HYDROELECTRIC POWER PLANTS

Low-Voltage Nominal Voltages and Voltage Variations

ÍNDICE PÁG.

1 - OBJECTIVE

The objective of this document is to define the main nominal voltages of low-voltage alternating-current systems, motors, general loads, and control devices used in hydroelectric power plants and based on these definitions and their variations, analyze the various operating conditions and their consequences on the overall performance of the installation.

2 - REFERENCE DOCUMENTS

2.1 - Standards

The standards mentioned or used in the development of this work are listed below. Other standards, such as British Standards, define additional values that can be analyzed using the same criteria adopted in this document.

ABNT – Brazilian Association of Technical Standards

IEC - International Electrotechnical Commission

ANSI – American National Standards Institute

NEMA - National Electrical Manufacturers Association

NEC – National Electrical Code

2.2 - Technical Bulletins and Spreadsheets

IT.EL.SA.CA.03 Generation Voltage Calculation

IT.EL.SA.AC.01 Power Transformers – Terminal Voltage Calculation

PL.EL.SA.CA.06 Generation Voltage Calculation

PL.EL.SA.AC.01 Power Transformers – Terminal Voltage Calculation

3 - INITIAL CONSIDERATIONS

A hydroelectric power plant consists of many pieces of equipment and systems with specific characteristics and applications. However, it also includes equipment commonly found in other types of facilities, such as pumps, compressors, transformers, material handling equipment, fire protection systems, HVAC systems, and others.

Therefore, the concepts applied in these installations can also be applied to other facilities, with the appropriate adaptations.

The voltages at the plant high-voltage substation, interconnected with the Brazilian Interconnected Power System (SIN), shall comply with ANEEL requirements. Voltage variations in medium- and low-voltage systems that do not supply energy to external consumers shall meet the requirements of the internal loads.

For example, voltages in medium-voltage systems are not necessarily required to comply with ANEEL voltage ranges, and voltage drops in feeders do not necessarily need to comply with standard limits, provided that the operation and integrity of the connected loads are not compromised.

When analyzing the behavior of a system, the worst operating conditions and the most unfavorable conditions of all equipment should not be considered simultaneously, as this may lead to the conclusion that any project is unfeasible. Nevertheless, means shall be provided to solve or mitigate possible problems.

In this document, a fictitious hydroelectric power plant is used as an example to simulate the actual steps required for system definition and operating conditions, as well as the alternatives that may be adopted by the engineer responsible for the study.

The spreadsheet associated with Technical Bulletin TE.EL.SA.CA.03 – Generation Voltage Calculation is extremely useful for evaluating alternatives, especially because, during the initial stages of a new project or refurbishment, it is often difficult to obtain operating voltage information for a plant whose characteristics have not yet been fully defined.

4 - NOMINAL VOLTAGES

The selection of nominal voltages for systems and components depends on local standards and regulations, customer requirements, installed equipment, and manufacturers available in the market.

Since this document focuses mainly on low-voltage systems in hydroelectric power plants, the voltage levels discussed will be those commonly used in such facilities. The concepts and evaluations presented are also applicable to other installations, particularly industrial plants.

Unlike some European countries and the United States, Brazil does not have a fully standardized set of nominal voltages for systems and equipment. Therefore, nominal voltages should be selected based on internationally recognized standards.

4.1 - Low-Voltage System Nominal Voltages

The nominal voltage of low-voltage systems shall be either 400 V or 480 V. In this document, a nominal system voltage of 480 V will be considered.

Existing systems with nominal voltages of 380 V and 440 V should, whenever possible, be converted to 400 V and 480 V, respectively. Motors and components can generally operate with these new voltage levels, provided that the overall system behavior is analyzed and any necessary adjustments are made.

It should be noted that the system frequency in Brazil is 60 Hz, as in the United States, whereas in Europe it is generally 50 Hz. The conversion from 50 Hz to 60 Hz in Brazil occurred during the 1960s and 1970s.

4.2 - General Load Nominal Voltages

General loads, except those consisting exclusively of motors, usually include transformers, heating systems, ventilation systems, air-conditioning systems, material handling equipment, and motors.

The nominal voltage of these loads shall be 400 V or 480 V, depending on the system nominal voltage. In this document, a nominal voltage of 480 V will be adopted.

4.3 - Motor Nominal Voltages

The nominal voltage of motors shall be 380 V for 400 V systems and 460 V for 480 V systems. In this document, a nominal motor voltage of 460 V will be considered.

In both existing and new installations, motors rated at 440 V may continue operating in 480 V systems. Whenever appropriate, they may be replaced with 460 V motors. Motors rated at 380 V do not need replacement because their nominal voltage is already suitable.

