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An Analytical and Genetic-Algorithm-Based Design Tool for Brushless Excitation Systems of Low-Medium Rated Synchronous Generators

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***Abstract*--The sizing procedures adopted for the everyday design of electrical machines are well known and consolidated. However, for brushless exciters of field wound, synchronous generators, there is significant room for improvement as the impact of the diodes' commutations in the rotating bridge rectifier are often neglected.**

This paper deals with the development of a fast analytical, genetic-algorithm-based design tool for the excitation systems of salient-pole, field wound synchronous generators. As vessel for this study, the exciter of a particular 400*kVA*is considered. The proposed tool is focused on achieving exciter designs that minimize the voltage drop due to the commutation processes in the rotating diode rectifier, with minimum impact on the overall efficiency.

***Index Terms*—Synchronous Generator, Excitation System, Diode Rectifier, Commutations.**

I. INTRODUCTION

The analytical models of an uncontrolled diode bridge and the related commutation modes have been extensively studied in literature [1-4]. However, there are some applications, such as power generating sets, where the diode commutation processes are often neglected. In low to medium rated Synchronous Generators (SGs), where the equivalent circuit's parameters of the exciter can be comparable with those of the main machine, the voltage drop caused by these commutations can be significantly large and has to be taken into account in the design process of the exciter.

Considering the above, a preliminary sizing procedure for the exciter of a 400*kVA*SG is proposed and successfully validated against Finite-Element (FE) and available experimental tests performed on a baseline machine prototype. Top level and detailed considerations of the implemented exciter design procedure are given in Section II. The second part of this work deals with a detailed sensitivity analysis, aimed at capturing the design parameters that are most sensitive to the voltage drop due to the diode commutations. These parameters are then used as input variables of a Genetic-Algorithm (GA) optimization tool. This is used to reduce the voltage drop, with minimum disruption on the machine design, while keeping the efficiency of the machine above acceptable limits. Finally, the best design solutions are compared to the existing machine and analyzed by FE for validation purposes.

II. PRELIMINARY SIZING OF THE EXCITER AND VALIDATION AGAINST FE AND EXPERIMENTAL RESULTS

A typical approach widely used in the design of electrical machines consists in a preliminary, analytical sizing which is then fine-tuned by FE analysis, to meet the desired requirements in line with the specific application. Sizing equations have been extensively studied and applied for the design of electrical machines [5-8] in a wide range of applications [9]. However, with recent advancements in computational resources, numerical techniques such as FE [10, 11] are often preferred to analytical methods due to the complexity and non-linearity of the studied problems. Recently, more innovative optimization techniques, employing GAs have been shown capable to further improve electrical machines' performance [12]. These techniques, which include deterministic and stochastic methods [13] are finding an ever increasing role in machine design, as the optimization synthesis of electrical machines is often a multi-objective problem [14]. A review of recent developments in electrical machine design optimization methods is presented in [15].

While the above has been widely described in the recent literature, to the authors' knowledge no such work has been applied to the exciters of SGs, in particular when the impact of the diode commutations is not negligible. As vessel for this study, a 5.35*kVA* exciter is considered.

A. Top-Level Design Considerations

A brushless excitation system, used in connection with the main SG, consists of a second, smaller generator mounted on the same shaft. The armature output leads of this 'inverted' machine (armature winding on the rotor) are connected to a bridge rectifier, whose DC output is then fed to the main SG field winding. No brushes, commutator or slip rings are required in this configuration. Overall control of the excitation is accomplished by the Automatic Voltage Regulator (AVR).

The first, essential requirement in the design procedure of the exciters is the need to operate at the same rotational speed as the main SG. A degree of freedom is permitted in the choice of the number of phases for the exciter's armature winding. However, a three-phase winding is by far the most common type, in conjunction with a three-phase, six-pulse diode rectifier which produces a low ripple DC output. This common arrangement, i.e. a three-phase exciter armature winding feeding into a three-phase rectifier, is shown in Fig. 1.

