Design Improvement of a Synchronous Generator based on Life-Cycle Analysis

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***Abstract*–An application of Life-Cycle Analysis (LCA) has been presented by taking into consideration the manufacturing, operation and the end-of-life phases of a three phase synchronous generator. The assessment of the environmental impact has been done by the Methodology for the Eco-design of Energy using Products (MEEUP). This methodology uses some previously acquired data that includes the generator's primary constituent materials for the manufacturing phase, the efficiency and the output power of the generator. The primary aim was to optimise the environmental impact of commercially available generators by varying the design parameters and to develop a design procedure to do the same. For this, two generators having the same output power but different efficiencies have been taken into account and the total environmental influence for both of them has been calculated. A generator design has also been proposed keeping in mind the primary objective.**

***Index Terms* - Synchronous generator.Life cycle analysis.Efficiency.Methodology for the eco-design of energy using products.Environmental optimization.**

I. Introduction

Synchronous generators are one of the most used electrical generators in the world. Synchronous generators hold a certain advantage over other generators in the way that they can be operated at a constant speed independent of the electrical load on the machine. This is particularly advantageous when the generator is used to convert mechanical torque to electrical energy that can be directly connected to the grid with minimal power electronics. The generators in question here are those that are used in the automotive industry and have considerable lower efficiencies.

Taking its basis on the study presented in the EUP Lot 11 motors[1], the European Commission regulation EC 640/2009 has set guidelines for the eco-design of electric generators. These guidelines indicate the minimum efficiency that a generator needs to have in order to conform to the specifications of eco-design of generators by classifying various synchronous generators having different parameters namely; number of poles (2, 4 or 6); rated voltage (1000V); operating frequency (50 or 60 Hz) and a rated power, under three primary categories based on their efficiencies (IE1, IE2, or IE3 that has been specified in the standard IEC60034)[2].
Life-Cycle Analysis (LCA) is an analytical tool used to comprehensively quantify and interpret the environmental flows to and from the environment (including air emissions, water effluents, solid waste, and the consumption/depletion of energy and other resources), over the life cycle of a product or process. There are many methods that could be applied in order to do the LCA of electrical equipments[3] [4] with even ABB using another method that is based on the international standards ISO 14040-43[5]. Due to the simplicity and ease of application as it has been characterized in the cited report, EUP lot 11 motors [1], the MEEUP methodology has been used.

In the work reported here, the MEEUP methodology was applied to two doubly excited synchronous generators having a power rating of 1.2 kW. The MEEUP methodology uses a spreadsheet where in which LCA is applied to a set of variables, namely the quantity of materials used in manufacturing the motor, and the generator losses during the service life. In this spreadsheet, the environmental impact factors are applied as they have been documented in MEEUP 2005 and 2009 [6][7]. By this method, the influence of changes in the design parameters on the environmental impact of each motor was assessed. These real generators were then subsequently compared to a proposed generator that was designed in order to optimize the environmental impact.

II. Calculation

In this section, a thorough description of the formulae and the methodology used is presented. The MEEUP methodology has been applied to fathom the environmental impact in the manufacturing phase, service phase, recycling and lastly, waste disposal. In order to do all this, it is imperative to know two main things; first, the bill of the materials that was used in the manufacturing of the generator and second, the performance parameters of the generators during its service phase. The methodology is a very simple procedure that involves a spreadsheet comprising of two following parts:

1. Inputs (weight of materials; service life performance, emissions during the service life, and energy consumption; recycling and waste disposal)

2. Results that are presented as a list of environmental indicators (Total primary energy, heavy metals, global warming potential, acidification emissions, water used, waste produced)

Keeping in mind the above course of action, the two real generators were taken and then by assuming various characteristics of the generator, the losses of the generators were theoretically carried out. These losses were then compared to the actual experimental data and if the theoretical and experimental readings did not match, some changes in the assumptions were made. This is consecutively done until the two are very close and within a specific error limit. The bill of materials was then

Table I. Material Requirements

Generator Type	Wfe (kg)	Wcu (kg)	Wal (kg)	Wst (kg)
IE1 efficiency class	7.2	2.42	1.87	2.22
IE2 efficiency class	8.8	2.62	2.05	2.82
Proposed	6.9	1.96	2.87	1.54

calculated taking into consideration these assumed data and then the MEEUP methodology was carried out. The same has been explained in the * figure. The efficiency of these generators has been calculated according to the standard IEC60034-2-1 [8], using the summation of losses method.

