# HYDROELECTRIC POWER PLANT
# Generation Voltage Calculation

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## 1 - PURPOSE

The purpose of this technical information is to calculate the voltage of the Powerhouse generating units and a hydroelectric plant, depending on the configuration of the generation system, the tension of the associated substation, the characteristics of the generating units, the step-up transformer data, and the operating conditions, to assist in the analysis of the behavior of voltages in the auxiliary services of the plant.

The result of this technical information, in addition to the definition of the criteria for calculating the voltage of the generation, will be the production in Excel, of spreadsheet to calculate the value of the voltage of the generation, based on the data necessary for its determination.

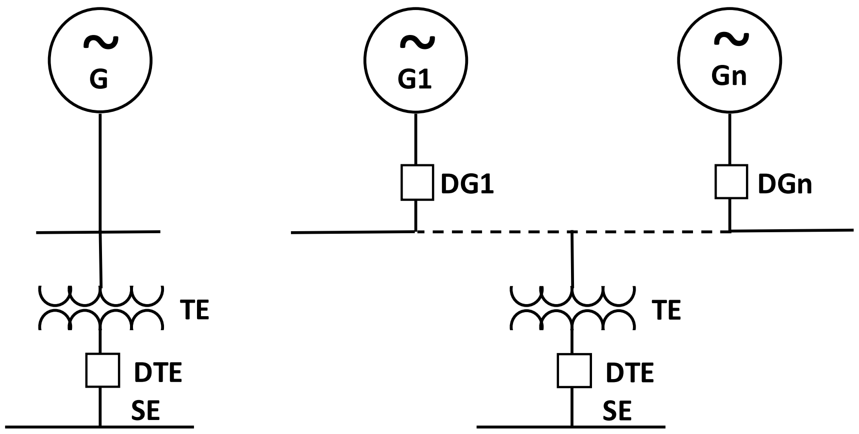
## 2 - REFERENCE DOCUMENTOS

### 2.1 - Spreadsheets

PL.EL.SA.CA.06.R0 Hydroelectric Power Plant - Generation Voltage Calculation

## 3 - GENERATION SYSTEM CONFIGURATION

For the purposes of this technical information, the configuration of a Powerhouse with one or more generating units, associated with a step-up transformer, will be considered.




In the case of only one generator unit by step-up transformer, synchronization of the unit with the substation is done through the DTE circuit breaker. In the case of more than one generator unit by step-up transformer, the synchronization of the first unit with the substation is done through the DTE circuit breaker and the other units are synchronized, in the generation bar, through the circuit breakers of the respective units DG1, ..., DGn.

## 4 - FACILITIES CHARACTERISTICS

The facilities characteristics are defined by users according to project data and manufacturers, applicable standards, regulatory bodies, and operating practices. The following data are commonly used references, which can be changed by the user depending on their information.

### 4.1 - Generating Units

The rated power of each generating unit is usually equal to the power of the step-up transformer. In the case of grouping with several units, the rated power of each unit is the corresponding fraction of the step-up transformer. For example, in a system with two generator units per step-up transformer, each unit has rated power equal to 50% of the power of the step-up transformer.

The normal variation in the operating voltage of the generating units is ±10%.

### 4.2 - Step-Up Transformers

The step-up transformers, or single-phase step-up transformer set, for the purpose of this technical information shall also be treated as Step-Up transformers.

Due to high power, step-up transformers have cooling systems, usually equipped with one or two stages of forced ventilation. Each ventilation condition corresponds to a power, and each ventilation stage increases the base power by 1/3. Thus, for example, a transformer with rated power of 60MVA, with a ventilation stage has its power increased to 80MVA and with two stages has its power increased to 100MVA. Therefore, a step-up transformer with rated power of 60MVA and two ventilation stages can transmit the energy generated by 2 generating units of 50MVA or 4 of 25MVA.

The rated voltage of the primary winding (low voltage) shall be equal to the rated voltage of the generating units and the rated voltage, of the secondary winding (high voltage), equal to the rated voltage of the associated substation; The secondary winding has leads, which are typically 2 x ± 2.5% of the rated voltage.

The rated impedance of the step-up transformers is defined by the user in the design phase, and the exact values of impedance and resistance are obtained, by tests, in the transformers factory. The rated impedance of transformers, when not otherwise specified, always refers to the rated power. For example, the rated impedance of a 60/80/100MVA step-up transformer (ONAN/ONAF1/ONAF2) may be referred to the rated power of 60, 80 or 100MVA.