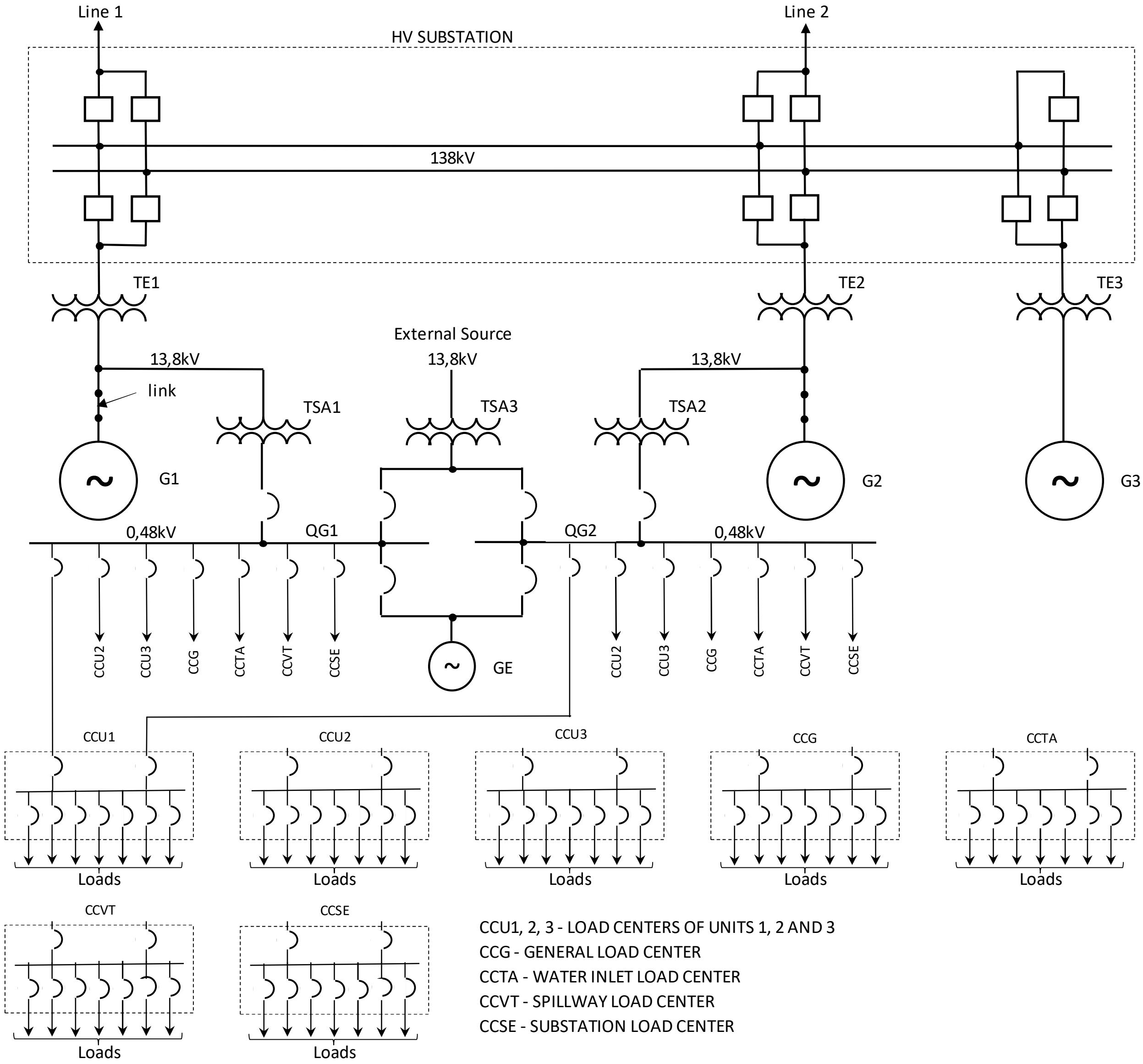
4.4 - Control Transformers and Control Devices

For 400 V systems, control transformers shall have a 400/115 V ratio, and control devices shall have a nominal voltage of 115 V.

For 480 V systems, control transformers shall have a 480/120 V ratio, and control devices may have nominal voltages of either 120 V or 115 V, depending on the considerations adopted and the results obtained.

5 - POWER PLANT ALTERNATING CURRENT SYSTEM

The basic configuration of the electrical system of a hydroelectric power plant can be represented by the single-line diagram shown below.



The generating units (G1, G2 and G3) produce the energy that is transmitted to the National Interconnected System (SIN) through the step-up transformers (TE1, TE2 and TE3) and the high-voltage substation.

The generating units also supply the energy required by the plant low-voltage electrical installations. In the example considered, two units (G1 and G2) are responsible for this supply through the auxiliary service transformers TSA1 and TSA2.

The high-voltage substation may also supply the low-voltage installations through the step-up transformers TE1 and TE2 and the auxiliary service transformers TSA1 and TSA2, disconnecting the generator link(s) from the corresponding unit(s). This arrangement is normally used when one or more generating units remain out of service for an extended maintenance period.

An external source may also supply the low-voltage installations through auxiliary service transformer TSA3.