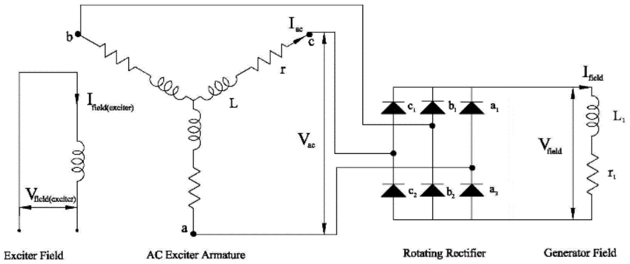

Fig. 1: Basic circuit of a three-phase, star connected exciter feeding into a three-phase bridge rectifier
[Courtesy of Cummins Power Generation]

The operational requirements of the exciter are usually defined by the operation of the generator, including its transient performance. This usually results in an 'over-sizing' of the machine in order to meet the required transient performance. In other words, when the main SG operates at full-load condition, the exciter is expected to work in linear conditions. Also the AVR parameters play an important role in the design of this machine and in particular, it constraints the choice of the field winding resistance. Another important aspect to consider in the exciter design is the voltage drop due the diode commutation processes. Considering all this, a preliminary sizing procedure is implemented and described below. A summarizing scheme of the implemented sizing procedure is illustrated in Fig. 2.

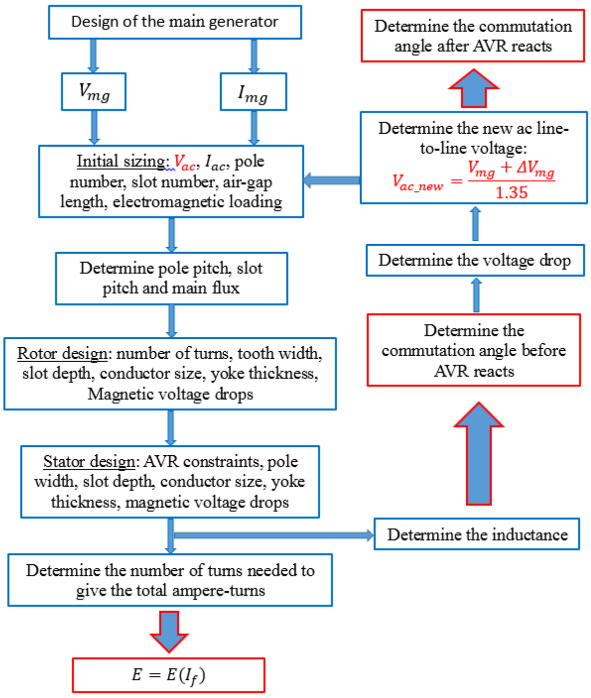

Fig. 2: Top level flow chart of the exciter sizing procedure

B. *Analytical Sizing Procedure*

The initial sizing of an exciter is strictly related to the operational requirements of the main generator. These include:

- The prime mover rotational speed *n*;
- The field voltage V_{field} and the field current I_{field} required by the generator at steady state operation
- The field voltage $V_{field(OL)}$ and the field current $I_{field(OL)}$required by the generator on overload/transient operation.

At this design stage, classical diode bridge theory [1] is usually used to convert between DC and AC quantities, where the commutations aspects are often neglected. Hence, the line-to-line voltage and the phase current of the exciter can be derived as shown in (1) and (2), respectively.

$$V_{ac} = \frac{V_{field}}{1.35} \tag{1}$$

$$I_{ac} = I_{field} \cdot 0.82 \tag{2}$$

Similarly, the maximum line voltage and phase current can be estimated from $V_{field(OL)}$ and $I_{field(OL)}$. It is then possible to estimate the apparent power of the exciter and, assuming an initial value for the power factor $\cos\varphi$ (a typical choice is $\cos\varphi = 1$), the real power can be also calculated.

The choice of the number of poles is also an important step of the design process. In general, a basic rule can be considered: the stator and rotor yokes' thickness decreases by increasing the number of poles $2p$.

Initial values of the electric loading and the airgap magnetic loading are necessary to estimate the well-known $D_{ag}^2 L$ [5, 8], where D_{ag} is the airgap diameter and L the axial length of the machine. In applications where the frame which hosts the exciter limits the machine length, this can be used as an input for the design. Alternatively, when a family of exciters has to be designed using the same stator and rotor laminations, then an appropriate ratio L/D_{ag} can be used as an input of the design process.

The rotor and the armature winding design procedures are not reported in detail in this paper, as they are similar to the approaches shown in literature for the most common electrical machines [8]. However, the outputs of this sizing stage are listed below:

- The number of rotor slots;
- The number of turns per phase;
- The conductor's cross-sectional area;
- The rotor tooth width;
- The rotor slot width;
- The rotor slot depth.