The real impedance of the step-up transformer, obtained in the factory tests, must be within the tolerance limits set out in the standards. The resistance of the transformer varies with the temperature of the windings, i.e., depending on the load and ventilation conditions. In the absence of resistance information, it is suggested the adoption of the rated value of 1%.

### 4.3 - High Voltage Associated Substation

The voltages considered in the high voltage bus of the substation associated must be in accordance with those defined in the table below (ANEEL).

**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

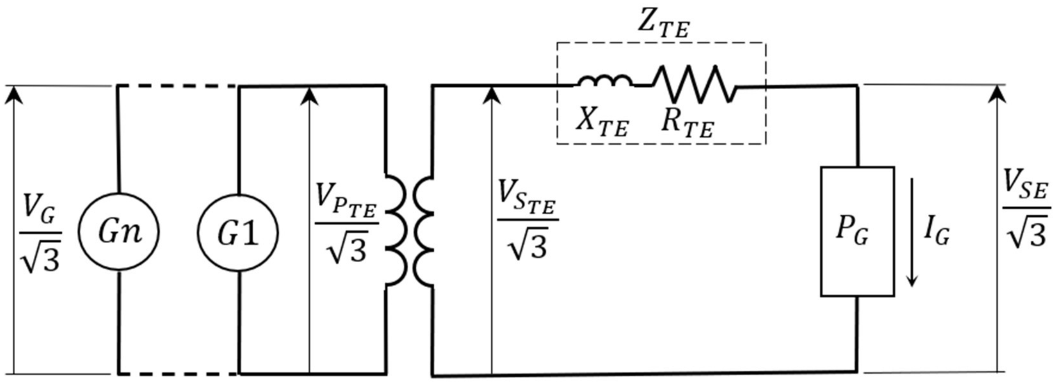
| Tensão de Atendimento (TA) | Faixa de Variação da Tensão de Leitura (TL) em Relação à Tensão de Referência (TR) |
|---|---|
| Adequada | 0,95TR≤TL≤1,05TR |
| Precária | 0,90TR≤TL<0,95TR ou 1,05TR<TL≤1,07TR |
| Crítica | TL<0,90TR ou TL>1,07TR |

## 5 - GENERATION VOLTAGE

The calculation of the generation voltage will be done considering that all the power generated by the units is transmitted to the substation associated, through the step-up transformer.

### 5.1 - Basic Circuit

The following figure represents the circuit of the system that will be analyzed:




Where:

$G_{1,}, G_{n,}$ Generator unit(s) associated with the step-up transformer.

$V_G$ Voltage of the generating unit(s) $G_{1,}, \ldots, G_{n,}$

$V_{P_{TE}}$ Voltage in the primary step-up transformer.

$V_{S_{TE}}$ Voltage in the secondary step-up transformer.

$Z_{TE}$ Impedance of step-up transformer

$X_{TE}$ Step-up transformer reactance.

$R_{TE}$ Step-up transformer resistance.

$P_G$ Power supplied by the generator unit(s) through the step-up transformer.

$I_G$ Current of power supplied through the step-up transformer.

$V_{SE}$ Voltage of substation associated.

### 5.2 - Step-up Transformer Secondary Circuit Equation

For the basic circuit we can write that:

$$\frac{\overrightarrow{V_{S_{TE}}}}{\sqrt{3}} = \frac{\overrightarrow{V_{SE}}}{\sqrt{3}} + \overrightarrow{I_G} \cdot \overrightarrow{Z_{TE}}$$

Whereas:

$$\overrightarrow{V_{SE}} = \left(\frac{V_{SE}}{\sqrt{3}}, 0\right)$$

Where:

$V_{SE}$ - Bus voltage of substation associated. (kV)

$$\overrightarrow{I_G} = \left(\frac{P_G}{\sqrt{3}\,V_{SE}}, -\varphi_{PG}\right)$$

Where:

$I_G$ - Current of power supplied through the step-up transformer (kA).

$P_G$ - Total power passing through the step-up transformer (MVA)

$V_{SE}$ - Bus voltage of substation associated (kV)

$FP$ - Total power generation power factor

$\varphi_{PG}$ – Total load power factor angle powered by step-up transformer.

$$\varphi_{PG} = acos(FP)$$

$$\overrightarrow{Z_{TE}} = \left(Z_{TE_k}, \theta_{TE}\right)$$

Where:

$Z_{TE_k}$ - Impedance of the step-up transformer in the secondary tap k (Ω)

$k$- Used tap of the secondary winding of step-up transformer in pu. For example, for the tap -5% k=0.95; for the tap -2.5% k=0.975; for rated tap k=1; for the tap +2.5% k=1.025; for the tap -5% k=0.95.