To facilitate understanding of the analyses presented in this document, the following equipment characteristics will be considered.

5.1.1 - High-Voltage Substation

In Brazil, the operating voltage limits of a 138 kV substation are established by ANEEL and may be classified as adequate, precarious or critical.

Tabela 2 – Pontos de conexão em Tensão Nominal igual ou superior a 69 kV e inferior a 230 kV

Tensão de Atendimento (TA)	Faixa de Variação da Tensão de Leitura (TL) em Relação à Tensão de Referência (TR)
Adequada	0,95TR≤TL≤1,05TR
Precária	0,90TR≤TL<0,95TR ou 1,05TR<TL≤1,07TR
Crítica	TL<0,90TR ou TL>1,07TR

IEC 61000-3 recommends that the reference voltage be defined as the nominal system voltage.

For this study, the 138 kV substation voltage will be considered within the adequate range, from 95% to 105% of the nominal voltage, corresponding to 131.1 kV to 144.9 kV. If the voltage falls within the precarious or critical range and affects plant operation, the engineer may select another tap position on the primary winding of the step-up transformer to perform the necessary adjustments.

5.1.2 - Generating Units G1, G2 and G3

Nominal Voltage: 13.8 kV

Rated Power: 100 MVA

Generated Power and Power Factor: 100 MVA at 0.95 PF

5.1.3 - Step-Up Transformers TE1, TE2 and TE3

Rated Power: 100 MVA

Voltage Ratio: 13.8 / 138 (±2 × 2.5%) kV

Impedance: 10%

Resistance: Transformer resistance will be considered equal to 1%.

The tap position of the 138 kV winding is defined by plant operation and depends on system conditions. However, if this information is unavailable, simulations may be performed to evaluate the various possibilities and assist in defining the auxiliary low-voltage system.

5.1.4 - Auxiliary Service Transformers TSA1, TSA2 and TSA3

Rated Power: 1000 kVA

Voltage Ratio: 13.8 (±2 × 2.5%) / 0.48 kV

Impedance: 6%

Resistance: Transformer resistance will be considered equal to 1%.

Normal Constant Load and Power Factor: 460 V, 300 kVA, PF = 0.85

Maximum Constant Load and Power Factor: 460 V, 600 kVA, PF = 0.85

Normal Variable Load and Power Factor: 480 V, 75 kVA, PF = 0.90

Maximum Variable Load and Power Factor: 480 V, 150 kVA, PF = 0.90

Note: The AC system is redundant. Under normal conditions, each auxiliary service transformer supplies approximately half of the plant load but has sufficient capacity to supply the entire load. The normal load corresponds to both transformers operating simultaneously, whereas the maximum load corresponds to operation with only one transformer in service.

For the purposes of this document, constant loads are understood to be those consisting primarily of motors, while variable loads represent all other loads.

5.1.5 - External 13.8 kV Source

The external 13.8 kV source may originate either from a transformer connected to the high-voltage substation or from a utility company. For this study, it will be assumed that the source is supplied directly by the utility. Therefore, its voltage shall comply with the ANEEL limits established for the 13.8 kV system.

The source voltage will be considered within the adequate range, corresponding to 93% to 105% of nominal voltage.

Tabela 3 – Pontos de conexão em Tensão Nominal superior a 1 kV e inferior a 69 kV

Tensão de Atendimento (TA)	Faixa de Variação da Tensão de Leitura (TL) em Relação à Tensão de Referência (TR)
Adequada	0,93TR≤TL≤1,05TR
Precária	0,90TR≤TL<0,93TR
Crítica	TL<0,90TR ou TL>1,05TR

Thus, the external source voltage may vary between 12.834 kV and 14.49 kV.

5.1.6 - Emergency Diesel Generator Set

Although the emergency diesel generator set is also one of the power sources for the plant low-voltage system, it is not included within the scope of this document because it represents a regulated voltage source that requires specific evaluation and selection criteria. Its nominal voltage shall be 480 V.

6 - GENERATOR TERMINAL VOLTAGES

Using the spreadsheet PL.EL.SA.CA.06, Generation Voltage Calculation, referenced in the documents, simulations of the voltage at the generating units can be performed considering the following conditions:

- High-voltage substation voltage varying between the minimum and maximum nominal limits (131.1 kV to 144.9 kV);
- Generating units operating at rated power and rated power factor;
- 138 kV winding tap position equal to 1.00;
- 138 kV winding tap position equal to 1.025.

Under these conditions, the following results are obtained:

Generators Units - Voltage				
Minimum/Maximum Voltage at the HV Substation (kV)	131,1		144,9	
Power Supplied by G1/G2 - FP	100MVA - FP 0,95		100MVA - FP 0,95	
TE1/TE2 Tap	1,00	1,025	1,00	1,025
Voltage in G1/G2 (kV)	**13,76**	**13,46**	**15,07**	**14,73**

For tap position 1.00, generator terminal voltages vary between 13.76 kV and 15.07 kV.

