RATED VOLTAGES AND VOLTAGE VARIATIONS

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1 - PURPOSE

In Brazil, defining the rated voltages of the system and equipment is a problem that always arises when a project is started. This occurs because there are no norms or standardizations in Brazil that define these voltages. Therefore, the purpose of this technical information is to approach this subject so that the user has more information to make their decisions and arguments to present to the client.

Another subject that will be the object of this technical information are the problems of voltage variations in loads, due to voltage variations in the sources and drop voltage in the circuits involved. In this analysis, the applicable rules and permissible limits on loads will be considered.

2 - RATED VOLTAGES

As the focus of this site is more for low voltage systems of hydroelectric plants, the voltage levels of these facilities will be more approached, but may also be valid for other areas, especially industrial ones.

It is not possible to define, a priori, what rated voltages and care should be adopted to meet the needs of an installation, because this definition depends on the requirements of the customer, the equipment, components used and the available resources. Therefore, this definition must be made considering all variables.

In Brazil there are no standardized rated voltages for low voltage systems, neither for systems nor for equipment. What exists on the subject are the definitions given by Decree No. 41.019 of February 26, 1957 and amended by Decrees No. 73.080 of November 5, 1973 and No. 97.280, of December 16, 1988.

In Decree No. 41.019 of February 26, 1957, Article 47 defined that:

“Art 47. Deverão ser adotadas preferencialmente, nas novas instalações de serviço de energia elétrica, as seguintes tensões nominais:
.....
III - Na distribuição secundária:
Trifásica a 220, 380 e 440 volts, monofásica a 110, 127 e 220 volts.
IV - Na utilização de energia para tração elétrica urbana:
600 volts, corrente contínua.
....
Parágrafo único. As tensões nominais na distribuição secundária referem-se aos pontos de entrega da energia; nos demais casos referem-se à extremidade de alimentação da linha.”

In Decree No. 73.080 of November 5, 1973 , Article 47 was amended to:

"Art 47. Deverão ser adotadas pelas concessionárias de serviço de energia elétrica, em novas instalações, as seguintes tensões nominais:
....
III - Para distribuição secundária de corrente alternada em redes públicas: 380-220 e 220-127 volts em redes trifásicas a quatro fios, e 230/115 volts em redes monofásicas a três fios.
§ 1º A tensão nominal de um sistema é o valor eficaz da tensão pelo qual o sistema é designado.
§ 2º Tensões nominais diferentes das indicadas neste artigo, somente poderão ser utilizadas em reforço ou extensão de redes já existentes utilizando tais tensões, desde que técnica e economicamente justificado. “

With Decree No. 97.280 of December 16, 1988 , the updated wording of Article 47 for low voltage is:

"Art 47. Deverão ser adotadas pelas concessionárias de serviço de energia elétrica, em novas instalações, as seguintes tensões nominais:

....

III - Para distribuição secundária de corrente alternada em redes públicas: 380/220 e 220/127 volts, em redes trifásicas; 440/220 e 254/127 volts, em redes monofásicas;

§ 1º A tensão nominal de um sistema é o valor eficaz da tensão pelo qual o sistema é designado.

§ 2º Tensões nominais de transmissão e subtrasmissão ou distribuição primária diferentes das indicadas neste artigo, somente poderão ser utilizadas em reforço ou extensão de linhas ou redes já existentes, desde que técnica e economicamente justificável

....".

According to ANEEL (National Electric Energy Agency), to know what the rated voltage of the secondary distribution system is, we should know which is the city and the local concessionaire. Therefore, there are a variety of rated voltages, and all are legally valid. Among these voltages we can mention 440/220V, 380/220V, 254/127V, 230/115V, 220/127V. For example, according to ANNEL's website, Tensões Nominais Secundárias por Município, in the city of Alcobaça - Bahia, COELBA distributes energy at the voltages of 440/220V, 380/220V and 254/127V.

