A Data-Driven Study Based on Field Experience to Assess the Rated Voltage of Hydropower Generators

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***Abstract*-- The definition of the rated voltage of a hydropower generator is a difficult task that depends on several electrical, mechanical, and construction features. Naturally, the trade-off between influence variables must be solved to reach a minimum cost. This work contributes making a deep analysis of the most critical constraints and proposing an expedited formulation for defining the rated voltage of a generator based on successfully constructed generators deployed worldwide.**

***Index Terms*-- Hydrogenerator, modeling, efficiency, voltage.**

NOMENCLATURE

a	Number of parallel circuits of stator coils
A	Pole surface area (m²)
A_i	Linear current intensity (kA/m).
B	Flux density (Wb/m²)
c	Utilization factor
D	Stator bore and rotor diameter (m)
f	Frequency (Hz)
I	Rated current (kA)
I_a	Current in parallel circuits (kA)
J_b	Current density (A/mm²)
k_{ff}	Magnetic induction wave shape form factor
k_w	Winding factor
L	Stator and rotor length (m)
n	Rotational speed (r/min)
N_{ph}	Number of stator winding turns per phase
N_S	Number of coils per phase
p	Number of rotor poles
Q_s	Number of slots per phase
S	Rated power (MVA)
U	Rated voltage (kV)
V	Terminal voltage (kV)
α_i	Pole enclosure factor
β_{max}	Peak value of magnetic field (Wb/m²)
ϕ	Magnetic flux per pole (Wb)
τ_p	Coil pitch

I. INTRODUCTION

The specifications of a hydrogenerator regard rated values such as power, voltage, power factor, speed, mounting, cooling, protection, and others that, in short, are listed in the machine nameplate in accordance with [1]. The design of a hydrogenerator begins with defining key parameters related to the type of connected hydro turbine, frequency of the grid, number of poles, civil construction, power, power factor, and operation regime.

Considering all these variables, achieving an optimal solution becomes highly complex without analyzing additional parameters, including the stator bore's diameter, the stator slots' width and height, the air gap length, and the geometry of the poles [2-4]. On the other hand, requested performance requirements have continuously increased. Manufacturers and designers are constantly confronted with new requirements or new criteria for enhanced performances [5-7].

Within all the decision variables, voltage is the central variable because it directly affects, at different levels of dependence, all the others, including power, current, speed, insulation, number of slots, number of coils in each phase, and so forth.

The definition of rated voltage represents the optimal technical balance between the rated power and the number of parallel circuits. Furthermore, the flexibility in selecting the number of parallel circuits is intrinsically linked to the rated speed, as the number of parallel stator winding circuits is determined by the number of rotor poles, as outlined in (1) [7].

$$U \cong 4\, k_{ff}\, \alpha_i\, L\, f\, k_w\, N_{ph}\, \beta_{max} \left(\frac{\pi D}{2p}\right) \tag{1}$$

A high-rated voltage requires enhanced insulation and results in higher magnetic induction levels, increasing the design complexity and cost. In contrast, a low-rated voltage results in more parallel circuits, further complicating the design and driving up costs. Consequently, selecting a rated voltage that deviates substantially from the optimal value and leads to suboptimal performance, inefficient electromagnetic configurations, and increased manufacturing expenses.

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It is essential that the rated voltage be carefully determined by the manufacturer, ensuring that once the desired transmission voltage is achievable via high-voltage transformers, the rated voltage is chosen to optimize both technical performance and cost-efficiency in the machine's overall design.

II. Variables to Consider

Disregarding the existence of a gearbox, the speed of a hydrogenerators is defined by the hydro turbine, which, in turn, depends on the number of units in the hydropower plant, net head, suction height, and other factors. The speed of the generator shaft will define the number of pole pairs.

$$p = \frac{60\, f}{n} \tag{2}$$

The number of pole pairs dictates the mounting of the generator, if horizontal or vertical, regarding the shaft position, as shown in Fig. 1. Excepting hydrogenerators applied to pumped storage power plants, horizontal mounting is preferred for speeds from 3600 r/min down to about 300 r/min, as the generator would have a smaller diameter and a longer length. The reciprocal method occurs for speeds lower than 300 r/min, and vertical mounting is preferred. A valuable general equation shows generator power as a function of the Stator's bore diameter, length, and rotational speed:

$$S = c\, D^2 L\, n \tag{3}$$

The utilization factor ranges from 5 to 15, and it is a function of the relation between power and the number of poles of a generator. The value of the utilization factor has dramatically evolved, mainly due to the evolution of insulation materials, allowing the installation of a generator with more power in the same volume [9].