The calculations took the following steps:

1. Compiling the initial motor data
   The manufacturers below mentioned data was used
   - Rated power output (P_{out})
   - Rated Voltage (V_1)
   - Rated excitation voltage (V_f)
   - Synchronous speed (N_s)
   - Frequency (f)
   - Number of poles (p)
2. Selecting the design parameters
   The following parameters are chosen:
   - Airgap diameter (D)
   - Overall length (L)
   - Specific electric loading (ac)
   - Airgap flux density (B)
   - Stator and rotor current densities (δ_1 and δ_2 respectively)
3. Determining the bill of materials used
   The primary constituents of the generators are:
   - Iron mass (W_{Fe})
   - Copper mass (W_{Cu})
   - Steel mass (W_{St})
   - Aluminium mass (W_{Al})
4. Calculation for the input power, losses and subsequently efficiency.

Based on the parameters available to us, namely the input power rating (P_{in}), different losses (as given below) and subsequently the efficiency (μ) was calculated by using Equations 1-12[9]. These losses comprise of mainly stator copper losses (P_{c1}), rotor or excitation copper losses (P_{c2}), iron losses (P_{fe}), frictional and windage losses (P_{Me}), and stray load losses (P_{Sll}).

$$P_{in} = 11.B_{avg}.ac.D^2.L.N_s.K_{ws} \times 10^{-3}\ KVA \quad (1)$$

where Kws is the stator winding factor

$$P_{c1} = \frac{\rho_{Cu}.W_{Cu}.\delta_1^2}{\gamma_{Cu}}\ VA \quad (2)$$

$$P_{c2} = \frac{\rho_{Cu}.W_{Cu}.\delta_2^2}{\gamma_{Cu}}\ VA \quad (3)$$

where

ρ_{Cu} is the resistivity of copper

γ_{Cu} is the density of copper

$$P_{Fe} = W_{Fe\,(teeth)} \times [(K_h.f.B_{tm}^2) + (K_e.f^2.B_{tm}^2)] + W_{Fe\,(yoke)} \times [(K_h.f.B_{ym}^2.k_h) + (K_e.f^2.B_{ym}^2.k_e)] \quad (4)$$

$$K_e = \frac{\pi^2.t^2}{6\rho} \quad (5)$$

where

K_h is the hysteresis specific losses coefficient.

B_{tm} is the maximum flux density in the teeth. ($B_{tm} = 1.8\ B$)

K_e is the eddy current specific losses coefficient.

B_{ym} is the maximum flux density in the yoke. ($B_{ym} = 1.4B$)

k_h is the hysteresis loss coefficient due to uneven distribution of flux in yoke.

k_e is the eddy current loss coefficient due to uneven distribution of flux in yoke.

t is the thickness of the laminates.

Assuming frictional and windage losses (P_{Me}) to be 0.2-0.8% of the total KVA rating.

The stray load losses (P_{sll}) is assigned as the percentage of the input power as it has been characterized in the IEC60034-2-1:

$P_{out} \leq 1kW$	*$P_{sll} = P_{in}$ x 0.025*
$1kW < P_{out} \leq 10{,}000\ kW$	*$P_{sll} = P_{in}$ x [0.025-0.005 log 10(Pout)]*
$P_{out} > 10{,}000\ kW$	*$P_{sll} = P_{in}$ x 0.005*

The efficiency of the machines was calculated using Eq. 6:

$$\eta = \frac{P_{in} - P_{c1} - P_{c2} - P_{Fe} - P_{Me} - P_{sll}}{P_{in}} \quad (6)$$

The winding characteristics for the stator and the rotor were found out by using the following equations:

$$Z_s = \frac{0.0045\ V_1.p.m}{K_{ws}.D.L.B_{avg}} \quad (7)$$

$$Z_r = \frac{0.0045\ V_f.p.m}{K_{ws}.D.L.B_{avg}} \quad (8)$$

$$I_1 = \frac{\pi.D.ac}{Z_s} \quad (9)$$

$$I_2 = \frac{\pi.D.ac}{Z_r} \quad (10)$$

$$A_s = \frac{I_1}{\delta_1} \quad (11)$$

$$A_r = \frac{I_2}{\delta_2} \quad (12)$$

where

Z_s is the number of stator wires.

m is the number of phases.