BA - Bahia | Alcobaça

COELBA	
Tensão Nominal 1	440/220 volts
Tensão Nominal 2	380/220 volts
Tensão Nominal 3	254/127 volts

There is no standardization of rated voltages of systems and equipment in Brazil, as it exists in other countries in Europe and in the United States. For example, in most European countries, which use the International Electrotechnical Commission (IEC), the rated voltage of the three-phase system is 400V and the rated voltage of the motors is 380V; in England, which uses the BS standard (British Standards), the rated voltage of the system is 415V and the rated voltage of the motors is 400V; in the United States, using the NEMA (National Electrical Manufacturers Association) standard, the rated voltage of the three-phase system is 480V and the rated voltage of the motors is 460V.

The ABNT standards are mainly based on the recommendations of the IEC, but the rated voltage of the systems and equipment are not defined, which leads us to adopt, in most cases, rated voltages of 380V, 440V, 460V and 480V for systems and 380V and 440V for motors. What could be done, since equipment and material manufacturers also serve other markets, and many of these manufacturers originate from other countries, is to adopt the voltages defined in international standards such as IEC or NEMA. In Brazil, ABNT standards are based on the IEC, but we do not adopt the rated voltages defined therein.

We recall that both in the United States and in Europe there have been updates of the rated voltages of the systems and motors. In the United States, in the 1960s, the rated voltage of the system was 480V and 440V motors, and the rated system voltage was maintained at 480V and the rated motors voltage was changed to 460V. In Europe, in the 1980s, the rated voltage of the system and motors was 380V, and the rated voltage of the system was changed to 400V, and the rated voltage of the motors was maintained at 380V. It is also worth mentioning that the frequency in the United States is 60Hz and in Europe 50Hz.

The rated voltages of equipment, such as control transformers, relays, contactors, etc., are manufactured in accordance with international standards. Therefore, as the rated secondary voltage of the control transformers is 115V and the ratios that meet the standards are, for example, 3.5 and 4, the rated ratios of the control transformers should be 402.5-115V and 460-115V. Based on the standards, we can conclude that transformers of 380-115V, 440-115V and 480-115V would be special, i.e. for transformers 380-115V the ratio would be 3.30; for 440-115V transformers the ratio would be 3.82; for 480-115V transformers the ratio would be 4.17.

Due to the above, and in the lack of definition of Brazilian standards, the recommendation should be to adopt the following voltages:

Reference Europe
For motors with rated voltage: 380V.
Rated system voltage: 400V.
Control transformer: 402.5-115V (Ratio 3.5)
Rated voltage of relays, contactors etc.: 110V

United States Reference
For motors with rated voltage: 460V
Rated system voltage: 480V.
Control transformer: 480-120V (Ratio 4)
Rated voltage of relays, contactors etc.: 115V

To meet any existing systems
For motors with rated voltage: 440V
Rated system voltage: 460V.
Control transformer: 460-115V (Ratio 4)
Rated voltage of relays, contactors etc.: 110V

Note: The preference should be for the 480V voltage for systems and 460V for motors, as in the United States, where the frequency is 60Hz, equal to that of Brazil. The national industry, to also serve other markets, manufactures the motors for rated voltages of 380, 440, 460V and equipment (relays, contactors, etc.) for 110 and 115V, with frequencies of 50 and 60Hz, because the frequency in other countries, such as Latin America and Europe, is 50Hz. In this way, it serves both national and imported systems and equipment.

3 - VOLTAGE VARIATIONS

In this item will be analyzed the voltage variations, that occur in the feeders of the installations and equipment, and the permissible limits recommended by the manufacturers of components and equipment, standards and the needs of the facilities.

Standards recommend limits for voltage dropouts in feeder circuits. However, these limits are maximum recommended values that should be analyzed with the other variables of the systems and installations.

According to the Voltage Classification Range – Tensões de Regime Permanente da ANEEL (Table 3 below) the adequate voltage at the feeder points of medium voltage systems can range from 93 to 105% of the reference voltage. The voltage limit values at the connection points can vary between 90 and 105% of the reference 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

IEC 61000-3 recommends the definition of the reference voltage as the nominal voltage of the system.