Despite (3) being a mechanical expression in nature, it is directly related to electrical power. The components of this equation can be written as [2-4]:

$$c = \frac{\pi^2}{\sqrt{2}}\, k_w\, A_i\, B, \tag{4}$$

The linear current intensity is:

$$A_i = \frac{I\, Q_s}{\pi\, D} = \frac{a\, I_a\, Q_s}{\pi\, D}. \tag{5}$$

The flux density is obtained through the pole magnetic flux. For a sinusoidal distribution of the induction, yields:

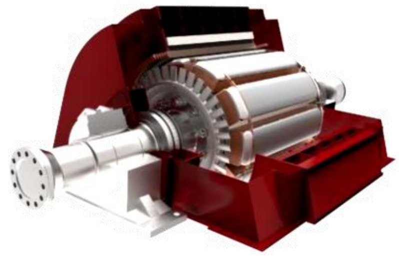
$$B = \frac{\emptyset\, p}{D\, L} \tag{6}$$

With simplifications, unit corrections, and for a given coil pitch, rearranging.

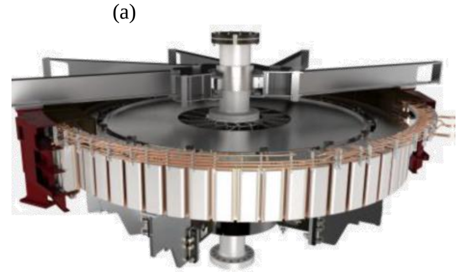
$$S = \frac{2\pi}{\sqrt{2}}\, f\, N_s \emptyset\, I \tag{7}$$

Which eventually is the power per phase:

$$S = U\, I \tag{8}$$



(a)



(b)

Figure 1. Hydrogenerators mounting, horizontal (a) applied to small hydro power plants, and vertical (b) applied to large hydropower plants, according to the shaft position.

The previous demonstration shows how the mechanical power and electrical power are intrinsically interconnected and interdependent in a generator design.

As stated before, defining the rated terminal voltage is a difficult task that results from a trade-off between several aspects of the machine design. Some of them are described below.

A. *The influence of current*

For a given terminal voltage, the higher the generator's power, the higher the current will be, as the current is directly proportional to the power and inversely proportional to the terminal voltage. The rated voltage, current, the number of parallel circuits in each armature phase, and the conductor current density limit are closely related.

In most hydrogenerators, the stator windings are star-connected, and the phase current is the same as the terminal current. Thus, the current in any given conductor is the phase current divided by the number of parallel circuits in that phase.

The higher the rated voltage, the lower the current, reducing the current density in the conductors. For optimal designs, it ranges from 2.5 to 4.5 A/mm² for air-cooled generators.

B. *The influence of speed*

The right-hand side of (4) is mechanical in nature, dimensions, and speed, and they are related to the left-hand side, the electric power. Therefore, the product voltage-current is also dependent on the rotational speed. A higher speed allows achieving a given power in a smaller volume, and the reciprocal is true.

The rotational speed directly influences the size of the excitation system, as the generated voltage is proportional to the magnetic flux variation. A higher speed allows the same voltage to be obtained with a smaller number of stator coils or a smaller excitation system than a low-speed generator.

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That is why it is easy to reach high voltage with a small excitation system in turbine generators that runs at 1800 or 3600 r/min, allowing the use of brushless excitation systems, while static excitation systems, with large currents, are used in hydrogenerators that run at a lower speed.

C. Efficiency constraints

The characteristics of silicon steel sheets are associated with the losses due to hysteresis and eddy currents. Using non-oriented grain with a thickness of 0.35 mm increases manufacturing and assembly costs. Thus, manufacturers have been opting for sheets with a thickness of 0.5 mm, with magnetic losses ranging from 2.3 to 2.9 W/kg at 1.5 T and 50 Hz.

The most common action to reduce the stator winding losses is to increase the cross-sectional area of the copper bars. However, this approach is associated with reducing the thickness of the insulating walls to avoid increasing the dimensions of the slots and, consequently, the iron losses [8].

It is worth noting that increasing the number of strands and their corresponding reduction in dimensions, although it reduces the skin effect, leads to higher manufacturing costs. Furthermore, the extra iron losses in the stator teeth and the rotor pole shoe losses can be reduced by appropriately selecting the number of slots, winding slot pitch, and air gap length.

D. The connection to the grid

A generator can be connected to the power system either directly or through a power transformer, depending on voltage requirements and system design.

If the generator is connected directly, its terminal voltage must match the power system voltage to ensure proper synchronization and stable operation. Any mismatch could lead to inefficiencies or system issues.

When a transformer is used, the generator can operate at any appropriate generation voltage. The transformer's turns ratio adjusts this voltage to match the power system level, providing more flexibility in generator design and integration, especially in high-voltage transmission systems.