Z_r is the number of rotor wires.
I_1 is the stator current.
I_2 is the rotor current.
A_s is the stator wire cross-sectional area.
A_r is the rotor wire cross-sectional area.

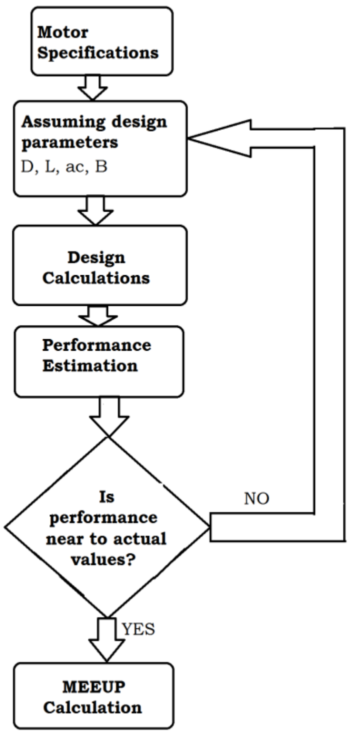

Fig 1. Calculation procedure to find out real generator parameters

5. Comparison of the calculated values to the actual values:
Two generators were tested in order to determine their respective losses and efficiency, as it has been depicted in IEC60034-2-1 and IEC60034-4. The tests that are necessary for the methodology of summation of losses are:

- Measurement of stator resistance
- A no-load test at seven voltages (includes the rated current)
- A loaded test at six electrical loads (includes the rated load)
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6. Evaluation of environmental impact
The bill of the materials was calculated from the design parameters; suitable operating load, life cycle length, and operating hours per year were assumed along with operating efficiency and output power. Subsequently, with this data the various outputs of the MEEUP methodology [10] was available.

III. DESIGN PARAMETER MANIPULATIONS FOR PROPOSED MOTOR

To reduce the environmental impact of the generators in question, the procedure described in the figure was used. The parameters were decided on the basis of four primary limiting values:

1) L/D (at a constant value of $D^2.L$)
2) B (at a fixed value of ac.B)
3) ac (at a constant value of ac.δ_1)
4) δ_1(at a constant value of ac.δ_1)

Equations 13-16 were used to calculate the variations in the material quantities with changes in the design parameters.

$$W'_{Fe} = \left[W_{Fe(stator)}\frac{D'^2.L}{D^2.L}\right] + \left[W_{Fe(rotor)}\frac{(D'^2 - D_{sh}^2).L'}{(D^2 - D_{sh}^2).L}\right]$$
(13)

$$W'_{Cu} = \left[W_{Cu(stator)}\frac{ac'.D'.L'.\delta_1}{ac.D.L.\delta_1'}\right] + \left[W_{Cu(rotor)}\frac{ac'.D'.L'.\delta_2}{ac.D.L.\delta_2'}\right] \quad (14)$$

$$W'_{Al} = W_{Al}\frac{(D'+h).L'}{(D+h).L} \quad (15)$$

$$W'_{St} = W_{St}\frac{L'}{L} \quad (16)$$

Where h is the width of the enclosure

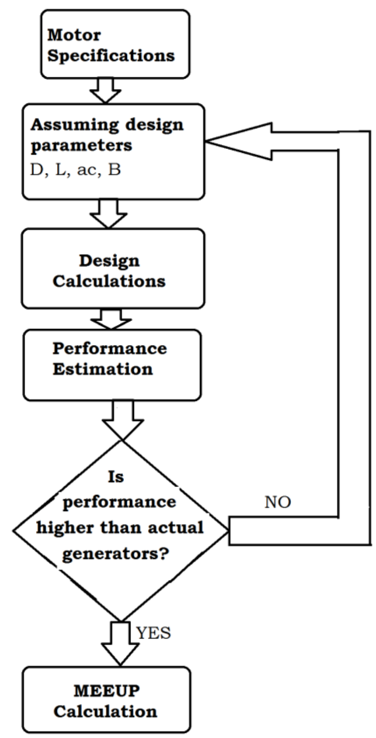

Fig. 2 Calculation procedure for proposed generator

To minimize the material required and the environmental impact of the materials, a program was written by using MATLAB. The program uses the parameter ratio constraints as given below and the program follows the block diagram given below.