$\theta_{TE}$- Step-up transformer impedance angle.

$$\theta_{TE} = arc\ cos.\frac{R_n}{Z_n}$$

Where:

$R_n$- Rated resistance of the step-up transformer (%)

$Z_n$- Rated impedance of the step-up transformer (%)

**5.3 - Step-up Transformer Impedance**

Considering that the transformer power is constant, for any shunt used of secondary winding, we must:

$$Z_{TE_n} = \frac{{V_{S_{TE_n}}}^2}{P_{TE_n}} \cdot \frac{Z_n}{100}$$

$$P_{TE_n} = \frac{{V_{S_{TE_n}}}^2}{Z_{TE_n}} \cdot \frac{Z_n}{100}$$

Where:

$Z_{TE_n}$- Rated impedance of the step-up transformer (Ω).

$V_{S_{TE_n}}$- Rated secondary voltage of the step-up transformer (kV)

$P_{TE_n}$- Step-up transformer rated power (MVA)

$Z_n$- Step-up transformer rated impedance (%)

### 5.4 - Step-up Transformer Impedance for Any Tap k

$$\boldsymbol{Z_{TE_k} = \frac{{V_{S_{TE_k}}}^2}{P_{TE_n}} \cdot \frac{Z_n}{100}}$$

Where:

$Z_{TE_k}$- Impedance of the step-up transformer in the k tap (Ω)

$V_{S_{TE_k}}$- Voltage in the k secondary tap of step-up transformer (kV)

$P_{TE_n}$- Rated power of step-up transformer (MVA)

$Z_n$- Rated impedance of the step-up transformer (%)

Replacing: $P_{TE_n}$

$$Z_{TE_k} = \frac{{V_{S_{TE_k}}}^2}{\frac{{V_{S_{TE_n}}}^2}{Z_{TE_n}} \cdot \frac{Z_n}{100}} \cdot \frac{Z_n}{100}$$

$$Z_{TE_k} = Z_{TE_n} \cdot \frac{{V_{S_{TE_k}}}^2}{{V_{S_{TE_n}}}^2}$$

Replacing

$$V_{S_{TE_k}} = k . V_{S_{TE_n}}$$

and

$$Z_{TE_n} = \frac{{V_{S_{TE_n}}}^2}{P_{TE_n}} \cdot \frac{Z_n}{100}$$

Have:

$$Z_{TE_k} = \frac{{V_{S_{TE_n}}}^2}{P_{TE_n}} \cdot \frac{Z_n}{100} \cdot \frac{\left(k . V_{S_{TE_n}}\right)^2}{{V_{S_{TE_n}}}^2}$$

$$Z_{TE_k} = \frac{{V_{S_{TE_n}}}^2}{P_{TE_n}} \cdot \frac{Z_n}{100} \cdot \frac{k^2 {V_{S_{TE_n}}}^2}{{V_{S_{TE_n}}}^2}$$

$$Z_{TE_k} = \frac{k^2 {V_{S_{TE_n}}}^2}{P_{TE_n}} \cdot \frac{Z_n}{100}$$

With the data of the impedance and resistance of the transformer we can consider that:

$$\boldsymbol{\overrightarrow{Z_{TE_k}} = \left( \frac{k^2 {V_{S_{TE_n}}}^2}{P_{TE_n}} \cdot \frac{Z_n}{100}, \theta_{TE} \right)}$$

Where:

$Z_{TE_k}$- Impedance of the step-up transformer in the k tap (Ω)

$V_{S_{TE_n}}$- Rated secondary voltage of the step-up transformer (kV)

$P_{TE_n}$- Rated power of the step-up transformer (MVA)

$k$- Tap used of the secondary winding of the step-up transformer in pu. For example, for the tap -5% k=0.95; for the tap -2.5% k=0.975; for the rated tap k=1; for the tap +2.5% k=1.025; for the tap -5% k=0.95.