E. The role of new materials

Despite the improved design of new materials and manufacturing processes that allow the reduction of insulating walls of winding coils while maintaining dielectric strength, the insulation system remains a significant challenge for designers and manufacturers [9-10].

Over the years, the thickness of the insulation walls of stator bars has decreased significantly. The replacement of asphaltic resins with mica, fiberglass, and epoxy-based vacuum pressure impregnation (VPI) process was a technological milestone and contributed to improving insulation performance.

Additionally, introducing epoxy into nanocomposites based on SiO_2, Al_2O_3, ZnO, and MgO has significantly improved the dielectric properties, thermal conductivity, and resistance to corona effects. This enables the design of machines with higher rated power and rated voltage while still using an air-cooling system.

III. State-Of-The-Art Evaluation

An extensive research was developed involving constructed and already installed hydrogenerators. Figure 2 presents the rated voltages of more than 300 generators above 1 MW, successfully constructed and deployed worldwide.

In Fig. 2, four groups can readily be identified, represented by different colors. The first group of small generators have rated powers varying from 1 to 5 MVA. The second group, ranging from 5 MVA to 60 MVA are classified as average power.

Generators from 60 MVA to 300 MVA are considered of high power and accomplishes the third group. The fourth group are composed by the very-high power generators, above 300 MVA to a 1111.11 MVA generator constructed and operating in China.

It has been noted that generators until 5 MVA may have a generation voltage of less than 6.9 kV, while generators from 5 MVA up to 50 MVA are typically connected at 10, 11, and 13.8 kV. Such voltages are compatible with the distribution system's voltage levels, and generators can be directly connected to the system or through a transformer.

For generators between 50 MVA and 300 MVA, the terminal voltages above 10 kV to 16 kV are commonly found. Nevertheless, beyond 300 MVA, the generators have terminal voltages used to be larger than 15 kV. The state-of-the-art points to a maximum voltage of 24 kV for an 1111.11 MVA generator.

The Fig. 2 shows a range of voltages for a same generator power. Of course, there is some flexibility when designing the machine, which may meet some technical constraints.

The variation in rated voltage for generators with the same rated power may occur either due to an indirect connection to the power system via a step-up transformer or due to the rated voltage of the power system in the case of a direct connection. The rated power system voltage in which the generator is connected may vary from country to country.

It can be observed in Fig. 2 that a large range of power, from 5 MVA to roughly 500 MVA, may have terminal voltage of 13.8 kV.

The majority of these generators are connected through transformers to high voltage transmission lines, and 13.8 kV is a kind of standardization of both generator terminal voltage and transformer primary winding voltage.

Based on the data provided in Fig. 2 and using statistical methods, an equation can be obtained to estimate the rated voltage generation as a function of the generator rated power can be obtained [11]:

$$V = 2.3\ [1 + \ln(S)] \tag{9}$$

Disregarding low-voltage generators, (9) is valid for power values ranging from 1 to 1100 MVA. Any rated voltage chosen above that obtained with the application of (9) would be of practical development and result in an optimal output current for the same rated power.

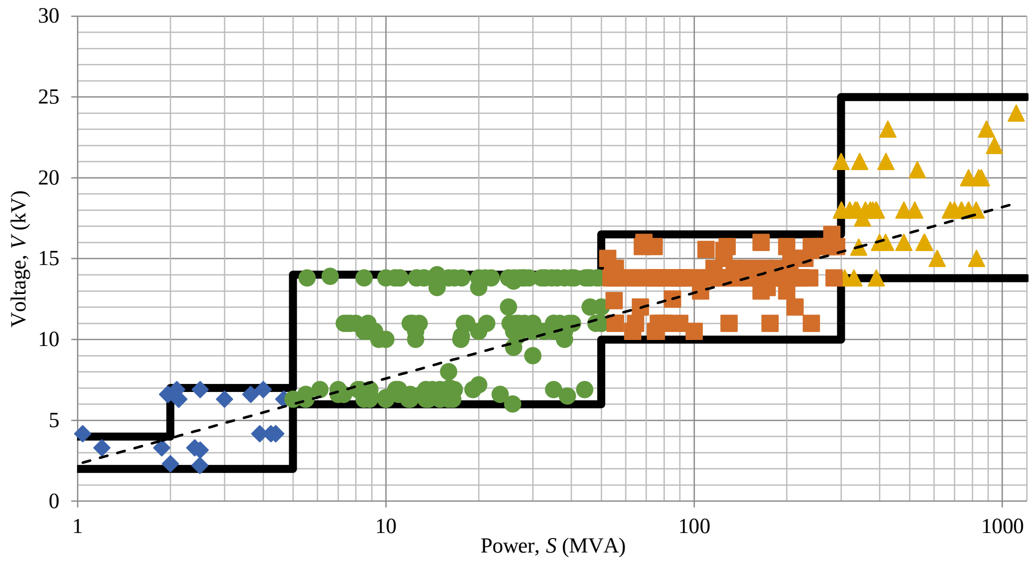

Figure 2. Rated voltage of more than 300 constructed hydrogenerators, including Bulb and high-speed generators.

