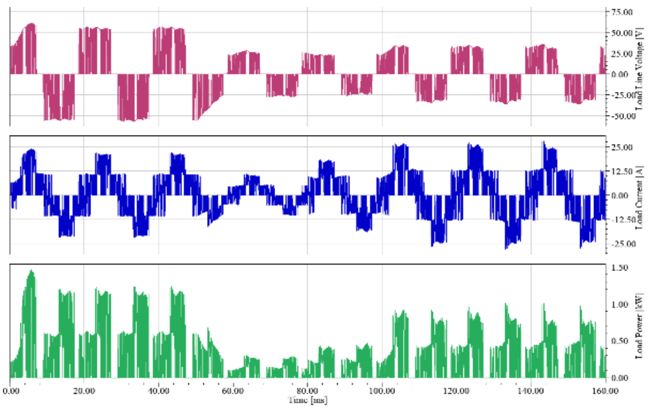

Figure 10. Load side results

Although the cases, herein mentioned as speed and load, are varying instantly; the reaction of the generator can be interpreted as quite good. Even at 90 ms where the saved data is showing minimum generator speed and minimum load level, the generator is able to produce more than 24 V line voltages which is regarded as rated design value.

V. Comparative Experimental Studies

Prototype test setup for the generator is shown in Fig. 11. Rotor of the generator is mounted directly to mechanical power source with the help of coupling. This experimental evaluation environment comprises a 1 kW PM synchronous generator prototype, measurement devices, variable speed drive and induction motor as a mechanical power source for ensuring rotational speed of PMSG which is simulating different wind speed levels.

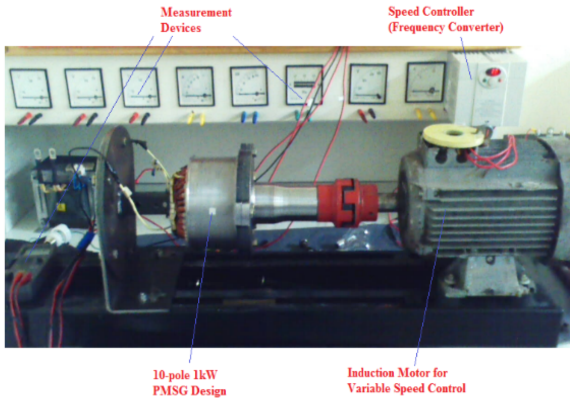

Figure 11. Experimental bed for comparative studies

The calculated no-load voltage is 28 V and the measured voltage is 30.5 V. At rated load conditions, the generated line voltages are recorded via a power analyzer in which all line-to-line voltages (*AB-AC* and *BC*) can be tracked easily. The RMS value of the generated line voltages is 26.7 V for *AB*, 24.84 V for *BC* and 25.97 V for *CA* as shown in Fig. 12.

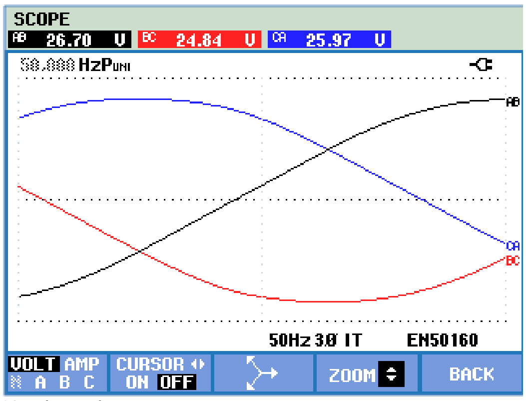

Figure 12. Line voltages

The terminal voltage at rated operating conditions is 24 V and the frequency 50 Hz. The tests are carried out in order to obtain the closeness of agreement between the simulations and the experimental results. These studies are realized at rated speed of 600 rpm and 400 rpm generator speeds for an output power ranging from 600 W to 1300 W. Corresponding test results are shown in Fig. 13, 14 for both 600 and 400 rpm.