For tap position 1.025, generator terminal voltages vary between 13.46 kV and 14.73 kV.

Both ranges are within acceptable operating limits for the generating units.

The engineer may perform additional simulations using other transformer tap positions and operating voltages to select the configuration best suited to the plant requirements.

For this document, tap position 1.00 will be adopted.

The resulting voltage range in the 13.8 kV system will be between 99.71% and 109.20% of nominal voltage.

Although these values differ from the voltage limits defined by ANEEL, this is not a utility connection point and therefore those restrictions do not apply.

7 - LOW-VOLTAGE SYSTEM VOLTAGES

The voltage at the secondary terminals of the auxiliary service transformers depends on the power source and the operating conditions of the installation. The low-voltage system may be supplied by generating units G1 and G2, by the high-voltage substation through transformers TE1 and TE2, or by the external source.

As can be seen, by selecting the tap positions of the step-up transformers and auxiliary service transformers, the low-voltage system voltage can be adjusted. The objective is to prevent the maximum equipment voltage from being exceeded. The maximum system voltage should be limited to 110% of nominal voltage, i.e., 528 V for a 480 V system.

For motors, it should be considered that, with the practices adopted to mitigate possible problems, they may be subjected to voltages above or below those normally specified in standards. These practices include specifying motors designed for Class B insulation but manufactured with Class F materials and selecting a service factor greater than 1.00.

Potential overvoltage and undervoltage effects on motors are summarized in the table obtained from the book *Motors Application and Maintenance Handbook* by Robert W. Smeaton.

General Efect of Voltage Variation on Induction-motor Characteristics				
Characteristics		Voltage variation		
		120% voltage	110% voltage	90% voltage
Starting and max running torque		Increase 44%	Increase 21%	Decrease 19%
Sychronous Speed		No change	No change	No change
% slip		Decrease 30%	Decrease 17%	Increase 23%
Full-load speed		Increase 1,5%	Increase 1%	Decrease 114%
Eficiency	Ful load	Small Decrease	Increase 0,5-1% point	Decrease 2 points
	3/4 load	Decrease 0,5-2 points	Practically no change	Practically no change
	1/2 load	Decrease 7-20 points	Decrease 1-2 points	Increase 1-2 points
Power factor	Ful load	Decrease 5-15 points	Decrease 3 points	Increase 1 point
	3/4 load	Decrease 10-30 points	Decrease 4 points	Increase 2-3 points
	1/2 load	Decrease 15-40 points	Decrease 5-6 points	Increase 4-5 points
Full-load current		Decrease 11%	Decrease 7%	Increase 11%
Starting current		Increase 25%	Increase 10-12%	Decrease 10-12%
Temperature rise full load		Decrease 5-6°C	Decrease 3-4°C	Increase 6-7 °C
Max overload capacity		Increase 44%	Increase 21%	Decrease 19%
Magnetic noise - no load in particular		Noticealble Increase	Increase slightly	Decrease slightly

It can be stated that both undervoltage and overvoltage can be tolerated in most cases, including 440 V motors that are often retained during hydroelectric plant refurbishments.

7.1 - Generating Units as the Power Source

Considering that the high-voltage substation (138kV) voltage is in the range of 131.1kV to 144.9kV, that the generating units operate at nominal power and power factor, that the step-up transformers are in tap 1.00, and that the auxiliary service transformers TSA1 and TSA2 are in tap 1.00, using the spreadsheets related in the reference documents, for the estimated load conditions, we have:

Voltage on the Secondary of TSA 1 and TSA2 - Power Supply for Generator Units						
Minimum/Maximum Voltage at the HV Substation (kV)	131,1			144,9		
Power Supplied by G1/G2 -FP	100MVA - FP 0,95					
TE1/TE2 Tap	1					
Voltage in G1/G2 (kV)	**13,76**			**15,07**		
TSA1/TSA2 Tap	1					
Constant Load 460V, PF 0.85 (MVA)	0	300	600	0	300	600
Variable Load 480V, PF 0.90 (MVA)	0	75	150	0	75	150
Voltage on the TSA1/TSA2 Secondary (V)	**478,61**	**471,49**	**464,08**	**524,17**	**517,47**	**510,53**

The minimum voltage on the secondary side of transformers TSA1 and TSA2 will be between 464.08V and the maximum 524.17V, which correspond, respectively, to 100.89% and 113.95% of the nominal voltage of the motors and between 96.68% and 109.92% of the nominal voltage of the general loads and the system.

The normal operating condition of the plant occurs when the low-voltage installations are supplied by the generating units, through the two auxiliary service transformers. The normal voltage of the low-voltage installations will depend on the voltage value at the high-voltage substation and will be between 471.49V and 517.47V, which correspond, respectively, to 102.50% and 111.41% of the nominal voltage of motors and between 98.23% and 107.81% of the nominal voltage of the general loads and the system.