According to the Voltage Classification Range – Tensões de Regime Permanente da ANEEL (Table 12 below) the adequate voltage at the feeder points of low voltage systems can vary from 92 to 105% of the rated voltage. The voltage limit values at the connection points can vary between 87 and 106% of the rated voltage.

Tabela 12 – Faixas aplicadas às tensões nominais inferiores a 1 kV para formação das Tabelas 4 a 11

Tensão de Atendimento (TA)	Faixa de Variação da Tensão de Leitura (TL) em Relação à Tensão Nominal (TN)
Adequada	0,92TN≤TL≤1,05TN
Precária	0,87TN≤TL<0,92TN ou 1,05TN<TL≤1,06TN
Crítica	TL<0,87TN ou TL>1,06TN

If we consider the appropriate voltage operating ranges, in the feeder of an installation, and apply the permissible voltage falls in the standards to the various circuits, probably few equipment could work with the variations recommended by the manufacturers and even by the standards themselves.

From the NBR 5410 standard we have:

6.2.7 Quedas de tensão

6.2.7.1 Em qualquer ponto de utilização da instalação, a queda de tensão verificada não deve ser superior aos seguintes valores, dados em relação ao valor da tensão nominal da instalação:

a) 7%, calculados a partir dos terminais secundários do transformador MT/BT, no caso de transformador de propriedade da(s) unidade(s) consumidora(s);

b) 7%, calculados a partir dos terminais secundários do transformador MT/BT da empresa distribuidora de eletricidade, quando o ponto de entrega for aí localizado;

c) 5%, calculados a partir do ponto de entrega, nos demais casos de ponto de entrega com fornecimento em tensão secundária de distribuição;

d) 7%, calculados a partir dos terminais de saída do gerador, no caso de grupo gerador próprio.

Considering the case of hydroelectric plants, the maximum voltage drop, from the secondary terminals of the MV/LV transformer to the load, should be 7% of the rated system voltage. It happens that, in hydroelectric plants, MV/LV transformers are most often directly powered by the generator, and this generator also has an operating range, usually at ±10% and, despite operating in a smaller range, for example, +10%, -5%, we still have the voltage drop in the MV/LV transformer itself and circuit components, such as panels and cables.

If the generator is at 95% of the rated voltage, the rated voltage of the low voltage system is 480V and the rated voltage of the motors is 460V, even though there is no voltage drop in the MV/LV transformer, if the voltage drop in the load meets the drop of 7% of the rated voltage, the operating voltage of the motors will be:

$V_T = 480x0{,}95 = 456V$

$V_M = 456 - 480x0.07 = 422.4V$

Where:

V_T - Voltage in the terminals of the MV/LV transformer

V_M - Voltage in the motors

The voltage in the motors will be 422.4V which corresponds to 91.8% of its rated voltage.

If we consider the same previous condition, but with the generation voltage with 110% of the rated voltage, the operating voltage of the motors will be:

$V_T = 480x1{,}10 = 528V$

$V_M = 528 - 480x0{,}07 = 494.4V$

Where:

V_T - Voltage in the terminals of the MV/LV transformer

V_M - Voltage in the motors

The voltage in the motors will be 494.4V which corresponds to 107.5% of its rated voltage.

If we want the operating voltage of the motors to be at least 95% of their rated voltage, i.e., 437V, which corresponds to 91% of the rated voltage of the system, the voltage drop should be:

For generation voltage with 95% of rated voltage.

$V_T = 480x0.95 = 456V$

$V_M = 456 - 480xd_V = 437V$

$$d_V = \frac{456 - 437}{480} = 0.04$$

That is, the voltage drop should be 4% of the rated voltage of the system, instead of 7%.

This will imply that when the generator is operating at voltage of 110% of the rated voltage, the operating voltage of the motors will be:

$V_T = 480x1.10 = 528V$

$V_M = 528 - 480x0.04 = 508.8V$

corresponds to 110.6% of the rated voltage of the motors.

