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A Theoretical Approach in the Design of Single Frame 28 V DC and 270 V DC Dual Voltage Generator

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ABSTRACT

Armored Fighting Vehicles (AFVs) generally operate with a 28 V DC electrical system. However, the demand for electrical power in AFVs has exceeded the capabilities of the existing 28V system. The additional load growth necessitates larger wire sizes, which adds extra weight and cost to the vehicle. Introducing a dual-bus architecture (28 V DC and 270 V DC) can lead to the efficient operation of the electrical system while meeting future demand. This paper presents the design of a Brushless Direct Current (BLDC) Dual Voltage Generator (DVG), which simultaneously outputs two voltages (28 V DC & 270 V DC) from a single frame across a wide operational speed range. The design process includes a detailed description of the individual stages, accompanied by analytical parameters and software-generated results. The modeling and analysis of the generator were carried out using Motorsolve design software. The obtained results are presented and thoroughly discussed in this paper.

Keywords: AFV; BLDC generator; Dual voltage generator; Simcenter motorsolve

NOMENCLATURE

K	:	Output coefficient
D	:	Internal diameter of stator (m)
L	:	Gross length of stator core (m)
N_s	:	Rotation speed (rpm)
B_{av}	:	Specific magnetic loading (T)
ac	:	Specific electric loading (A/m)
K_w	:	Winding factor
T_{ph}	:	Number of stator turns per phase
E_{ph}	:	Induced EMF per phase (V)
A	:	Number of parallel paths
f	:	Frequency of induced voltage (Hz)
φ	:	Flux per pole (wb)
Z_s	:	Conductors per slot
τ_s	:	Slot pitch
P	:	Number of poles

1. INTRODUCTION

In the present scenario, all the loads in Armoured Fighting Vehicles (AFVs) are connected to a 28 V DC bus architecture. However, many new electrical and electronic systems shall be introduced in the vehicle in the near future to improve performance and combat effectiveness. With the existing 28 V DC voltage in military vehicles, there will be difficulties in meeting power demands due to the growing electrical loads, largely driven by the advent of power electronics[1]. Introducing a dual voltage architecture in the vehicle would be a viable solution. In this dual voltage architecture, the high-power loads, such as electric drives used for gun and turret rotation, would operate at a high voltage of 270 V DC, while other loads would operate at 28 V DC. This improves the efficiency of the distribution system as well. The new architecture requires simultaneous generation and distribution of two DC voltage levels, namely 28 V DC and 270 V DC. These voltages can be achieved through a dual voltage generator or using step-up or step-down converters. Generating 270 V DC offers certain advantages over a step-up converter, primarily in terms of space-saving[2], in addition to enhancements in reliability and performance.

Therefore, for the present case, it is proposed to meet the requirements by designing a single-frame dual voltage generator with an Automatic Voltage Regulator (AVR). The brushless DC generator has a simple multistage construction, high reliability, and high power density in variable speed drive applications such as automotive, aerospace, and other industrial applications. The DVG is a single power unit consisting of two BLDC generators along with their rectifier units built on a single shaft, housed in a single frame with a built-in coolant pump. Each power stage (28 V & 270 V) comprises a main generator and an exciter. All the stages of the generator are coupled to a single shaft powered by a diesel engine that rotates in the speed range of 3400 rpm to 13000 rpm. The excitation current for the main generators of high voltage and low voltage is provided by their respective exciters, which receive input power from the vehicle's battery bank through a digital automatic voltage regulator[3]. The automatic voltage regulator maintains the output voltage within specified limits for variable speed

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and load conditions. The constraints on space and the prime mover, imposed by the present vehicle configuration, have necessitated the conception of this complex generator design, which is the first of its kind. This paper presents the detailed design procedure and the results of the analytical design. The design is verified using design software, and the results are discussed.

2. LITERATURE REVIEW

In recent years, single-stator dual-rotor and dual-stator single-rotor machine configurations have been proposed by many researchers to improve the performance[4-6]. Dual voltage architecture has been proposed for providing size and weight reduction in electrical generation systems[7]. Dual stator generators for windmill applications[8] and electrical vehicle applications are increasing nowadays due to their high power density. In normal practice, excitation is achieved by using additional permanent magnet stages, but this approach has disadvantages such as increased cost of permanent magnets and mechanical limitations of surface-mounted permanent magnets at high speeds, leading to demagnetization at higher temperatures[9-11]. In the proposed dual voltage generator, each generator stage has its own exciter stage instead of permanent magnets[12], and the excitation current is fed through the regulator. Very limited literature is available on the two-stage single voltage generator, and few papers exist on dual voltage generators with suitable converters.

3. PROPOSED DESIGN

3.1 Specifications

The technical requirements of the dual voltage generator are as follows:

Generator type:	Brushless Dual Voltage DC generator
Nominal voltage:	28 ±0.3 V DC and 270 V DC±3 V DC
Nominal output:	15 kW@28 V and 10 kW@ 270 V
Speed range:	3500 rpm to 13000 rpm
Efficiency:	> 80 % with cooling
Cooling:	Liquid flow cooling
Coolant admission temperature:	120 °C ±5 °C
	Dimensions
Length:	400 mm
Diameter:	220 mm
Mass (weight):	Approx. 75 kg