7.2 - High-Voltage Substation as the Power Source

When the low-voltage system power source is the HV substation, considering that the high-voltage substation voltage (138kV) is in the range of 131.1kV to 144.9kV, that the step-up transformers are on tap 1.00, and that the auxiliary service transformers TSA1 and TSA2 are on tap 1.00, 0.975, or 0.95.

For these calculations, use the spreadsheet PL.EL.SA.AC.01 Power Transformers - Terminal Voltage Calculation, related in reference documents, considering that for the step-up transformers, the primary nominal voltage is that of the high-voltage side (138kV). For the estimated load conditions, we have:

Voltage on the Secondary of TSA 1 and TSA2 - High Voltage Substation Power Supply						
Minimum/Maximum Voltage at the HV Substation (kV)	131,1			144,9		
TE1/TE2 Tap	1					
Constant Load on TE1/TE2 460V, FP 0.85 (MVA)	0	300	600	0	300	600
Variable Load 480V, PF 0.90 (MVA)	0	75	150	0	75	150
Voltage on the 13.8kV side of TE1/TE2 (kV)	**13,11**	**12,68**	**12,24**	**14,40**	**13,93**	**13,45**
TSA1/TSA2 Tap	1					
Constant Load on TE1/TE2 460V, FP 0.85 (MVA)	0	300	600	0	300	600
Variable Load 480V, PF 0.90 (MVA)	0	75	150	0	75	150
Voltage on the TSA1/TSA2 Secondary (V)	**456,00**	**433,44**	**410,00**	**500,87**	**477,34**	**453,07**
TSA1/TSA2 Tap	0,975					
Constant Load on TE1/TE2 460V, FP 0.85 (MVA)	0	300	600	0	300	600
Variable Load 480V, PF 0.90 (MVA)	0	75	150	0	75	150
Voltage on the TSA1/TSA2 Secondary (V)	**467,69**	**445,32**	**421,88**	**513,71**	**490,35**	**466,06**
TSA1/TSA2 Tap	0,95					
Constant Load on TE1/TE2 460V, FP 0.85 (MVA)	0	300	600	0	300	600
Variable Load 480V, PF 0.90 (MVA)	0	75	150	0	75	150
Voltage on the TSA1/TSA2 Secondary (V)	**480,00**	**457,65**	**434,60**	**527,23**	**503,74**	**479,67**

The tap position that closely approximates the supply voltages from the generating units is 0.95. The minimum voltage will be 434.60V and the maximum 527.23V, which correspond, respectively, to 94.48% and 114.62% of the nominal voltage of the motors and 90.54% and 109.84% of the nominal voltage of the general loads and the system.

This operating condition can be foreseen in the case where one of the generating units, G1 or G2, remains under maintenance for a long period, and the external source does not exist or is unavailable. In these cases, the corresponding auxiliary service transformer will operate with the other, from the other unit, at 50% of the load. The voltage of the low-voltage installations will depend on the voltage value at the high-voltage substation, and will be between 457.65 and 503.74V, which corresponds, respectively, to 99.49% and 109.40% of the nominal voltage of the motors and between 95.34% and 104.95% of the nominal voltage of the general loads and the system.

7.3 - External Source as the Power Supply

When the low-voltage system power supply is an External Source, considering that the source voltage is within the appropriate range of 93 to 105% of the nominal voltage, i.e., between 12.834kV and 14.49kV, as defined by ANEEL, and that the auxiliary services transformer TSA3 is in tap 1.00, 0.975 or 0.95, using the spreadsheet PL.EL.SA.AC.01 Power Transformers - Terminal Voltage Calculation, related in the reference documents, for the estimated load conditions, we have:

Voltage on the TSA3 Secondary - External Power Supply						
Tensão Mínima/Máxima na Fonte (kV)	**12,834**			**14,49**		
TSA3 Tap	1			1		
Constant Load on TE1/TE2 460V, FP 0.85 (MVA)	0	300	600	0	300	600
Variable Load 480V, PF 0.90 (MVA)	0	75	150	0	75	150
Voltage on the TSA3 Secondary (V)	**446,40**	**438,92**	**431,08**	**504,00**	**497,12**	**489,99**
TSA3 Tap	0,975			0,975		
Constant Load on TE1/TE2 460V, FP 0.85 (MVA)	0	300	600	0	300	600
Variable Load 480V, PF 0.90 (MVA)	0	75	150	0	75	150
Voltage on the TSA3 Secondary (V)	**482,59**	**450,88**	**443,60**	**516,92**	**510,50**	**503,85**
TSA3 Tap	0,95			0,95		
Constant Load on TE1/TE2 460V, FP 0.85 (MVA)	0	300	600	0	300	600
Variable Load 480V, PF 0.90 (MVA)	0	75	150	0	75	150
Voltage on the TSA3 Secondary (V)	**469,89**	**463,40**	**456,66**	**530,53**	**524,53**	**518,35**

The derivation that closely approximates the supply voltages from the generating units is 0.95. The minimum voltage will be 456.66V and the maximum 530.53V, which correspond, respectively, to 99.27% and 115.33% of the nominal voltage of the motors and 95.14% and 110.53% of the nominal voltage of the general loads and the system.