Primary function: To reduce the environmental impact
Parameters to calculate:
L, D, ac, B_{avg}, δ_1

Restricting Ratios:

$0.8 \leq L/D \leq 1.6$

$0.54 \leq B_{avg}\,(\mathrm{T}) \leq 0.65$

$50{,}000 \leq ac\ (A/m) \leq 75{,}000$

$3 \leq \delta_1 (A/mm^2) \leq 5$

$P_{out} = P_{rated} \pm 5\%$

Table II. Design parameters

Generator type	D (m)	L (m)	qc (A/m)	Bc(T)	δ_1(A/mm2)	δ_2(A/mm2)
IE1	0.082	0.11	68,000	0.58	4.7	4.2
IE2	0.0812	0.134	55,000	0.57	4.3	3.6
Proposed	0.0934	0.084	63,000	0.65	3.5	3.2

The program for minimizing the environmental impact takes into consideration Eqs. 1-16 as well as the environmental impact ratios employed in the MEEUP methodology in the LCA[10]

IV. Results And Conclusions

The table 1 shows the assumed and estimated parametric values for the two actual generators and the proposed generator. The table 2 represents the bill of materials required to manufacture these generators and the proposed generator. This table is used to apply the MEEUP methodology for the manufacturing phase of life. In table 3, the results after the MEEUP methodology have been represented. These values are obtained by taking into consideration the manufacturing process, the service-life (considering 4000 hrs of operation, life cycle of 12 years, and full load operation), and the end-of-life phases. Figure 3 is a graphical representation of the MEEUP results on a comparative scale. The losses calculation for the service life hasbeen done by taking into consideration Equations 1-16 [9] and they have been compared to the laboratory test results that have been done by standard IEC60034-2-1[8].

Table III. MEEUP results

	Unit	IE1	IE2	Proposed
Resources				
Total Energy	MJ	2,44,236	1,78,598	1,34,972
Water (process)	L	15,654	11,334	8,334
Waste, non-haz./landfill	g	3,04,654	2,54,697	1,89,337
Emissions (Air)				
Greenhouse Gases	kg CO2 eq.	10,052	7,445	5,666
Acidification, Emissions	g SO2 eq.	56,876	44,776	32,593
Heavy metals	mg Ni eq.	4,043	3,289	2,659
Particulate matter (PM, dust)	g	1,452	1,178	834
Emissions (water)				
Eutrophication	g PO4	8	7	6

It can be seen that the total environmental impact of the IE2 generator is far lower than that of the IE1 generator. This is mainly because of the fact that the IE2 generator has a higher efficiency, which is one of the most important parameter for skewing the environmental impact. The higher efficiencies in the IE2 generator is mainly because of a better quality of magnetic lamination and better magnetic core. This is characterized by the higher production phase environmental impact of the IE2 generator than the IE1 generator. In the proposed motor design, the main aim has been to decrease the iron and copper losses without much consideration to the production phase environmental impact. When the proposed generator efficiency is compared to IEC60034[2], we see that the new generator is an IE3 generator. This has been done by limiting the values of the losses without changing the input power. Hence, it has been concluded that in order to minimize the environmental impact of any generator, we simply need to increase its efficiency as it is only the service phase which has the greatest potential for energy savings.

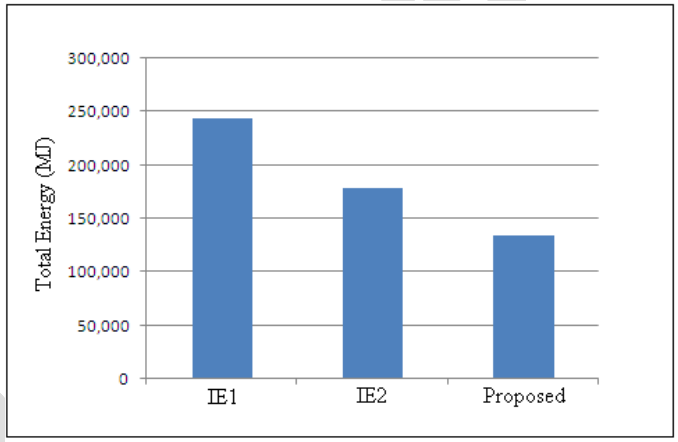

Fig 3. Graphical representation of MEEUP results

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