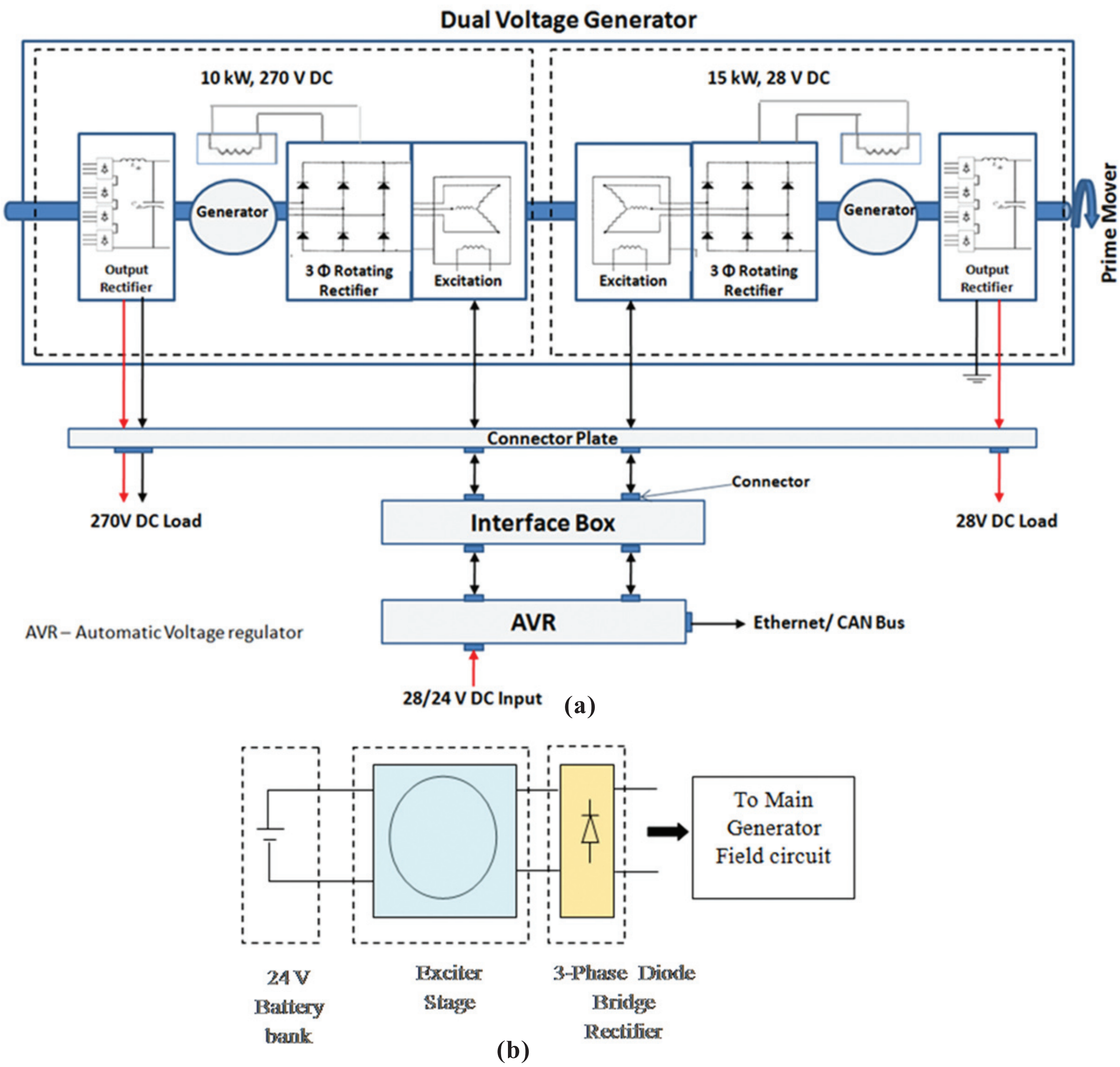

Figure 1. (a) Architecture of Dual Voltage Generator (DVG); and (b) Main generator field circuit power flow schematic.

From the specifications, it is clear that the variation in the input speed range requires a field-controlled synchronous generator. To achieve brushless excitation, a two-stage BLDC generator configuration is proposed for the current application. Each BLDC generator consists of two stages: the main generator and the exciter. Therefore, a total of four generators are required: a low-voltage generator and its exciter, as well as a high-voltage generator with its exciter. The novelty lies in the conception of housing these two generators in a single enclosure, eliminating the need for two prime movers. However, this configuration increases the complexity of the system in terms of performance and cooling, making the design very challenging. The schematic diagram representation of the four-stage dual voltage generating system is shown in Fig 1(a). Another possible way to achieve dual voltage is by using power electronic circuits such as DC-DC converters. However, compared to the dual voltage generator, power electronic converter circuits suffer from inherent shortcomings, such as higher cost and weight, as they require expensive filter and control circuitry, especially in the context of a vehicle application[13].

The dual voltage generating system consists of two 2-stage generators enclosed separately in a single enclosure for 28 V and 270 V DC generation. Due to the wide variation in input speed and the limitations of having two drive ends in the current vehicle application, a 4-stage dual voltage generator configuration is considered the most suitable choice. For each voltage generation, an exciter and a main generator are required, along with the 12-pulse rectifier circuit[14]. This 12-pulse rectifier is chosen to minimise the ripples in the rectified AC voltage.

3.2 Stages Involved in the Design of DVG

Different stages involved in the design of the 25kW BLDC Generator are as follows:

- Exciter field
- Exciter armature
- Rotating rectifier
- Main generator field
- Main generator armature
- 12 pulse rectifier
- Automatic Voltage Regulator (AVR)
- Cooling system

Design Stages from S.No. 1-7 have to be made for 28 V DC and 270 V DC separately.