This condition occurs if one or both generating units, G1/G2, remain under maintenance for an extended period. In these cases, the corresponding auxiliary service transformer TSA3 will operate with the other transformer, from the other unit in operation, at 50% of the load. The voltage of low-voltage installations will depend on the value of the external source voltage, and will be between 463.40 and 524.53V, which correspond, respectively, to 100.74% and 114.03% of the nominal voltage of the motors and between 96.54% and 109.28% of the nominal voltage of the general loads and the system.

This condition may also occur in cases where the units stop, for example due to a system instability problem and the emergency diesel generator is unavailable.

7.4 - Summary of the Evaluated Voltages

Maximum voltages generally occur when transformers are unloaded. Therefore, with the selections adopted, the occurrence of overvoltage in low-voltage systems becomes highly unlikely.

The summary of the minimum, normal, and maximum voltage limits for the selected conditions is shown in the following table:

Power supply	Minimum Voltage (V)	Normal Voltage (V)	Maximum Voltage (V)
Generating Units	464,08	471,49-517,47	524,17
HV Substation	434,60	457,65-503,74	527,23
External Source	456,66	463,40-524,53	530,53

The assessment of the operational possibilities of the low-voltage system of the power plant under consideration allows for a range of alternatives that can be explored by the responsible professional. In this case, the only restriction made was to avoid overvoltage. On the other hand, avoiding overvoltage implies admitting undervoltage that must be analyzed and, when necessary, mitigated with punctual interventions to avoid major problems.

Under normal operating conditions, the low-voltage system is powered by generating units G1 and G2, and the operating voltage will oscillate between 471.49 and 517.47V, depending on the voltage at the high-voltage substation and the tap used in the step-up transformers TE1 and TE2 and auxiliary service transformers TSA1 and TSA2. The other possibilities are contingencies that may occur, but they are temporary conditions.

Minimum voltages in low-voltage systems can occur in cases of minimum voltages at the power sources and, simultaneously, maximum loads on the installations. During the operation of new or renovated facilities, adjustments can be made to improve the operating conditions of the systems.

New products that emerge on the market and updates to standards should be considered in the development of projects. Reducing equipment costs and using new techniques should be part of the definition of the facilities and, whenever possible, be applied to the installations.

8 - LOAD VOLTAGES

The voltage across the loads will depend on the voltage at the low-voltage power supplies, the system configuration, and the feeder circuits involved. In the case considered, the loads are fed directly by specific installation panels, which in turn are fed by general panels that, due to the low-voltage system configuration, are located close to the auxiliary service transformers.

Since low-voltage system configurations can vary depending on the dimensions of the powerhouse, the number and power of the units, as well as other factors not considered here, general considerations will be made that apply to the conditions of any configuration.

8.1 - Voltage Drop Limits

Standards typically define voltage drop limits in circuits, depending on their purpose and the operating conditions of the loads. However, the important thing is that, regardless of these limits, starting from the source voltage, the voltage at the load meets its operating conditions. As an example, we can cite the NBR 5410 standard, which defines that:

"6.2.7.1 At any point of use in the installation, the voltage drop must not exceed the following values, given in relation to the nominal voltage of the installation:
6.2.7.1 a) 7%, calculated from the secondary terminals of the MV/LV transformer, in the case of a transformer owned by the consumer unit(s);"

For hydroelectric plants, the maximum voltage drop from the secondary terminals of the MV/LV transformer to the load should be 7% of the system's nominal voltage. However, in hydroelectric plants, the Medium-Voltage/Low-Voltage transformer are, most of the time, directly fed by the plant's generators. The plant's generators also have a limiting operating range, generally ±10%, and even when operating within a smaller range, for example, +8%, -5%, the voltage drop in the MV/LV transformer itself and circuit components, such as switchboards and cables, must still be considered. Therefore, this 7% limit can be unintentionally respected, but it should not be a rigid limitation.

For Load Centers of specific installations, which are close to the General Load Centers, it is not necessary to limit the voltage drop in their feeders because, due to the sizing based on current carrying capacity and circuit length, the voltage drop is usually low. Situations are frequently encountered where, to slightly reduce the voltage drop in a feeder, the nominal cable cross-section must be so large that it is sometimes not even possible to connect it to the load. Examples include motors, which have junction boxes with limited dimensions. In these cases, attempts should be made to reduce the voltage drop in other feeders.

Note that when the low-voltage system is supplied by the HV Substation, a minimum voltage of 434.60V was calculated for the worst operating conditions, i.e., minimum voltage at the substation and maximum load on the auxiliary service transformers. This calculation also considered that the resistance of the step-up transformer is 1%, when this value can be much lower as it depends on the power and temperature of the transformer, which in turn depends on the load. The values of the transformer resistances, when not available, can be obtained using the X/R ratio in the figure below, which for the 100MVA step-up transformer is approximately 0.27%, considering X/R equal to 38.