IV. Application of the Derived Equation

The derived equation is simple to apply and accurately reflects the current state of the art in generator design. Its versatility allows it to be employed in a wide range of applications, from academic contexts, such as teaching in undergraduate and graduate electrical engineering courses, to practical scenarios involving the design of rotating electrical machines and the development of user-defined technical specifications.

One of the key strengths of this equation is its ability to assist in resolving the inherent trade-offs among the primary variables that influence the definition of a generator's rated voltage.

These variables include the terminal current, the thermal and dielectric properties required for conductor insulation, the rated speed (determined either by the number of rotor poles and the system frequency, or by the primary mover machine), and the connection topology, whether the generator is directly connected to the power grid or through a step-up transformer.

Consequently, the equation proves particularly useful in the preliminary design phase of electrical machines, including those applied in hydroelectric power generation systems.

Nearly two-thirds of the evaluated generators have rated terminal voltages exceeding the value derived (9), depicted in Fig. 3. This trend aligns with established engineering practices, as higher terminal voltages reduce current levels, thereby minimizing thermal stress and facilitating more efficient generator designs by addressing critical trade-offs in sizing.

Terminal current is a crucial design parameter, particularly in determining the number of parallel circuits per phase in the armature winding.

As rated terminal current increases, more parallel paths are required, leading to more complex winding configurations, and higher manufacturing costs, as a greater copper consumption is expected.

Using (9) to define terminal voltage automatically sets the terminal current based on the machine's rated power, as showed in Fig. 4.

It is worth noting that there are straight lines in the log-log representation relating the maximum rated current covering some ranges of rated power, that could be clearly seen in this figure.

This enables designers to estimate the required number of parallel conductors per phase, using known current density limits. Thus, the equation is a valuable tool for early design decisions, ensuring both feasibility and performance.

V. Conclusions

The selection of the rated voltage is a critical design decision. A low-rated voltage increases the armature current, more copper must be used and a higher number of parallel circuits is necessary to limit the current to the maximum current density of the conductors. On the other hand, a higher terminal voltage increases the insulation requirements, increases the rotor current and the excitation system robustness for a low speed lower than 300 r/min. Thus, selecting the appropriate rated voltage is a trade-off that must be solved involving a range of possible rated voltages, costs of copper, insulation materials, and the cooling system. Although there is no strict rule for determining the rated voltage of a generator, this work presented a suitable equation to be applied to this purpose, based on the state-of-the-arts of successfully deployed synchronous generators applied to hydropower plants worldwide, covering a large number, more than 300 units, covering diverse rated speeds and rated powers.

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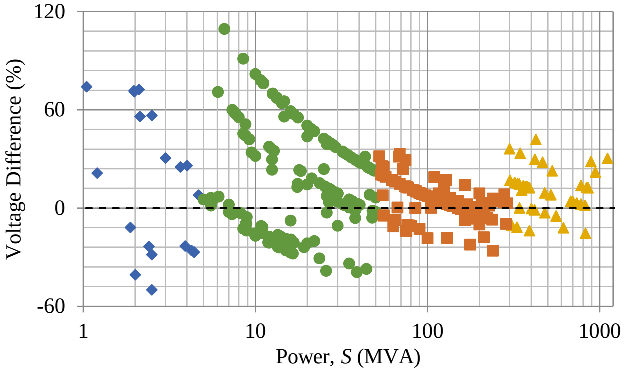

Figure 3. Percentage voltage difference between the declared nameplate rated terminal voltage and the value obtained using (9).

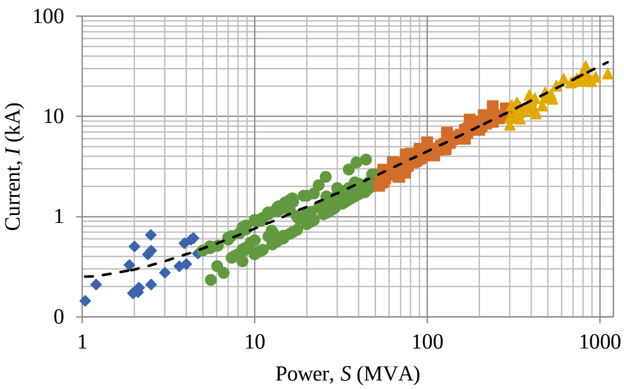

Figure 4. Percentage voltage difference between the declared nameplate rated terminal voltage and the value obtained using (9).

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