The main focus of this paper is to present the work carried out in the design, simulation, and analysis of the power stages and their excitation stages of the dual voltage generator, considering manufacturing aspects.

The exciter power rating can be evaluated by determining the exciter current drawn by individual power stages in the DVG. The rated exciter current delivered by the 28 V and 270 V exciter stages is 18.4 A and 15.5 A respectively to the power stages. The power required for 28V excitation stage is evaluated as follows.

AC current required for 28 V Power stage (from exciter stage) =18.4 A

AC output voltage from exciter stage ($V_{line\text{-}line}$) = 18 V

Power factor (p.f) = 0.8 lag

Power rating of 28 V exciter stage $= \sqrt{3} \times V_{Line} \times I_{Line} \times pf$

$= \sqrt{3} \times 18 \times 18.4 \times 0.8 = 0.46\,kW$

Similarly for the 270 V power stage, exciter power rating

$= \sqrt{3} \times V_{Line} \times I_{Line} \times pf$

$= \sqrt{3} \times 15.5 \times 18 \times 0.8 = 0.38\,kW$

Specifications of exciter stages are listed in Table 1 and specifications of high voltage and low voltage sides are given in Table 2.

Table 1. Specifications of 28 V and 270 V exciter stages

Specification	28 V exciter stage	270 V exciter stage
Output power (kW)	0.459	0.386
Input speed (RPM)	3400–13000	3400–13000
AC voltage (L-L)	18 V	18 V

Table 2. Specifications of 28 V and 270 V power stages

Specification	28 V stage	270 V stage
Output voltage (after rectification)	28 V DC	270 V DC
Output power (kW)	15	10
Input speed (RPM)	3400–13000	3400–13000
Compliance of standards	Mil-Std 1275 E	Mil-Std 704 F

3.3 Automatic Voltage Regulator

A digital Automatic Voltage Regulator (AVR) is utilised to regulate the output voltage at both terminals, namely 28 V DC and 270 V DC, for variable loads within the speed range of 3400 to 13000 rpm. The AVR senses the output voltage, generates corrective signals and provides varying field current according to corrective signals to maintain constant output voltage[15]. This is achieved by continuously monitoring the respective output terminals and controlling the excitation current to the exciter, which in turn governs the excitation voltage to the respective generator using PWM technique. Consequently, there is no voltage drop at the terminal resulting from sudden load increase or speed decrease as it is compensated by adjusting the field excitation through the AVR. Careful consideration has been given to sizing the magnetic circuits to ensure that magnetic saturation at low speed and full load conditions remains within acceptable limits. The generator design presents significant challenges in terms of electrical design at minimum speed and mechanical aspects at higher speeds. The focus of this paper is limited to the electrical and electromagnetic design aspects of the proposed multistage generator, which represent the most critical components imposing constraints on the overall generator size. The AVR component will be addressed in future work.

3.4 Design of Dual Voltage Generator

3.4.1 Basic Electrical Design Flow

The design of dual voltage generator was carried out by considering the power and voltage requirements of individual stages. Each stage has its own parameters. The general design flowchart is given in Fig. 2.

3.4.2 Major Design Parameters

Estimating the stack length and inner diameter of a machine is the primary step in designing rotating electrical machines. The output equation of the machine establishes the relationship between the power generated and the gross volume of the machine.

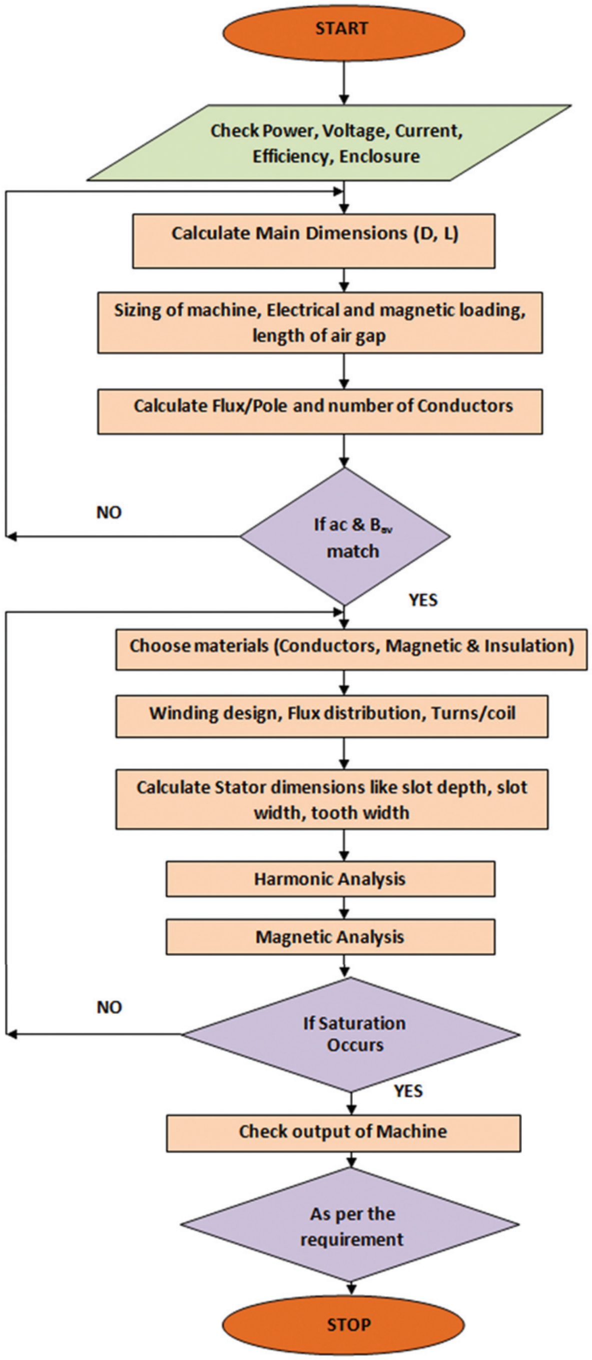

Figure 2. Flow chart for design of electrical machine.