The airgap thickness has to comply with the general and always valid considerations concerning the minimization of the magnetic voltage drop in the airgap and the mechanical constraints due to the movement of the rotating parts present in the machine. However, as well as for the number of poles, in the second part of this work it will be shown how the airgap length can play an important role in the design synthesis of the particular exciter considered in this work, as it can significantly affect the voltage drop due to the diodes' commutations.

As well as for the rotor design, the calculations related to the stator (i.e. the pole width, the pole arc width and the yoke thickness) are not shown as they comply with the classical theory and sizing equations of electrical machines.

After the steps described above, all the dimensions of the exciter needed for determining the magnetic voltage drops along the parts of the machine are known. It is then possible to evaluate the total magneto-motive force F_{TOT} that the exciter field winding has to provide to compensate for the magnetic drops.

One method to design the exciter field winding is in accordance with the AVR parameters. These are

- The AVR maximum output voltage;
- The continuous and intermittent DC current levels;
- The reference value for the field resistance $R_{field(ex)}$.

Simple geometrical considerations allow one to determine the mean length $l_{field(ex)}$ of one turn of the exciter stator winding. Hence, it is possible to determine the cross sectional area of one conductor as given in (3), where σ_{Cu} is the copper conductivity and $V_{field(ex)}$ is the exciter field voltage.

$$S_{field(ex)} = \frac{F_{TOT} \cdot 2p \cdot l_{field(ex)}}{V_{field(ex)} \cdot \sigma_{Cu}} \tag{3}$$

Finally, the number of turns per pole can be calculated as shown in (4), allowing for the completion of the preliminary sizing of the exciter.

$$N_{pole(ex)} = \frac{R_{field(ex)} \cdot S_{field(ex)}}{2p \cdot l_{field(ex)} \cdot \sigma_{Cu}} \tag{4}$$

C. No-load curve, inductance and efficiency determination

Having determined all the dimensions of the stator and rotor parts and the design of the armature and the field windings, the next step consists in estimating the no-load characteristic of the exciter. By implementing the magnetization curve of the ferromagnetic materials used for the rotor and stator stacks, it is a simple task to extrapolate the no-load rotor output voltage as a function of the stator field current.

Also the inductance can be determined once the machine design is completed. Both the magnetizing and the leakage inductances can be evaluated by using the classical *d-q* model [8]. The *d-q* magnetizing inductance L_{d-q} is shown below in (5), where all the variables involved in its evaluation can be observed.

$$L_{d-q} = \frac{12 \cdot \mu_0 \cdot L \cdot \tau_P}{\pi^2 \cdot 2p \cdot \delta_{d-q}} (k_w \cdot N^2) \tag{5}$$

In (5), μ_0 is the permeability of the free space, τ_P the pole pitch, k_w the winding factor, N the number of turns per phase and δ_{d-q} is the equivalent airgap calculated along the *d*- and the *q*-axis, respectively.

The final step of this design stage consists in determining the machine losses, aiming at evaluating the overall efficiency of the considered 5.35kVA exciter. Although the loss estimation is a challenging task, especially when analytical expressions have to be employed, the following terms can be estimated and used for sensitivity and optimization purposes:

- Resistive losses, from the winding geometry and the estimated currents in the stator and rotor phases;
- Iron losses, from the geometry of the magnetic parts, the operating flux densities and the specific loss of the ferromagnetic steel;
- Mechanical losses, by using the well-known experimental Schuisky's equation [16].

A relatively accurate approximation of the losses and efficiency of the machine can then be achieved.

D. Voltage Drop duo to the Commutation Processes and New Operating Point

The operation of an uncontrolled diode bridge of an excitation system of SGs is frequently deteriorated, due to the inherent delay that the supply inductance creates in the system. This can result in significant overlap in the conduction periods of the diodes. In the case of a brushless excitation system, the supply inductance is represented by the phase inductance L_{exc} of the exciter, which can be calculated by manipulating the inductance L_{d-q} shown in (5). The ensuing voltage drop ΔV can be described by (6), where ω is the excitation frequency.

$$\Delta V = \frac{3\omega L_{exc} I_{field}}{\pi} \tag{6}$$

Having determined the voltage drop due to the commutation processes in the diode rectifier, a 'new' operating point, i.e. the output voltage V_{ac_new} of the exciter, can be defined as shown in (7), where the classical theory of diode rectifiers is used to convert between DC and AC quantities.

$$V_{ac\_new} = \frac{V_{field} + \Delta V}{1.35} \tag{7}$$

This new operating voltage can be used to reiterate the sizing procedure and restart the calculation from (1), as shown in Fig. 2. This therefore allows one to account for the voltage drop due the diode commutations, which is often neglected in low to medium rated SGs, such as the one analyzed in this paper.