$Z_n$- Rated impedance of the step-up transformer (%)

$\theta_{TE}$ – Step-up transformer impedance angle

Whereas:

$$\theta_{TE} = arc\ cos.\frac{R_{TE_k}}{Z_{TE_k}}$$

Note: The e values $R_{TE_k}$ and $Z_{TE_k}$ must be on the same unit, i.e., both in pu, % or Ω.

### 5.5 - Calculation of the Secondary Voltage of the Step-up Transformer

With the data defined in the previous items, the circuit equation of the secondary of step-up transformer can be written as follows:

$$\frac{\overrightarrow{V_{S_{TE}}}}{\sqrt{3}} = \frac{\overrightarrow{V_{SE}}}{\sqrt{3}} + \overrightarrow{I_G}\,.\overrightarrow{Z_{TE}}$$

$$\frac{\overrightarrow{V_{S_{TE}}}}{\sqrt{3}} = \left(\frac{V_{SE}}{\sqrt{3}}, 0\right) + \left(\frac{P_G}{\sqrt{3}\,V_{SE}}, -\varphi_{PG}\right).\left(\frac{k^2 {V_{S_{TE_n}}}^2}{P_{TE_n}}.\frac{Z_n}{100}, \theta_{TE}\right)$$

$$\frac{\overrightarrow{V_{S_{TE}}}}{\sqrt{3}} = \left(\frac{V_{SE}}{\sqrt{3}}, 0\right) + \left[\left(\frac{P_G}{\sqrt{3}\,V_{SE}}.\frac{k^2 {V_{S_{TE_n}}}^2}{P_{TE_n}}.\frac{Z_n}{100}\right), (-\varphi_{PG} + \theta_{TE})\right]$$

Multiplying the terms by $\sqrt{3}$

$$\overrightarrow{V_{S_{TE}}} = (V_{SE}, 0) + \left[\left(\frac{P_G}{V_{SE}}.\frac{k^2 {V_{S_{TE_n}}}^2}{P_{TE_n}}.\frac{Z_n}{100}\right), (\theta_{TE} - \varphi_{PG})\right]$$

Whereas:

$$A = \frac{P_G}{V_{SE}}.\frac{k^2 {V_{S_{TE_n}}}^2}{P_{TE_n}}.\frac{Z_n}{100}$$

In the complexes form we have:

$$\overrightarrow{V_{S_{TE}}} = (V_{SE} + j0) + [A.cos(\theta_{TE} - \varphi_{PG}) + jA.sen(\theta_{TE} - \varphi_{PG})]$$

$$\overrightarrow{V_{S_{TE}}} = \left(V_{SE} + A.cos(\theta_{TE} - \varphi_{PG})\right) + jA.sen(\theta_{TE} - \varphi_{PG})$$

$$|V_{S_{TE}}|^2 = (V_{SE} + A.cos(\theta_{TE} - \varphi_{PG}))^2 + (A.sen(\theta_{TE} - \varphi_{PG}))^2$$

$$V_{S_{TE}} = \sqrt{(V_{SE} + A.cos(\theta_{TE} - \varphi_{PG}))^2 + (A.sen(\theta_{TE} - \varphi_{PG}))^2}$$

## 6 - GENERATION VOLTAGE CALCULATION

The secondary voltage in the step-up transformer depends of the voltage applied to the primary and the tap used in the secondary. Thus, if a transformer is ratio $V_P$ - $V_S$, with taps in the secondary, the secondary voltage $V_{S_{TE}}$ in the transformer will be:

$$\frac{V_{P_{TE}}}{V_{S_{TE}}} = \frac{V_{P_{TE_n}}}{kV_{S_{TE_n}}}$$

$$V_{P_{TE}} = \frac{V_{P_{TE_n}} V_{S_{TE}}}{kV_{S_{TE_n}}}$$

From the basic diagram circuit we can verify that the voltage of the generation is exactly equal to the voltage in the primary of the step-up transformer. So:

$$V_G = V_{P_{TE}} = \frac{V_{P_{TE_n}} V_{S_{TE}}}{kV_{S_{TE_n}}}$$

Replacing $V_{S_{TE}}$ we have:

$$\boldsymbol{V_G = \frac{V_{P_{TE_n}}\sqrt{(V_{SE} + A.cos(\theta_{TE} - \varphi_{PG}))^2 + (A.sen(\theta_{TE} - \varphi_{PG}))^2}}{kV_{S_{TE_n}}}}$$

Being:

$$\boldsymbol{A = \frac{P_G}{V_{SE}} . \frac{k^2 {V_{S_{TE_n}}}^2}{P_{TE_n}} . \frac{Z_n}{100}}$$