Electrical output of the generator,

$$Q = KD^2LN_s \tag{1}$$

where,

$$K = \frac{11}{3}B_{av}(ac)K_w \times 10^{-3} \tag{2}$$

Number of stator turns per phase is given by

$$T_{ph} = \frac{E_{ph}A}{4.44 f \varphi K_w} \tag{3}$$

where,

$$\varphi = \frac{B_{av}\pi DL}{P} \tag{4}$$

Conductor per slot,

$$Z_s = \frac{2 \times Tph}{No.of\ stator\ slots} \tag{5}$$

Slot pitch,

$$\tau_s = \frac{\pi D}{No.of\ slots} \tag{6}$$

Table 3. Comparison of analytical and software parameters – main generators

Parameter	28 V generator power stage		270 V generator power stage	
	Analytical	Software	Analytical	Software
Stack length (mm)	60	68	53	58
Stator outer dia (mm)	198	198	198	198
Stator inner dia (mm)	151	151	151	151
Air gap length (mm)	1	1	1	1
Output power (kW)	15.7	15.4	10.5	10.3
Slot height (mm)	14.5	14.7	14.5	14.7
Tooth width (mm)	5.1	5	5.1	5
Stator conductor dia (mm)	2.32	2.8	1.6	1.79
Stator current density (A/mm^2)	15	16.5	15	16.5
Winding factor	0.9	0.966	0.9	0.966
Slot opening width(mm)	4.7 (open)	3.2 (semi open)	4.7 (open)	3.2 (semi open)

Table 4. Comparison of analytical and software parameters- exciters

Parameters	28 V generator exciter stage		270 V generator exciter stage	
	Analytical	Software	Analytical	Software
Stack length (mm)	12	12	10	10
Stator outer dia (mm)	198	198	198	198
Stator inner dia (mm)	151.2	151.2	151.2	151.2
Air gap length (mm)	0.6	0.6	0.6	0.6
Output power (kW)	0.458	0.475	0.381	0.4
Slot height (mm)	12	12	12	12
Tooth width (mm)	5.1	5	5.1	5
Stator conductor dia (mm)	2.32	2.8	1.6	1.79
Stator current density (A/mm^2)	9.61	9	9.61	9
Winding factor	0.9	0.966	0.9	0.966
Slot opening width (mm)	5.87 (open)	5.8 (semi open)	5 (open)	5 (semi open)

Analytical calculations have been carried out to select specific electric and magnetic loading for the different stages of the generator. A specific magnetic loading of 1 Tesla has been chosen for both stages. The specific electric loading for the power stages varies within the range of 25000-26000 AT/m, while for the exciter stage, it ranges from 4000-4500 AT/m. Other machine design parameters, such as slot dimensions and current density, have also been considered. The parameters for the 28V and 270V power stages, as well as their corresponding exciter stages, were calculated analytically and provided as input to the Motorsolve design software. The analytical calculations for the two power stages of the dual voltage generator were conducted by referencing sources[16-21], and the individual power stages were modeled using Simcenter Motorsolve[22]. Parameter optimisation was performed in the software based on performance and output.

A comparison between the analytical parameters and the software parameters of the power stages and exciter stages is provided in Table 3 and Table 4, respectively.

3.5 Simulation of Dual Voltage Generator Stages

Simcenter Motorsolve is a software interface that combines analytical methods of electromagnetics with automated electromagnetic Finite Element Analysis (FEA) simulations. This software is primarily used for designing electrical machines without the need for initial calibration[23]. With Simcenter Motorsolve software, the process of material selection, machine dimensions, and iterations of performance parameters for electrical machines is simplified. Figure 3 depicts the working interface of the Simcenter Motorsolve software.

3.6 Selection of Magnetic Material

The machine's maximum operating frequency occurs at an operating speed of 13000 rpm, resulting in a maximum frequency of 866.67 Hz considering 8 poles. The lamination thickness of the magnetic material was selected to correspond to the high frequency. Additionally, the B-H curve, relative permittivity, and specific heat density of various magnetic materials were compared. The software simulated Hyperco14.A and M-19 magnetic materials for analysis.

3.7 Modelling of Armature Windings

The armature windings on the stators of the main generators in the 28 V and 270 V systems are designed based on the rectifier configuration used for converting the generator AC voltages to DC. A 12-pulse rectifier configuration is selected to comply with the ripple voltage and other performance parameters specified in Mil-Std 1275E[24] for the 28 V DC system and Mil-Std 704F[25] for the 270 V DC system. According to Mil-Std 1275E, the maximum allowable peak-to-peak ripple in the 28 V DC systems is 1.995 V, while in the 270 V DC system, it is 6V as per Mil-Std 704F. In a 12-pulse configuration, the peak-to-peak ripple in the output voltage will be around $0.034V_{ml}$ (V_{ml} represents the maximum line-to-line voltage), which falls within the tolerable limit.