Assuming an installation, with rated system voltage of 480V and motors with rated voltage of 460V, formed only by a general panel that feeds all loads, and this general panel is fed by an external source with rated voltage 480V, if the voltage of the power supply is 441.6V, i.e. 92% of the rated voltage, still within the appropriate voltage range, and consider a total voltage drop of 5% from the point of delivery, as provided for in NBR 5410, the operating voltage of the motors will be:

$V_M = 441.6 - 480x0.05 = 417.6V$

that is, 87% of the rated voltage of the system, which corresponds to 90.8% of the rated voltage of the motors.

If we consider the same previous condition, but with the feeder with 504V, i.e. 105% of the rated voltage, also within the appropriate voltage limit, the operating voltage of the motors will be:

$V_M = 504 - 480x0.05 = 480V$

corresponds to 104.3% of the rated voltage of the motors.

If we want the operating voltage of the motors to be at least 95% of their rated voltage, i.e., 437V, which corresponds to 91% of the rated voltage of the system, the voltage drop should be:

For voltage in the power supply with 441.6V (92% of the rated voltage of the system).

$V_M = 441.6 - 480xd_V = 437V$

$$d_V = \frac{441{,}6 - 437}{480} = 0.01$$

That is, the voltage drops up to the motors should be 1% instead of 5%.

For voltage in the power supply with 456V (95% of the rated voltage of the system).

$V_M = 456 - 480xd_V = 437V$

$$d_V = \frac{456 - 437}{480} = 0.04$$

That is, the voltage drops up to the motors should be 4% instead of 5%.

For voltage in the power supply with 504V (105% of the nominal voltage of the system), the voltage in the motors will be 480V, considering the voltage drop of 5%, which corresponds to 104.3% of the nominal voltage of the motors.

NBR 5410 also recommends that the sizing of the conductors that power engines must be such that, during motors start-up, the voltage drop at the terminals of the starting device does not exceed 10% of the respective rated voltage, respecting the limits for the other points of use of the installation.

The fact of using a nominal voltage of the system, greater than the nominal voltage of the motors, brings the advantage of being able to admit a voltage drop greater than that which would be admitted, if the nominal voltages of the motors were equal to the nominal voltages of the systems. However, it may occur that the source voltage is at the upper limit of the appropriate range and the voltage drop in the circuits is small, which may imply that the components operate with voltage above the recommended or permissible.

To properly size the components of an installation, it is important to know the operating range of the power supply voltage and the permissible operating voltage limits of the equipment involved (transformers, motors, contactors, relays, etc.). Based on this data it will be possible to define how to better meet all the needs of the installation and its components. However, as much as we try to meet these limits, it will be necessary to analyze some critical conditions that will certainly arise.

In hydroelectric plants, if we had to meet all the theoretical limits of voltages of power supplies and loads, all MV/LV auxiliary services transformers would have to be equipped with automatic load tap changers. In short, what should be done is to seek the best possible balance, with the available data, and try to minimize the most critical cases. The most important thing is to avoid overvoltage and manage the problems of the undervoltage.

In the examples considered, it was arbitrated that the value of the voltage of the generation would be between +10% and -5%. However, this value must be set for each installation and depends on the voltage of the high voltage system, the characteristics of the step-up transformer and the tap used for the high voltage winding of the step-up transformer. In the absence of this information, for the purpose of the low voltage system, consider that the generating unit operates with nominal load and power factor. For conditions of the associated high voltage system, consider the values established by ANEEL in the tables below:

Tabela 1 – Pontos de conexão em Tensão Nominal igual ou superior 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	0,93TR≤TL<0,95TR ou 1,05TR<TL≤1,07TR
Crítica	TL<0,93TR ou TL>1,07TR

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

Below are some considerations about the problems that typically arise and a way to resolve or attenuate them.