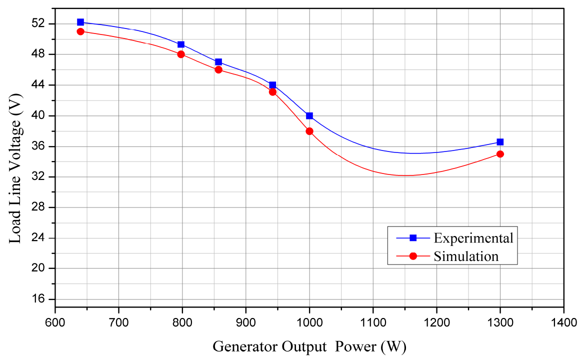

Figure 13. Load line voltage comparison at 600rpm with variable load

It can be evidently stated that the performance of the prototype is quite good even at low speeds. The differences in experiments and simulations are most likely due to the loss coefficients.

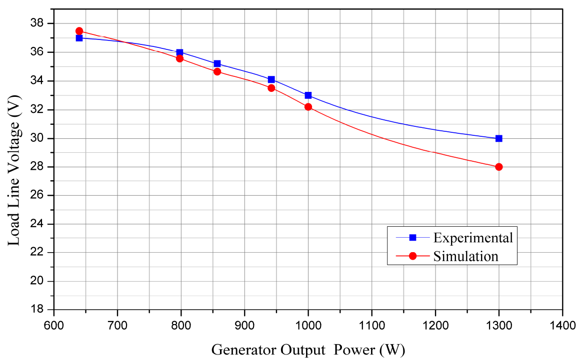

Figure 14. Load line voltage comparison at 400rpm with variable load

VI. CONCLUSION

In the study, a direct-drive outer-rotor type PMSG has been designed, analyzed and presented through analytical approach. Also, various optimization studies were carried out by evaluating the designs obtained as a result of analytical results. Electromagnetic solutions have been made by 3D finite elements method. Then as a result of optimization studies, 1 kW outer-rotor permanent magnet synchronous generator which gains optimal parameters have been come up for an off-grid application. At the same time, a fully coupled co-simulation which obtains various performance characteristics for different load and shaft speed situations has been carried out. It has seen that the designed and implemented model fits the need of a small scale wind turbine. The parameters and the simulations results obtained in the study have been validated with the experimental results.

REFERENCES

[1] Z. Guo and L. Chang, "FEM study on permanent magnet synchronous generators for small wind turbines", Proceedings of Canadian Conference on Electrical and Computer Engineering, pp. 641-644, Canada, 2005. doi:10.1109/CCECE.2005.155701

[2] C. Ocak, A. Dalcalı, E. Çelik and D. Uygun, "FEA-Based design improvement of small scale BLDCMs considering magnet thickness and pole embrace", Int'l Journal of Computing, Communications & Instrumentation Engg., Vol. 4, no. 2, pp. 31-35, 2017. doi:10.15242/IJCCIE.AE0417117

[3] M. V. Cistelecan and M. Popescu, "Study of the number of slots-pole combinations for low speed permanent magnet synchronous generators", Proceedings of IEEE International Electric Machines and Drives Conference, pp. 1616-1620, Turkey, 2007. doi:10.1109/IEMDC.2007.383671

[4] N. B. Misron, S. Rizuan, R. N.Firdaus, C. A. Vaithilingam, H. Wakiwaka and M. Nirei, "Comparative evaluation on power-speed density of portable permanent magnet generators for agricultural application", Progress in Electromagnetics Research, Vol. 129, pp. 345-363, 2012. doi:10.2528/PIER12050101

[5] J. Chen, C. V. Nayar and L. Xu, "Design and finite-element analysis of an outer-rotor permanent-magnet generator for directly coupled wind turbines", IEEE Transactions on Magnetics, Vol. 36, no. 7, pp. 3802–3809, 2000. doi:10.1109/20.908378

[6] J. H. J. Potgieter and M. J. Kamper, "Torque and voltage quality in design optimization of low-cost non-overlap single layer winding permanent magnet wind generator", IEEE Transactions on Industrial Electronics, Vol. 59, no. 5, pp. 2147–2156, 2012. doi:10.1109/TIE.2011.2159955

[7] S. Eriksson, H. Bernhoff and M. Bergkvist, "Design of a unique direct driven pm generator adapted for a telecom tower wind turbine, Renewable Energy", Vol. 44, pp. 453–456, 2012. doi:10.1016/j.renene.2012.01.090

[8] C. Dae-Won and Y. Yong-Min, "Cogging torque reduction in pm brushless generators for small wind turbines", Journal of Magnetics, Vol. 20, no. 2, pp. 176-185, 2015. doi:10.4283/JMAG.2015.20.2.176

[9] L. Petri, "Directly driven, low-speed pm generators for wind power applications", PhD. Thesis, Helsinki University of Technology, Helsinki, Finland, 2000.