For the production of high DC voltages in multi-pulse diode rectifiers, series connection is preferred, and the DC voltage decreases in parallel connection as the pulse number increases. In series connection, the DC voltage decreases with an increase in frequency (speed), but the effect of frequency is almost insignificant in the case of parallel connection[26-27]. Considering the ripple voltage requirements and the factors mentioned above, a 12-pulse diode rectifier with parallel connection is considered optimal for the low voltage, high current, variable speed AFV application.

The input AC voltage for the 12-pulse rectifier requires two 3-phase voltage groups that are phase-displaced by 30 degrees. Therefore, the armature windings are designed in such a way that 6-phase voltages are obtained from the generator terminals. The number of parallel paths for the

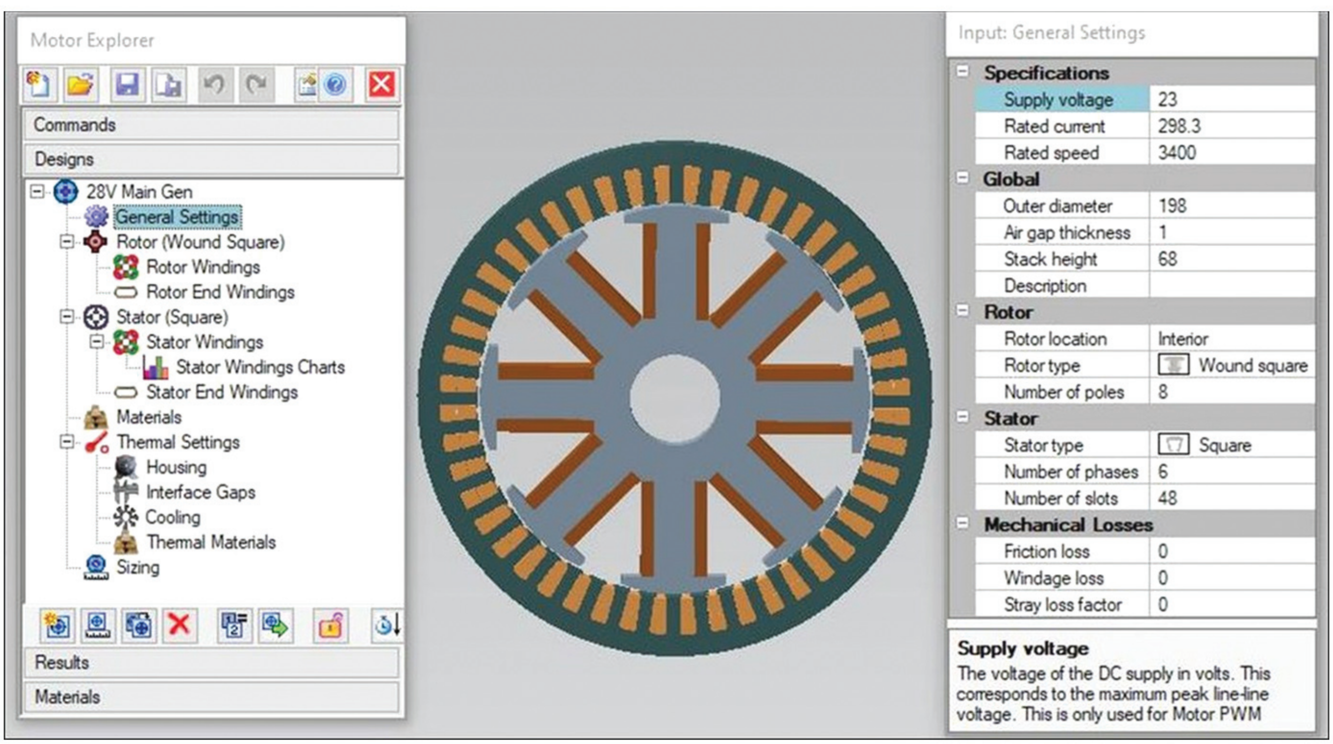

Figure 3. Simcenter motorsolve software interface.

Table 5. Comparison between full pitched and 1-slot short pitched

Parameters	28 V power stage		270 V power stage	
	Full-pitched	1-slot short pitched	Full-pitched	1-slot short pitched
No load voltage THD (%)	8.86	4.62	8.78	4.44
Full load voltage THD (%)	21.2	13	15.3	8.45
Current THD (%)	3.55	1.09	3.07	0.91
Voltage regulation (%)	30.2	28.8	19.1	17.9
Output voltage (V)	13.4	13	129	125

armature windings is chosen based on the required current and voltage ratings of each individual stage. Copper is selected as the winding material. The main generator windings are wye-connected and lap-wound, with 4 parallel paths for the 28 V stage and 1 parallel path for the 270 V stage.

In the AFV power system, isolation is necessary, and the reduction of harmonics on the load side typically requires large passive components such as inductors and capacitors. However, these components increase the size and cost of the generator setup. To address this, short-pitched windings are used in the generator itself to suppress harmonics. A comparison between full-pitch and 1-slot short-pitched winding configurations for the 28 V and 270 V outputs is provided in Table 5. Harmonic analysis of the no-load electromotive force (EMF) and full-load EMF of the two power stages was conducted, and the voltage regulation of each power stage was calculated using Simcenter Motorsolve software.

From Table 5, it is evident that full-pitched winding results in distorted voltage and current sinusoids, whereas short-pitched winding yields tolerable total harmonic distortion (THD). Short-pitched winding reduces the harmonic content and improves power quality[28]. Therefore, for AFV applications, it is recommended to use short-pitch winding, even though it provides reduced output voltage compared to full-pitch winding. The FFT analysis plot for the 28 V main generator output at full load is shown in Fig. 4(a), while the FFT analysis plot for the 270 V main generator output at full load is shown in Fig. 4(b). The output voltages exhibit the presence of the 5th, 7th, and 11th harmonics. As the harmonic order increases, the magnitude with respect to fundamental decreases. Harmonics of orders greater than 11 (such as 13, 17, etc.) are negligible.