3.1 - Power Supply

The voltage variation should be as small as possible, but this characteristic can often not be defined by the user. However, the range of variation of the voltage of the power supply should be very well defined and evaluated. It is also important to know, within extreme limits, what is the most likely range of operation. This information is important for defining the range of voltage variation in loads and the primary winding derivation to be used in the MV/LV transformer. Due at high cost, the alternative of using transformer with automatic load tap changer is the last option to be considered.

3.2 - Power Transformer

The rated power and impedance of the MV/LV transformer shall be defined within the nominal characteristics on the market. In open environments use oil-immersed transformers and indoors use only dry transformers.

3.3 - Rated System Voltage

The rated system voltage should be one of the recommended voltages. For motors with rated voltage of 380V adopt rated voltage system of 400V; for motors with rated voltage of 460V adopt rated voltage system of 480V.

3.4 - Rated Motors Voltage

The rated motors voltage must be 380V or 460V.

The Insulation Class must be Class F with Class B temperature elevation, i.e., motors must be designed and manufactured to operate with Class B insulation temperature limits (130°C), but insulated with Class F(155°C) materials. This practice allows heating, caused by critical operating conditions, not to compromise motor life. For example, motors operating at lower voltage than those recommended operate with a higher current than normal, proportional to the voltage reduction, which causes an increase in temperature above the permissible for Class B, but within the class F limit.

3.5 - Relays and Contactors

Voltages and contactors must have the rated voltage compatible with the system voltage. For systems with rated voltage 115V use voltages and contactors with rated voltage of 110V; for systems with rated voltage 120V use voltages and contactors with rated voltage of 115V. The operating voltages of the control must be observed so that the contactors do not open by undervoltage, or the coils burn by overvoltage

Must be avoided that contactors' controls working at voltages above 110% and below 85% of the rated voltage. However, there are contactors in the market who operate (remain closed) with voltages up to less than 70% of the nominal voltage, but this condition must be confirmed before being considered.

If the minimum voltage of alternating current control is lower than the minimum operating voltage of the contactors or control devices, direct current-driven contactors should be used.

3.6 - Motors Start

The starting of induction motors shall be, where possible, direct to full voltage. With the development of the soft starter industry and other drive devices, its use and benefits is making its application advantageous, especially in handling and lifting equipment such as cranes, gantries, clean grids etc., where its use is already standardized.

3.7 - System and Equipment Voltage Adjustments

The first care that should be taken in the definition of the systems, with respect to voltages, is to prevent controls equipment and its auxiliaries from being subject to overvoltage above the permissible ones defined by the manufacturers. This overvoltage occurs, more precisely, when the system supply voltage is at the maximum limit and the system is low on load. Therefore, this condition should define the choice of the derivation to be used in the primary MV/LV transformer, if any.

The derivation to be used can be defined with the aid of the following formula:

$$k = \frac{V_P V_{S_n}}{V_S \, V_{P_n}}$$

Where:

V_S- Voltage in the secondary of transformer (V)

V_P- Voltage in the primary of transformer (V)

V_{P_n}- Transformer's Primary Rated voltage (V)

V_{S_n}- Transformer's Secondary Rated voltage (V)

k - ratio between the voltage of the tap used (V_{P_x}) and the rated voltage of the transformer's primary.

Since transformers are, normally, supplied with derivations of ± 2 x 2.5% of the nominal voltage, i.e., k=0.95, 0.975, 1.0, 1.025 and 1.05, the derivation to be chosen should be the closest to the calculated value for k.

For example, a transformer with13800 rated ratio ± 2 x 2.5% - 480V can be powered by a source with the limits defined in the table below (ANEEEL).

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

Whereas a power supply is at the maximum limit, i.e., 14490V (+5%), and the maximum voltage in the secondary cannot exceed 528V (480+10%), the k value will be:

$$k = \frac{14490x480}{528x13800} = 0.9545$$

The derivation to be used should be -5%.

If the maximum voltage in the secondary cannot exceed 506V (460+10%), the k value will be:

$$k = \frac{14490x480}{506x13800} = 0.9960$$

The derivation to be used should be the nominal, i.e., 1.0.