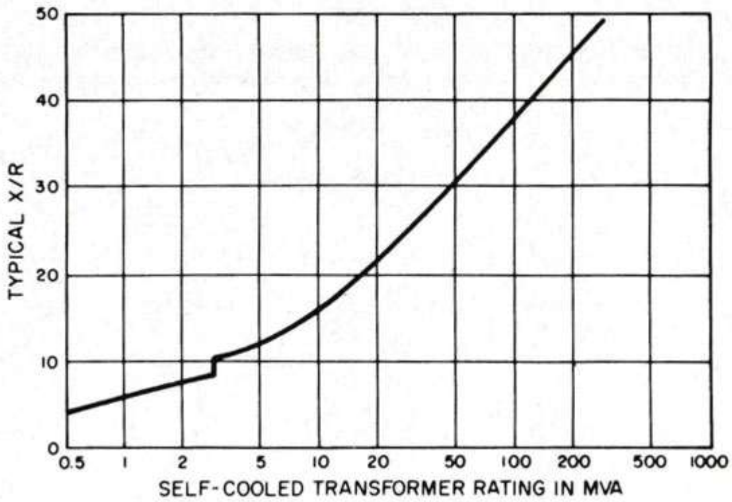


Fig N1.1
***X/R* Ratio of Transformers (Based on ANSI/IEEE C37.010-1979**

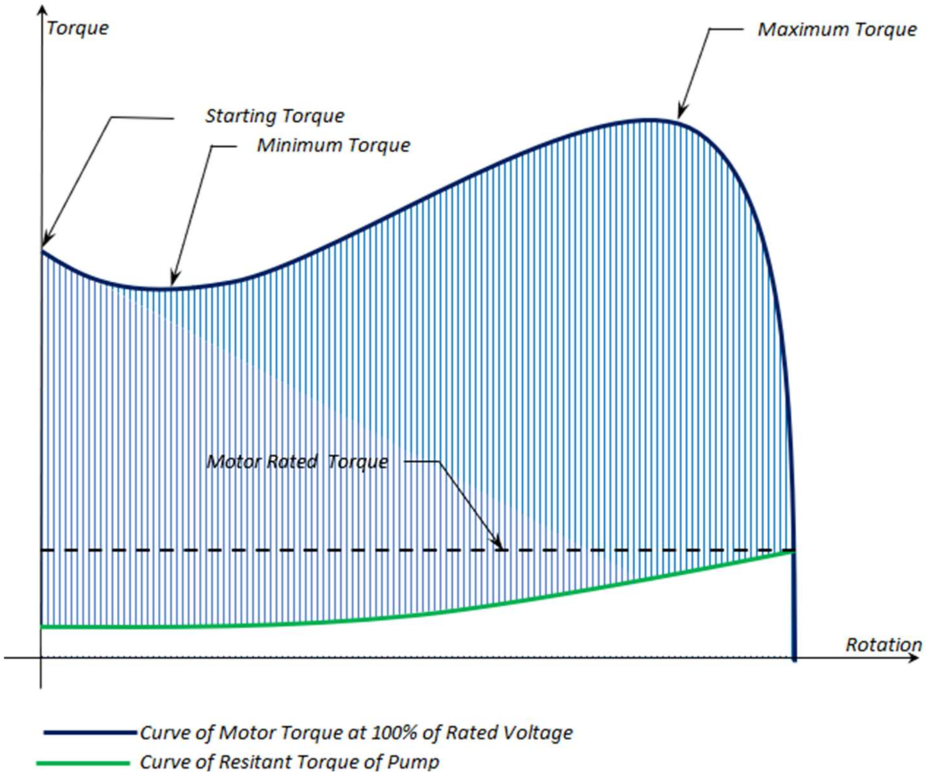
These considerations, like many others, can be made by professionals to address specific situations, but it is not necessary to adopt them generally.