The graph depicting the relationship between line-to-line voltage and generated power for the individual stages is shown in Fig. 4(c) for the 28 V stage and Fig. 4(d) for the 270 V stage, respectively. The load resistances of 0.052 Ω and 7.29 Ω were considered based on the output power rating for the 28V and 270 V stages, respectively. It is evident that as the line-to-line voltage increases, the power also increases. The variation of back EMF, line-to-line voltage, and output power with the source phase angle for the 28 V and 270 V stages is shown in Fig. 4(e) and Fig. 4(f), respectively. The waveforms of the back EMF and line voltage are not purely sinusoidal and contain harmonics. The selection of short-pitched winding is made to minimize the harmonic content.

Regarding the main dimensions of the machine, there were minimal changes between the theoretical and software dimensions. Slot width and tooth width were adjusted to prevent saturation at the tooth tips. The output power of the machine was analytically calculated around 3400 rpm with a power factor of 0.8 lagging. The slot opening width was determined for open slots, but in the simulation, semi-open slots were chosen to improve the magnetic parameters. It can be observed that the simulated parameter values closely match the analytical results.

3.8 Electromagnetic Analysis

During the electromagnetic analysis, the flux distribution in different parts of the generator was observed at full load conditions, and design optimization was performed to prevent saturation. The flux distribution plots for the main generators of the 28 V and 270 V stages are depicted in Fig. 5(a) and Fig. 5(b), respectively. In the air gap between the rotor poles and stator, the flux density for both the 28 V and 270 V main generators is approximately 1.1 T, while in the pole body, the flux density is around 2.4 T. The magnetic material used in the design, HiperCo, saturates above 2.5 T. Therefore, the machine does not experience saturation at full load.

3.9 Power stages of Dual Voltage Generator

The power generation in the 25 kW generator is achieved through two separate generators with ratings of 15 kW at 28 V and 10 kW at 270 V. These generators operate using a common drive system and are enclosed in a single enclosure. The main engine drives the generators, rotating at speeds ranging from 3,500 to 13,000 rpm. The exciter generator of the 28 V generator is designed to provide 0.46 kW of power. It supplies power to the field of the main generator upon receiving a signal from the AVR (Automatic Voltage Regulator) to maintain a constant output of 28 V DC.

Similarly, the exciter generator of the 270 V generator is designed to provide 0.38 kW of power. It also supplies power to the field of the main generator upon receiving a signal from the AVR to maintain a constant output of 270 V DC.

The power stages of the Dual Voltage Generator for the 28 V and 270 V outputs are illustrated in Fig. 5(c) and Fig. 5(d), respectively.

3.10 3D Model

The complete generator was modeled in 3D using CREO software to examine the feasibility of electrical and mechanical assembly and to analyze potential interferences for wire routing within the generator. Figure 6 illustrates the overall exploded view of the generator, showcasing the different components of the generator.

4. DISCUSSION

Table 6 presents a comparison between the specifications and the output obtained through simulation. The results indicate that the design has successfully produced output values that closely align with the desired targets. This congruence between simulated outcomes and intended values reflects the accuracy and efficacy of the design process.

Being a complex system and ab initio development, only design simulation was carried out to evaluate the performance and a 3D model was developed. The prototype development is under progress which will be presented in detail along with test results in future publication.