E. Final Considerations

In the previous sections, top level considerations and in-detail equations related to the design of an exciter for SGs have been described. In particular, it has been shown that the electromagnetic design of an exciter strongly depends on the operational requirements of the main SG, including its transient performance. This results in an 'apparent' over-sizing of the exciter in normal operating conditions. Hence, an accurate choice of the input parameters (i.e. flux densities, the current density, etc.) plays an essential role in the design process. Then, the classical sizing equations of electrical machines can be applied also to the design of the exciter. Finally, the voltage drop due to the commutations and the new voltage value at which the exciter has to work to compensate for it can be determined.

In order to validate the implemented procedure, FE and available experimental results of a baseline machine, i.e. an exciter of a 400*kVA* SG, are used. Details of these are shown below in the next section.

F. FE and Experimental validation of the Analytical Tool

The brushless exciter under analysis in this paper is a 5.35*kVA* machine, with a 14 poles field winding placed on the stator and a three phase armature winding on the rotor. The exciter is designed to provide ≈ 5*kW* (DC) to the field winding of the main SG, when it operates at full-load condition. The machine is characterized by a low ratio *l/D*(axial length/outer diameter). A 2-D FE model is built and a detailed analysis is carried out. To take advantage of the geometrical symmetries present in the machine, only (*1/7-th*) of the whole machine is analyzed, as shown in Fig. 3.

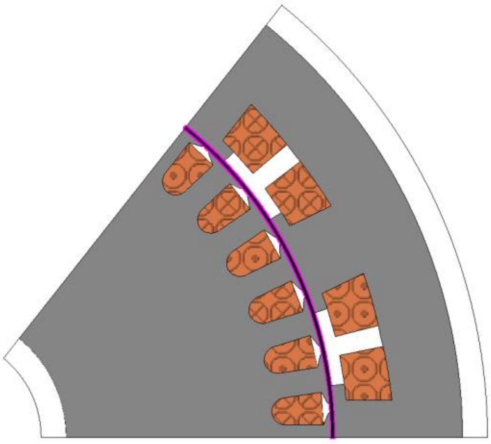

Fig. 3. 1 pole pair model of the 5.35*kVA* exciter

Considering all the above, transient with motion simulations have been performed to evaluate the open circuit characteristic of the exciter. This is found by measuring the no-load terminal voltage at different levels of the field current. Fig. 4 shows a comparison of the analytical and the FE results with the experimental measurements on the prototype, showing an excellent match amongst the three curves.

Further validation of the analytical model can include a comparison between analytical and FE results in terms of flux densities, current densities, etc. However, for the purposes of this study, i.e. the minimization of the voltage drop produced by the diodes' commutations, only the inductance's comparison is reported.

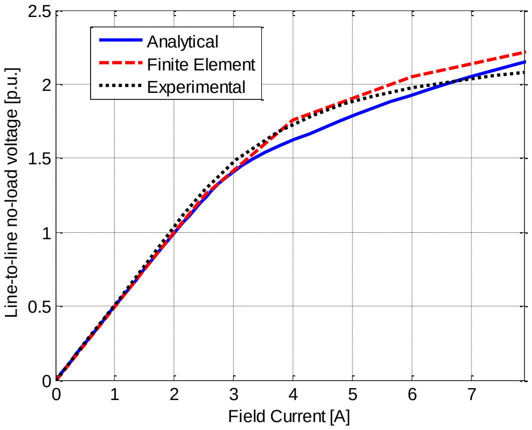

Fig. 4. No-Load Characteristics – Comparison.

Hence, static FE simulations have been performed according to the method described in [10] for the calculation of the inductance. An error less than 2% between the analytical and FE results has been found and therefore, an excellent match in terms of voltage drop is also registered. In particular, the analytically calculated ΔV is ≈ 32.3*V*, which is the 30% of the DC voltage needed by the rotor of the main SG when operating at full-load conditions. This confirms that the voltage drop due to the commutation processes can be significantly large in low to medium rated SGs.

All the above confirms the room for improvements in the exciter design procedure. Therefore, having validated the analytical sizing tool, this can be used for optimizations purposes. The following sections focus on a detailed sensitivity analysis aimed at limiting the exciter design space and on the development of an accurate GA-based design tool.