Of course, this setting will ensure that there will be no overvoltage in the system and will allow you to analyze and manage the undervoltage problems that arise.

It is worth remembering that there are systems defined as 480V±10%, which feed motors with rated voltage of 440V, that is, the motors could operate with up to 20% overvoltage. However, the problem of overvoltage in motors is not as critical as overvoltage in the command and control devices.

3.8 - Undervoltage in Systems

Undervoltage in equipment can cause problems in its operation, especially in lighting, command, and control systems.

Undervoltage problems are aggravated when the power supply voltage is in precarious or critical situation and the consumption of the installation loads is higher. For example, considering that the derivation used in the transformer is -5% and the supply voltage is 12420V (13800V -10%) the voltage in the secondary of transformer, without load, will be given by the formula:

$$V_S = \frac{V_P V_{S_n}}{kV_{P_n}}$$

That is,

$$V_S = \frac{12440x480}{0.95x13800} = 455.5V$$

The voltage of 455.5V will be the minimum voltage to be considered to develop the studies of the system. If the voltage is too low, the transformers can be specified with derivations, in the primary winding, different from normal ones such as + 2.5%, -3 x 2.5%, for example.

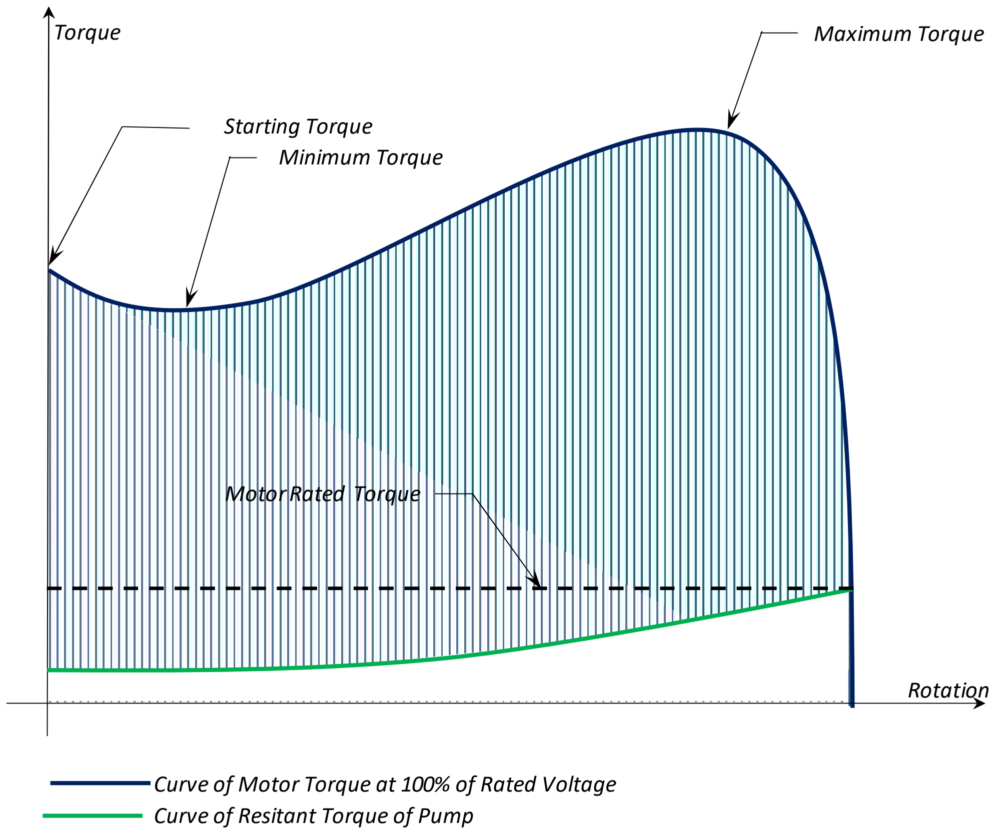
It is observed that for certain conditions of operation of the systems, the limits of voltage drop defined by the standards must not considered as mandatory, but as they are cited as maximum, the limits to be considered must be those necessary for the operation of the installations, even in precarious regimes.