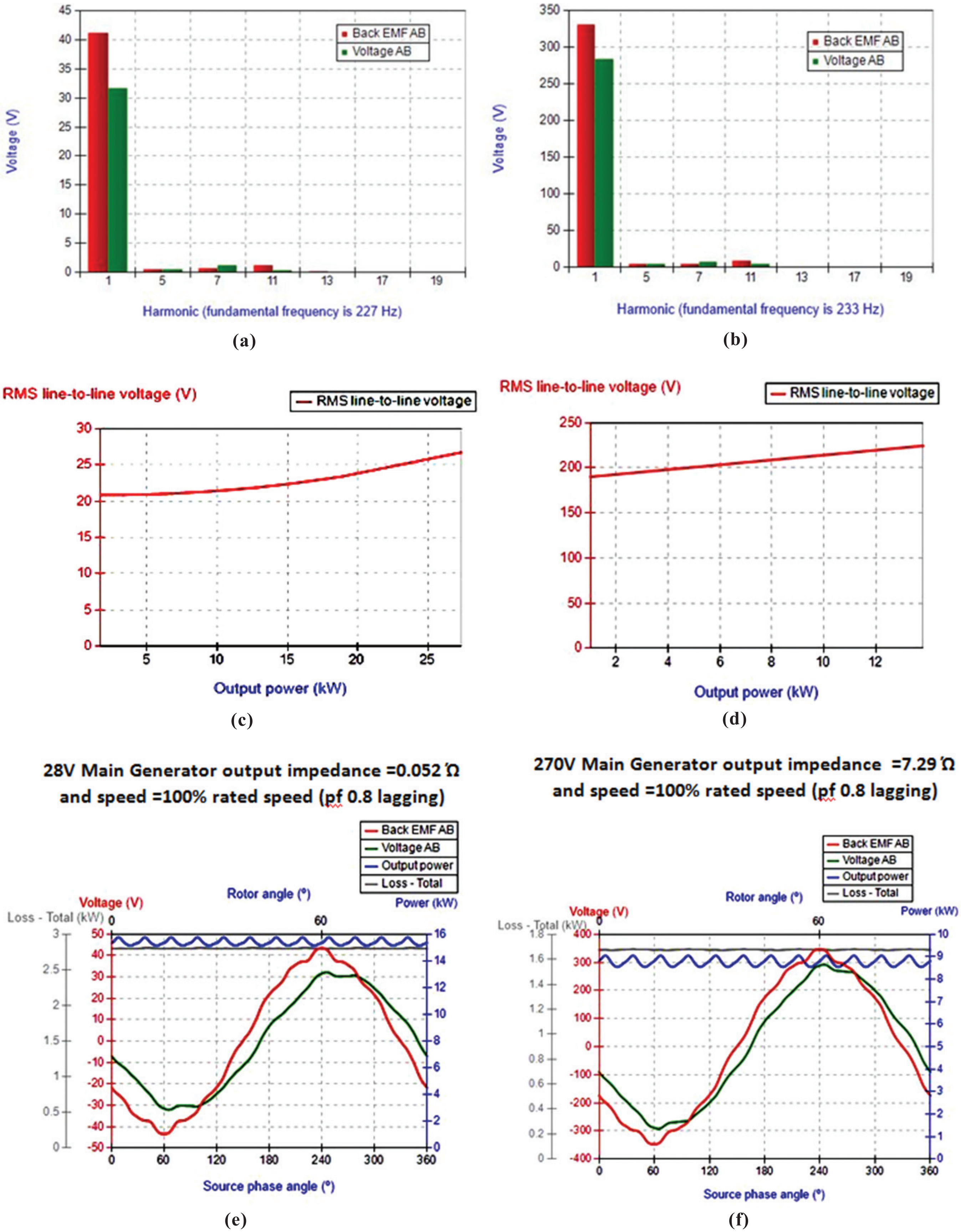

Figure 4. (a) FFT analysis of back EMF and full-load voltages for 28 V main generator; (b) for 270 V main generator; (c) Line to line voltage vs output power for 28 V stage; (d) for 270 V stage; (e) Motion analysis of 28 V stage and (f) Motion analysis of 270 V stage.

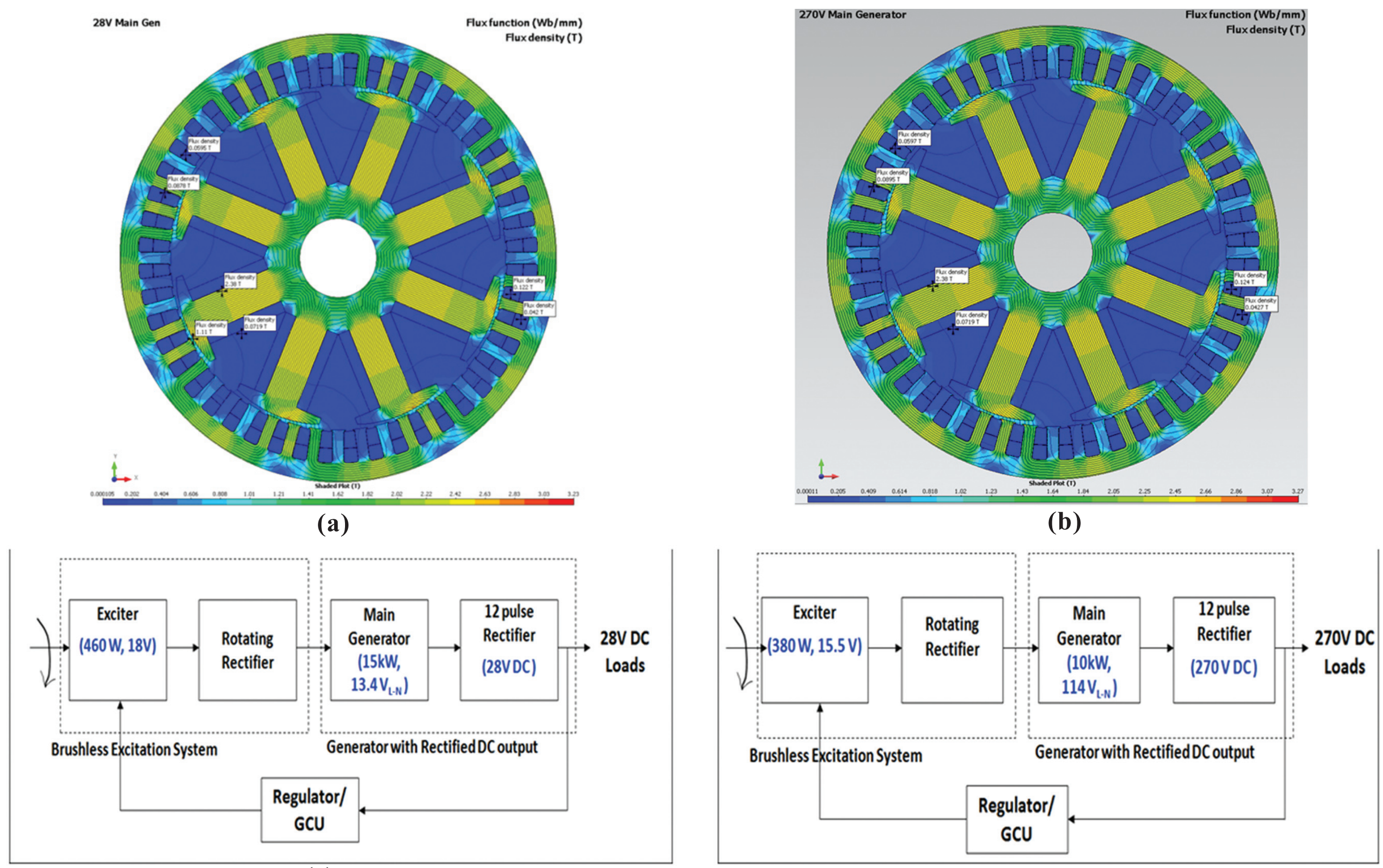

Figure 5. (a) Magnetic field plots for 28 V power stage at full load, (b) for 270 V power stage at full load, (c) Power stages in 28 V DC, and (d) Power stages in 270 V DC.