Where:

$V_G$ Voltage of generator(s) unit(s) $G_{1,}, G_{n,}$ (kV)

$V_{P_{TE_n}}$- Rated primary voltage of the transformer (kV)

$V_{S_{TE_n}}$- Rated secondary voltage of the transformer (kV)

$V_{SE}$- Voltage of substation associated (kV)

$P_G$ - Total power passing through the step-up transformer (MVA)

$P_{TE_n}$- Rated power of the step-up transformer (MVA)

$Z_n$- Rated transformer impedance (%) referred to the rated power

$\varphi_{PG}$ – Total load power factor angle powered by step-up transformer

$\theta_{TE}$- Step-up transformer impedance angle

$$\theta_{TE} = arc\ cos.\frac{R_n}{Z_n}$$

Where:

$R_n$- Rated resistance of the step-up transformer (%)

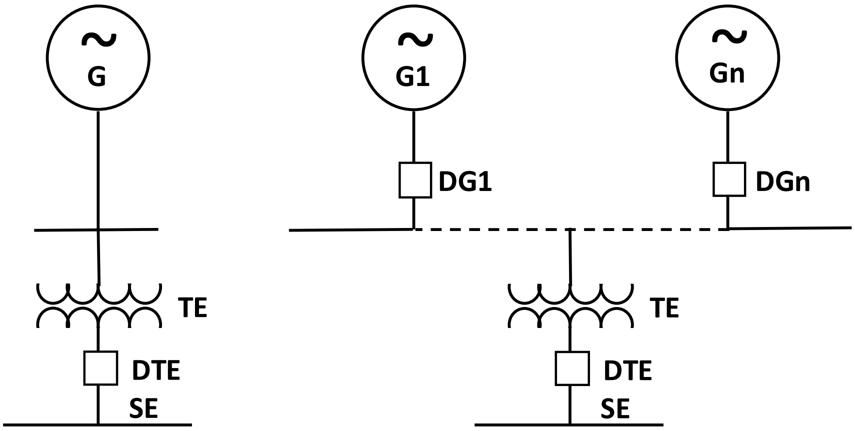
$Z_n$- Rated impedance of the step-up transformer (%)

$k$- Tap used of the secondary winding of the step-up transformer in pu. For example, for the tap -5% k=0.9 5; for the tap -2.5% k=0.975; for the rated tap k=1; for the tap +2.5% k=1.025; for the tap -5% k=0.95.

## 7 - APPLICATIONS

The purpose of this document, as defined at the beginning, is to help in the analysis of the voltage's behavior of the auxiliary services of the installation. In this analysis, the variation of the voltage of the generation can also be verified, from the synchronization phase to the supply of the maximum power generation, considering the voltage variations of the substation associated.

### 7.1 - Synchronizing of Units




Although there is more than one unit per step-up transformer, synchronization of the first unit occurs as if the others did not exist, that is, synchronization of the first unit is always done through the DTE circuit breaker.

The voltage of the generation that will allow the synchronization of the unit will be defined as a function of the voltage of the associated substation, the rated voltages of the step-up transformer and the secondary tap used. This voltage value is calculated by the following formula:

$$V_G = V_{P_{TE}} = \frac{V_{P_{TE_n}} V_{SE}}{k V_{S_{TE_n}}}$$

Where:

$V_G$ Voltage of the generator unit(s) $G_{1,}, G_{n,}$ (kV)

$V_{P_{TE}}$ Primary voltage of step-up transformer (kV)

$V_{P_{TE_n}}$- Primary rated voltage of the transformer (kV)

$V_{STE_n}$- Secondary Rated voltage of the transformer (kV)

$V_{SE}$- Voltage of associated substation (kV)

$k$- Tap used of the secondary winding of the step-up transformer in pu. For example, for the tap -5% k=0.95; for the tap -2.5% k=0.975; for the rated tap k=1; for the tap +2.5% k=1.025; for the tap -5% k=0.95.