The undervoltage is more critical for loads handling and lifting equipment, because as the torque of the motors is proportional to the square of the voltage, it may occur that, at a certain point in the curve, the motor is not able to drive the load. Therefore, for this type of loads should be used specific converters, as is already a common practice.

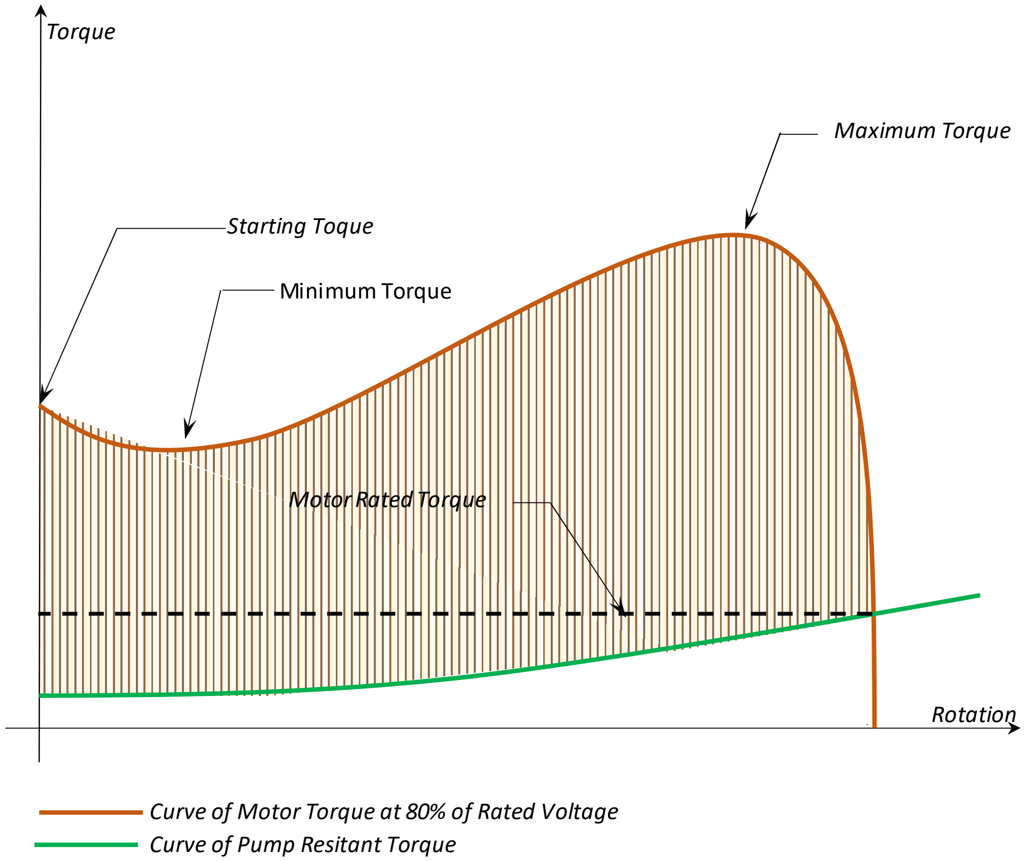
The start of pump and compressors motors can be done with voltages lower than those defined by the standards, provided that the motor departs within a certain time and the voltage drop caused does not affect the operation of its control and other loads of the system.

Note that the motors' star-delta start is made with a reduction of the voltage, that is, instead of start the motor with 100% of the rated voltage, it departs with 57.73% (phase-neutral voltage instead of phase-phase), which reduces the starting current of the motor and consequently the voltage drop in the feeders and control circuits, but also reduces the motor torque to 33% of the rated torque.