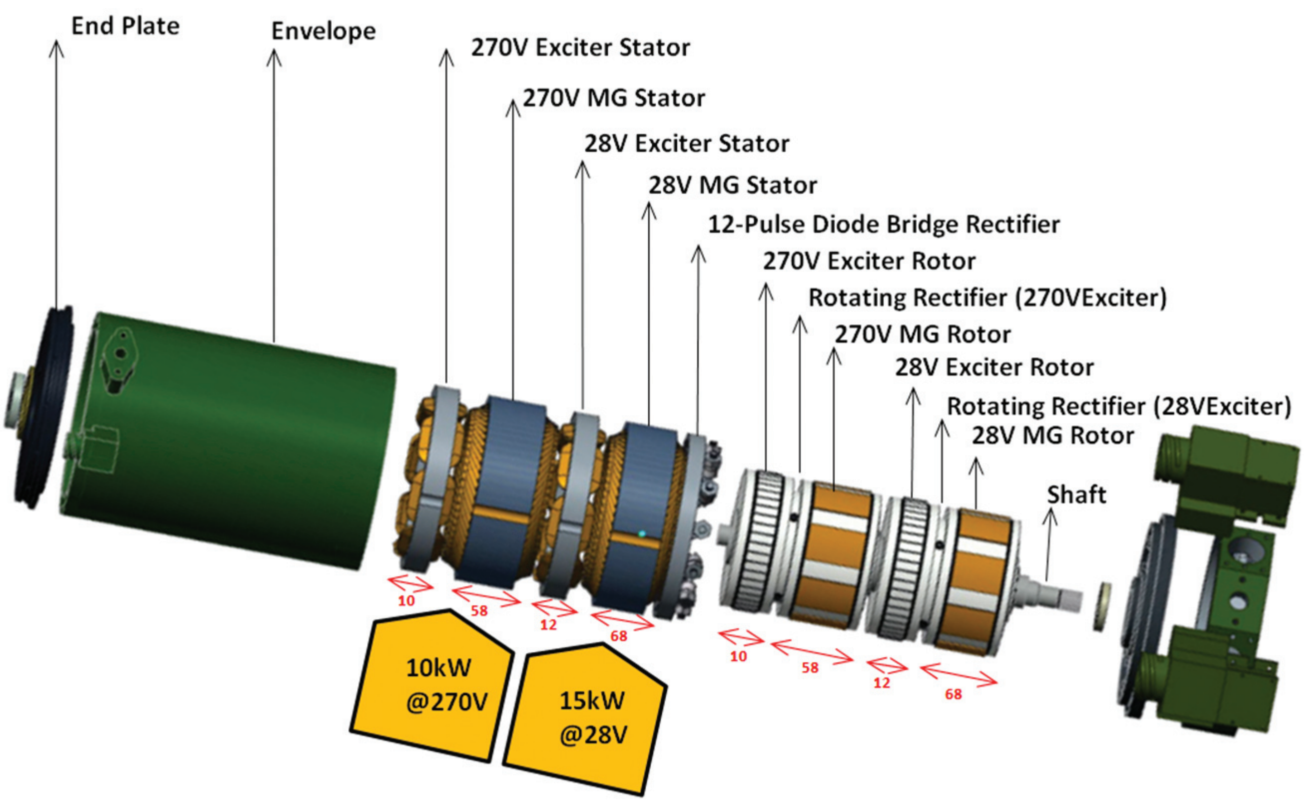

Figure 6. CREO model of dual voltage generator.

Table 6. Comparison of specifications and simulation outputs

	28 V Generator power stage		270 V Generator power stage	
	Specification	Simulation output	Specification	Simulation output
Output power (kW)	15	15.4	10	10.3
Output power of exciter (kW)	0.46	0.475	0.38	0.4

5. CONCLUSION

This research paper presents a comprehensive study on the design, simulation, and analysis of a sophisticated four-stage, single-frame Brushless Direct Current (bldc) generator. The main objective was to meet stringent specification requirements and optimise the design parameters across different load conditions. To ensure compliance with design specifications, a thorough harmonic analysis of the generator windings was performed. This analysis played a vital role in guaranteeing the desired performance characteristics. Additionally, the design process involved a detailed examination of the electrical performance and electromagnetic flux distribution within the generator. The accuracy of the design was verified by comparing the analytical results with those obtained from design software. The positive correlation between the two sources of data instilled confidence in the feasibility of constructing a prototype generator. Simulation techniques were instrumental in developing a highly detailed 3d model, which effectively addressed interconnectivity challenges among the four stages of the generator. This model serves as a solid foundation for future endeavours in realising a functional dual voltage generator. Overall, this research work contributes valuable insights into the design, simulation, and analysis of a complex bldc generator. The findings provide a stepping stone for advancing dual voltage generator technology and its applications in various fields.

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