[10] N. Madani, "Design of a PMSG for a vertical axis wind turbine", Master Thesis, Royal Institute of Technology, Sweden, 2011.

[11] L. Jian, G. Xu, Y. Gong, J. Song, J. Liang and M. Chang, "Electromagnetic design and analysis of a novel magnetic-gear-integrated wind power generator using time-stepping finite element method", Progress In Electromagnetics Research, Vol. 113, pp. 351–367, 2011. doi:10.2528/PIER10121603

[12] P. Makolo, "Wind generator co-simulation with fault case analysis", Master Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2013.

[13] A. M. Mihai, S. Benelghali, A. Simion, R. Outbib and L. Livadaru, "Design and fem analysis of five-phase permanent magnet generators for gearless small-scale wind turbines", Proceedings of 20th International Conference on Electrical Machines, Marseille, France, pp. 150–156, 2012. doi:10.1109/ICElMach.2012.6349856

[14] J. Pyrhonen, T. Jokinen and V. Hrabovcova, "Design of rotating electrical machines", John Wiley and Sons Ltd., pp. 154–160, 2008.

[15] G. Sizov, D. Ionel and N. Demerdash, "Multi-objective optimization of pm ac machines using computationally efficient FEA and differential evolution", Proceedings of IEEE International Electric Machines Drives Conference (IEMDC), pp. 1528 –1533, Canada, 2011. doi:10.1109/IEMDC.2011.5994836

[16] C. Ocak, İ. Tarimer and A. Dalcali, "Advancing pole arc offset points in designing an optimal pm generator", TEM Journal, Vol. 5, no. 2, pp. 126-132, 2016. doi:10.18421/TEM52-02

[17] G. Sizov, P. Zhang, D. Ionel, N. Demerdash and M. Rosu, "Automated bi-objective design optimization of multi-MW direct-drive pm machines using ce-fea and differential evolution", Proceedings of IEEE Energy Conversion Congress and Exposition (ECCE), pp. 3672 –3678, 2011. doi:10.1109/ECCE.2011.6064267

[18] D. Zhong, "Finite element analysis of synchronous machines", PhD. Thesis, the Pennsylvania State University, USA, 2010.

[19] Y. Zhang, K. T. Chau, J. Z. Ziang, D. Zhang and Liu C., "A finite element-analytical method for electromagnetic field analysis of electric machines with free rotation", IEEE Transactions on Magnetics, Vol. 42, no. 10, pp. 3392-3394 2010. doi:10.1109/TMAG.2006.879441

[20] W. Fengxiang, "Application and development tendency of pm machines in wind power generation system", Transactions of China Electrotechnical Society, Vol. 27, no. 3, pp. 12-24, 2012.

[21] A. El Shahat, A. Keyhani and H. El Shewy, "Sizing a high speed pm generator for green energy applications", Journal of Electrical Systems (JES), Vol. 6, no. 4, pp. 501-516, 2010.

[22] A. El Shahat, A. Keyhani and H. El Shewy, "400 kW six analytical high speed generator designs for smart grid systems", International Journal of Energy and Power Eng., Vol. 4, no. 3, pp. 210-227 2010.

[23] J. Krotsch and B. Piepenbreier, "Hybrid algorithm for multi-objective optimization of PMSM using massively distributed finite element analysis", 12th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), pp. 307–314 Brasov, Romania, 2010. doi:10.1109/OPTIM.2010.5510429

[24] M. Pinilla and S. Martinez, "Optimal design of permanent-magnet direct-drive generator for wind energy considering the cost uncertainty in raw materials", International Journal of Renewable Energy, Vol. 41, pp. 267–276, 2012. doi:10.1016/j.renene.2011.11.005