III. SENSITIVITY ANALYSIS

In the previous section, it has been highlighted how the exciter's phase inductance highly affects the voltage drop described by (6) due to the overlapping phenomena in the diode rectifier. It is then clear that all the parameters involved in (5) can be utilized to improve the overall performance and efficiency of the machine. Considering this, a sensitivity analysis on the main machine parameters that have an effect on the voltage drop is performed.

In Fig. 5 and 6, the results of this analysis can be observed. The number of pole pairs and the axial length of the machine are the design parameters that mostly influence the voltage drop as well as the efficiency. These parameters can achieve a lower voltage, however at the cost of a lower efficiency. The air-gap thickness also strongly affects the voltage drop, but without influencing the efficiency significantly. Also the split ratio (inner stator diameter/outer stator diameter), although shown in a small variation range due to geometrical constraints, seems to be an interesting parameter for the voltage drop minimization.

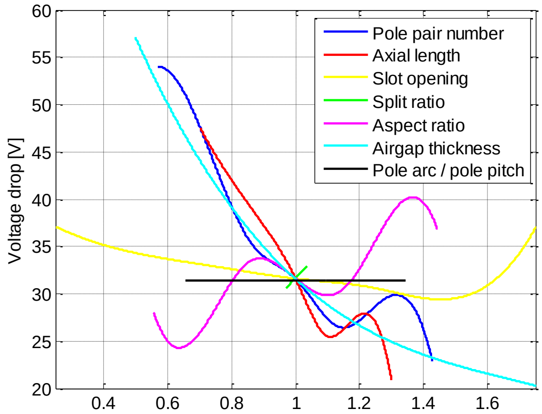

Fig. 5. Sensitivity analysis – voltage drop variation

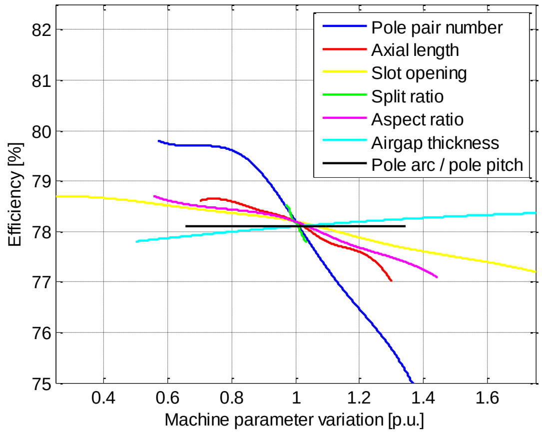

Fig. 6. Sensitivity analysis – efficiency variation

Considering the above, these design variables are then used as input parameters for the analytical-GA-based optimization design tool described in the following section.

IV. EXCITER OPTIMIZATION TOOL DESCRIPTION AND RESULTS

This section deals with the description of a purely analytical optimization tool aimed at finding possible design solutions which minimize the voltage drop, while keeping the efficiency above acceptable limits.

A. Input Variables

Resulting from the sensitivity analysis's results, the selected input parameters used for the optimizations are the followings:

- The number of pole pair *p*;
- The axial length *l*;
- The airgap thickness δ;
- The split ratio *SR*.

B. Optimization Strategy and Output Variables

The optimization process is initialized by a preliminary analysis of the design space. The second stage of this procedure consists in creating and analyzing an initial population of design, by using an appropriate multi-objective GA. This model then preserves the best designs in terms of voltage drop and efficiency and iterates until converging to one or more optimal solutions.

The output variables chosen as optimization objectives are therefore the voltage drop and the exciter field winding resistance $R_{field(ex)}$, which is an indicator of the efficiency as it affects power losses. However, priority is given to the voltage drop minimization objective. In particular, this has to be lower than the value estimated for the baseline machine ($\Delta V=32.2V$). On the other hand, it is sufficient that $R_{field(ex)}$ is kept between 18Ω and 21Ω, in order to comply with the constraints imposed by the AVR (see Section II.A) while keeping the efficiency above acceptable limits.

C. Optimization Results

The optimization results for the 5.35*kVA* exciter considered in this paper are shown in Fig. 7. It is shown how several designs can achieve a voltage drop (on the x-axis) that is lower than 30*V* and a field resistance (on the y-axis) that can be maintained under the reasonable value of 21Ω, as highlighted in the target area. In Table I, a selection of the better performing designs are compared to the existing one. It can be seen that significant improvements in terms of voltage drop reduction can be achieved. However, the efficiency ε is above 78% only if the number of pole pairs is 7. Amongst the optimal designs shown in Table I, the 'Proposed Design 1' seems to be the most interesting for the following reasons:

- The axial length is smaller than that of the existing machine, then allowing for a more compact design;
- The number of poles is the same as the actual machine;
- The air-gap is bigger than that of the baseline machine, then resulting in an increased number of field winding turns. However, the field resistance is 'controlled' by the implemented GA, allowing for the efficiency to be even improved;
- A voltage drop reduction of about 28% can be achieved.