The voltage of the associated substation must be within the limits defined by ANEEL. Considering that the voltage in the substation must be within the limits of adequate or precarious voltages, the values will be those defined in the following tables:

**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 |

**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 |

From the tables, for any rated voltage of the associated substation, the adequate voltage is between 95 and 105% of the voltage and that the maximum voltage, in precarious regime, is 107% of the rated voltage. The minimum voltage of the associated substation, in a precarious regime, is 90% of the rated voltage for systems with rated voltage between 69 and 230kV and 93% for systems with rated voltage equal to or greater than 230kV. Based on these values, the voltage in the generation, to allow synchronization of the first unit, must be indicated in the following table, calculated using the above formula:

| | | k- Tap Voltage Used from the Secondary (pu) | | | | |
|---|---|---|---|---|---|---|
| | | -5% | -2,5% | 0 | +2,5% | +5% |
| | | 0,950 | 0,975 | 1,000 | 1,025 | 1,050 |
| | | $V_G$-Generation Voltage (pu) (Values referred to the rated primary voltage of the step-up transformer) | | | | |
| Associated Substation Voltage (pu) | 0,9 | 0,9474 | 0,9231 | 0,9000 | 0,8780 | 0,8571 |
| | 0,93 | 0,9789 | 0,9538 | 0,9300 | 0,9073 | 0,8857 |
| | 0,95 | 1,0000 | 0,9744 | 0,9500 | 0,9268 | 0,9048 |
| | 1,05 | 1,1053 | 1,0769 | 1,0500 | 1,0244 | 1,0000 |
| | 1,07 | 1,1263 | 1,0974 | 1,0700 | 1,0439 | 1,0190 |

The voltages indicated in the table above are the voltages of the generating unit without load, that is, after synchronization, for the generation to supply power to the system, the voltage of the generation must be increased to compensate for the voltage drop in the step-up transformer. However, the voltage variation of the generation must be within the operating limits of the generating units and the maximum voltage supported by the installation components.

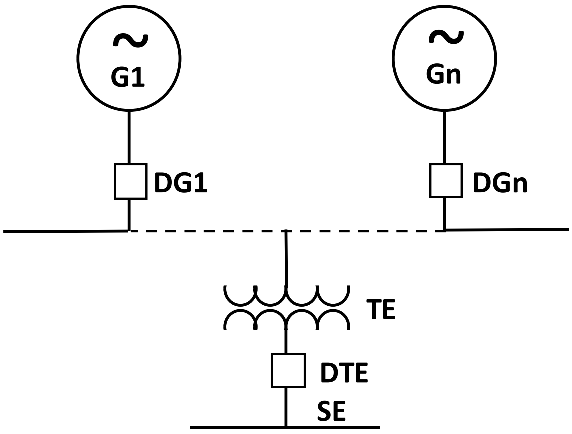
If the generation operating range is ±10%, for the conditions of the values, indicated in red (see table below), it will not be possible to obtain voltages that allow the unit to synchronize.

| | | k- Tap Voltage Used from the Secondary (pu) | | | | |
|---|---|---|---|---|---|---|
| | | -5% | -2,5% | 0 | +2,5% | +5% |
| | | 0,950 | 0,975 | 1,000 | 1,025 | 1,050 |
| | | $V_G$-Generation Voltage (pu) (Values referred to the rated primary voltage of the step-up transformer) | | | | |
| Associated Substation Voltage (pu) | 0,9 | 0,9474 | 0,9231 | 0,9000 | 0,8780 | 0,8571 |
| | 0,93 | 0,9789 | 0,9538 | 0,9300 | 0,9073 | 0,8857 |
| | 0,95 | 1,0000 | 0,9744 | 0,9500 | 0,9268 | 0,9048 |
| | 1,05 | 1,1053 | 1,0769 | 1,0500 | 1,0244 | 1,0000 |
| | 1,07 | 1,1263 | 1,0974 | 1,0700 | 1,0439 | 1,0190 |

For example, if the voltage of the substation associated is at 93% of the rated voltage, i.e., within the precarious range, but with the secondary transformer in the tap of +5%, the generation voltage should be 88.57% of the rated voltage to allow synchronization of the first unit, i.e., the voltage of the generation will be below the unit's operating limit.

### 7.2 - Voltage of the Generating Unit

Considering the example of the configuration of two equal generating units, connected to the substation associated through a step-up transformer, as shown below:




Whose installations information's are:

- Two generating units (G1, G2) of 50MVA, 13.8kV (±10%),

- A 60/80/100MVA step-up transformer (ONAN/ONAF1/ONAF2), 13.8kV/138 (± 2 x 2.5%) kV, impedance of 10% referred to the power of 60MVA, using the secondary tap corresponding to +2.5%.

- Substation associated of rated voltage of 138kV and with voltage of 141kV at the time considered.