8.2 - Measures to Mitigate Undervoltage

8.2.1 - Motors

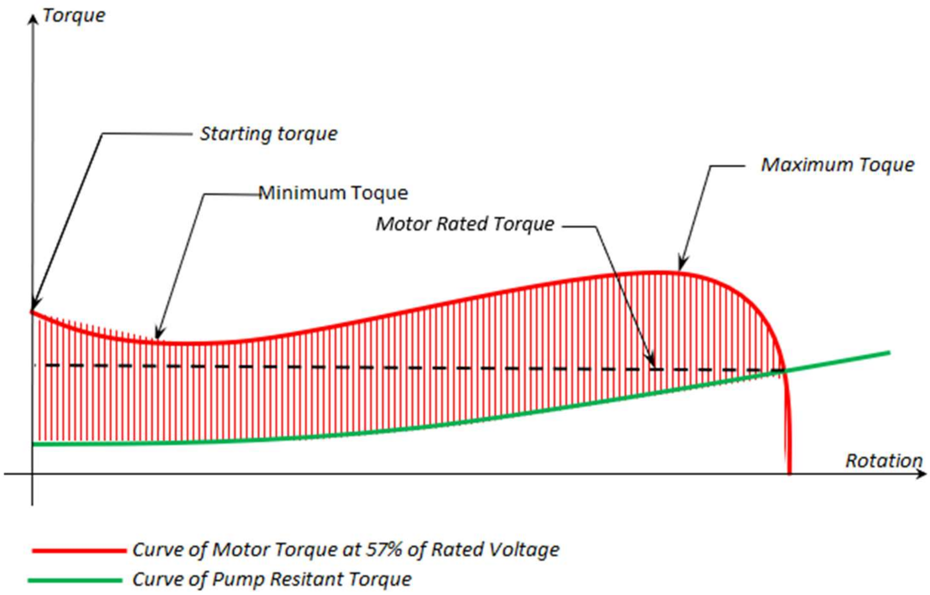
Direct starting at full voltage for induction motors is currently the most widely used method in hydroelectric power plant installations.

The figure below shows the torque vs. speed curves of the motor and the load torque, with 100% of the nominal voltage applied. The shaded area represents the acceleration torque that defines the starting time of the assembly.



The curve is typical for motors driving pumps and compressors.

The figure below shows the motor torque curve during star-delta starting, where 57% of the nominal voltage is applied, and the curve of the load's resistive torque.



As can be seen, the starting of pump and compressor motors can be done with voltages lower than those defined by the standards, provided that the motor starts within a certain time and the resulting voltage drop does not affect the operation of its control and other system loads.

The star-delta starting of motors is done by reducing the voltage at startup, that is, instead of starting the motor with 100% of the nominal voltage, it starts with 57.73% (phase-to-neutral voltage instead of phase-to-phase), which reduces the motor's starting current and consequently the voltage drop in the feeders and control circuits, but also reduces the motor torque to 33% of the nominal torque.

The shaded area represents the acceleration torque of the assembly. In the case of star-delta starting, when the rotation reaches approximately 90% of the nominal rotation, the connection is switched from star to delta, as the starting current is significantly reduced. Note that the motor could operate with reduced voltage (star connection), but the operating current, with a voltage of 57% of the nominal voltage, would be 175% of the nominal current, and the motor would suffer excessive heating.

With the emergence of new technologies and cost reduction, soft starters and frequency inverters can replace direct starting systems with systems that, in addition to reducing the cross-sections of the feeder cables, reduce voltage drops in motors with high starting currents.

In soft starters, the operation is like star-delta starting. Soft starters are adjusted to apply an initial voltage that overcomes the inertia of the load and increases the value of this voltage linearly until it reaches the nominal voltage. In this way, the motor has a faster and smoother start, reducing the starting current of the motors and, consequently, voltage drop in the feeders. Soft starters also have the advantage of protecting motors and monitoring various parameters.

8.2.2 - Transformers and Control Devices

Currently, control transformers with a wide variety of primary and secondary voltages are available on the market, such as 440/460/480-110/115/120V. Additionally, transformers with 2 x ±2.5% taps can be specified for spot voltage corrections.

Therefore, in principle, the choice of the most suitable nominal voltage is made based on the maximum voltage of the low-voltage system and the control and command devices, to prevent them from being damaged.

The nominal voltage of the coils of contactors, auxiliary relays, etc. may be 115 or 120V.

For the defined settings, it will be impossible for overvoltage to occur in the equipment and components, except for motors for which evaluations and recommendations have been made.

Contactors and relays have a pick-up and drop-out voltage of 85 and 70%, respectively, which may be lower depending on the manufacturer.

If the components still do not meet the voltage drop criteria, DC control components may be used.

9 - CONCLUSIONS

The conclusions presented in this document correspond to a specific set of assumptions adopted for supply voltages, load types, and transformer taps, as defined in the tables used. The objective of the study is not to exhaust all possible system configurations, but to provide technical support for the evaluation of design alternatives, with the responsible professional being responsible for analyzing other combinations when necessary.

Since there are many variables that can be applied and explored by the professionals responsible for the projects, there is no fixed rule for defining all the system variables. However, the documents TE.EL.SA.CA.03 Generation Voltage Calculation and PL.EL.SA.CA.06 Generation Voltage Calculation, associated with TE.EL.SA.AC.01 Power Transformers - Terminal Voltage Calculation and PL.EL.SA.AC.01 Power Transformers - Terminal Voltage Calculation are very useful tools to help with the task.

The remaining information provides supporting data that allows for the study of alternatives, bearing in mind that the personnel responsible for the operation and maintenance of the facilities can adopt practices to resolve, even if temporarily, any problems with system voltages. These alternatives include the use of other taps for step-up transformers, auxiliary services, and control systems.