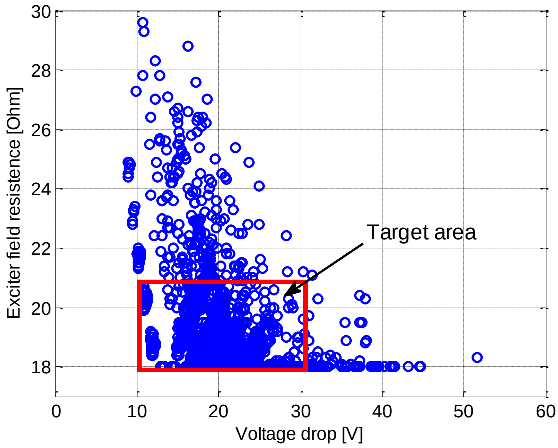

Fig. 7. Optimization results – Field winding resistance vs. voltage drop

TABLE I
EXAMPLE OF OPTIMIZED EXCITER DESIGNS
AND COMPARISON WITH THE EXISTING DESIGN

--------	*l*	*p*	*δ*	SR	ΔV	*ε*
Existing Design	50*mm*	7	1*mm*	0.753	32.2*V*	78.2%
Proposed Design 1	48*mm*	7	1.4*mm*	0.733	23.0*V*	78.9%
Proposed Design 2	53*mm*	7	1.2*mm*	0.746	21.4*V*	78.2%
Proposed Design 3	55*mm*	8	1.1*mm*	0.757	19.3*V*	76.6%
Proposed Design 4	47*mm*	9	1.3*mm*	0.739	22.7*V*	76.2%

V. FE ANALYSIS OF THE BEST DESIGN SOLUTION

The best performing solution (Proposed Design 1) identified above is then analyzed via a 2-D FE transient with motion simulation. The stator and rotor circuits are coupled to the 2-D FE model, as shown in Fig. 1. A comparison between the registered currents on the DC bus, i.e. the field winding of the main SG, is shown in Fig. 8. By using the same exciter field winding current for both the machines, it can be observed how the improved design achieves an augmentation of the current available at the main generator rotor terminals, potentially allowing for the exciter to work with a lower field winding current, which in turn results in improvements of the overall efficiency.

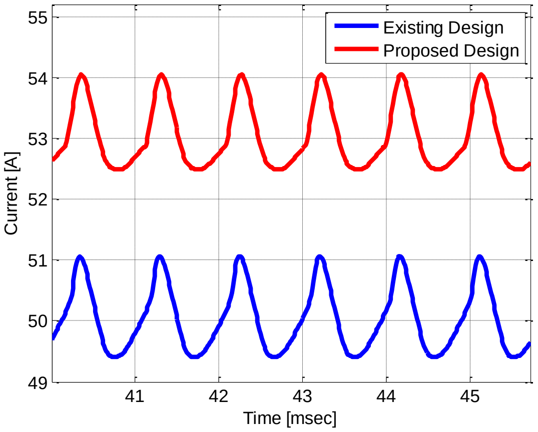

Fig. 8. Main generator rotor currents – Comparison.

VI. CONCLUSIONS

This paper deals with the development of a fully analytical, genetic-algorithm-based optimization design tool for the excitation systems of field wound SGs.

The analytical sizing procedure of a 5.35*kVA* exciter of a particular 400*kVA* SG is first implemented and then validated against FE and experimental measurements, showing that the impact of the diode commutations on the DC voltage available at the main generator rotor terminals can be significantly large.

A sensitivity analysis is then performed, aimed at capturing the main machine's design parameters that mostly affect the voltage drop due to the rectifier behavior. The results of this analysis are then used to set-up the design optimization tool.

The optimization results show that improved designs of the exciter can be achieved, which result in excellent achievements in terms of voltage drop reduction. As vessel for validating the optimization results, a FE analysis of the best design solution is carried out. The available current at the main generator rotor terminals is compared with that of the baseline machine, resulting in an increased output of 5.64%, which in turn results in an improved efficiency.

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