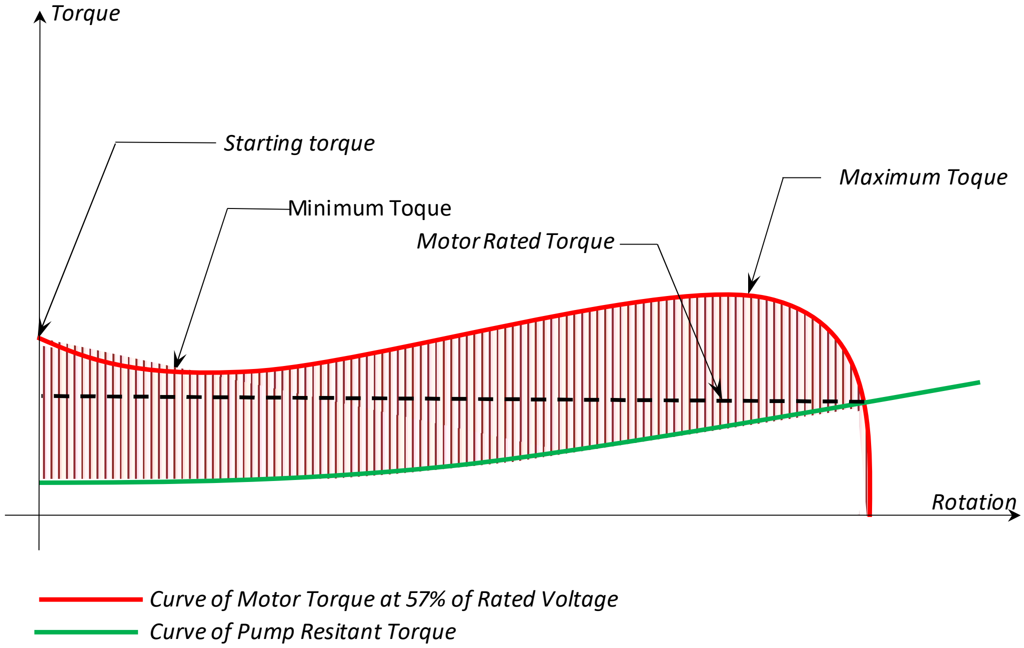
The following are the typical motor curves (torque x rotation) for pumps' drive.



In the figure above are shown the curve of the motor with 100% of the nominal voltage and the curve of the pump's resistant torque. The hatched area represents the acceleration torque that defines the starting time of the set.



In the figure above are shown the motor curves with 80% of the nominal voltage and the curve of the pump resistant torque. The hatched area represents the acceleration torque that defines the starting time of the set. Note that the area corresponding to the acceleration torque is smaller than that of the previous figure and therefore the starting time will be longer.



In the figure above are shown the motor curves with 57% of the rated voltage and the curve of the pump resistant torque. This condition corresponds to the motor with star-delta start.

The hatched area represents the acceleration torque of the set. In the case of star-delta start, when the motor rotation reaches approximately 90% of the nominal rotation, the star-delta connection is switched, and the starting current is greatly reduced. Note that the motor could even operate with reduced voltage (star connection), but the operating current, with a voltage of 57% of the rated voltage, would be 175% of the rated current and the motor would be overheated.

4 - MOST FREQUENT SITUATIONS

The situations that normally appear, with respect to variations and rated voltage, are that of an existing installation or a new project.

4.1 - Existing Installation

In an existing installation the equipment and components are defined, and the job consists of making the necessary adjustments in the installation, with a minimum of possible modifications.

4.2 - New Project

In a new project, the characteristics of the systems (configurations, rated voltages of the systems and components, permissible limits of use, types of materials, etc.) are defined and, based on estimated information, in the calculation memories and specifications of the equipment of the installations the equipment and components are defined.

The new project also has an existing installation feature, because the equipment and components are always sizing with preliminary data and, later, it is necessary to verify, with the actual data, whether the premises that were adopted in the initial design of the project continue to be respected.

5 - CONCLUSION

The definition of the nominal stresses of the systems and equipment can be made with some ease, but the limits of operation of the installations and components, on a permanent and transitional conditions, should be carefully studied to avoid and minimize problems that are normally encountered during the development of the work.