Determine the voltage of the generation, considering that one unit provides the power of 50MVA, with power factor 0.95 and that, the other unit provides 40MVA with power factor 0.95.

With the information available, and assuming that the resistance of the step-up transformer is 1% referred to the power of 60MVA, the worksheet can be filled as follows:

| SYSTEM DATA | | | |
|---|---|---|---|
| Generation, Substation and Step-up Transformer Data | $VP_{TEn}$ | Rated Primary Voltage of Transformer (kV) | 13,8 |
| | $VS_{TEn}$ | Rated Secondary Voltage of Transformer (kV) | 138 |
| | $P_{TEn}$ | Rated Power of Transformer (MVA) | 60 |
| | $Z_n$ | Rated Transformer Impedance (%) | 10 |
| | $R_n$ | Rated Resistance of Transformer (%) | 1 |
| | $k$ | Secondary Used Tap Voltage (pu) | 1,025 |
| | $P_G$ | Total Power Passing Through the Transformer (MVA) | |
| | $FP$ | Total Generation Power Factor | |
| | $V_{Gn}$ | Rated Generation Voltage (kV) | 13,8 |
| | $V_{SE}$ | Voltage at the Associated Substation (kV) | 141 |

| $V_G$ | 13,76 |
|---|---|
| *Generation Voltage (kV)* | |

| $V_G$ | 99,68 |
|---|---|
| *(% de $V_G$)* | |

Note that, without filling the load data, the voltage value of the generation is indicated with being 13.76kV (99.68% of $V_G$), which is the value of the voltage of the generation to synchronize the first unit. If the substation voltage value was 105%, i.e., at 144.9kV, the voltage value of the generation would be 14.4kV (102.44% $V_G$), as calculated in the table of the previous item.

The first unit will be synchronized, by the DTE high voltage circuit breaker, with the voltage of the first unit at 13.76kV. The second unit must be synchronized, by the 13.8kV DG2 circuit breaker, with a voltage of 13.76kV, if the first unit is no load, or in the voltage of the first unit, if the first unit is with load.

For the total defined power to be supplied, one generating unit must supply 50MVA with power factor 0.95 and the other with 40MVA with power factor 0.95. The total power provided will be indicated in the following table:

| | Load | MW | MVAR |
|---|---|---|---|
| G1 | 50MVA, PF 0,95 | 47,50 | 15,61 |
| G2 | 40MVA PF 0,98 | 39,20 | 7,96 |
| Total | 89,85MVA PF 0,97 | 86,70 | 23,57 |

Synchronizing the first unit with the 13.76kV generation voltage, to supply 50MVA power with 0.95 power factor, the generation voltage will be 14.26kV, as calculated in the spreadsheet.

| SYSTEM DATA | | | |
|---|---|---|---|
| Generation, Substation and Step-up Transformer Data | $VP_{TEn}$ | Rated Primary Voltage of Transformer (kV) | 13,8 |
| | $VS_{TEn}$ | Rated Secondary Voltage of Transformer (kV) | 138 |
| | $P_{TEn}$ | Rated Power of Transformer (MVA) | 60 |
| | $Z_n$ | Rated Transformer Impedance (%) | 10 |
| | $R_n$ | Rated Resistance of Transformer (%) | 1 |
| | $k$ | Secondary Used Tap Voltage (pu) | 1,025 |
| | $P_G$ | Total Power Passing Through the Transformer (MVA) | 50 |
| | $FP$ | Total Generation Power Factor | 0,95 |
| | $V_{Gn}$ | Rated Generation Voltage (kV) | 13,8 |
| | $V_{SE}$ | Voltage at the Associated Substation (kV) | 141 |

| $V_G$ | 14,26 |
|---|---|
| **Generation Voltage (kV)** | |

| $V_G$ | 103,36 |
|---|---|
| **(% de $V_G$)** | |

The second generating unit must be synchronized, through the DG2 circuit breaker, with the voltage of 14.26kV and the final voltage will be calculated for the total load of 89.85MVA, with power factor 0.97.

| SYSTEM DATA | | | |
|---|---|---|---|
| Generation, Substation and Step-up Transformer Data | $VP_{TEn}$ | Rated Primary Voltage of Transformer (kV) | 13,8 |
| | $VS_{TEn}$ | Rated Secondary Voltage of Transformer (kV) | 138 |
| | $P_{TEn}$ | Rated Power of Transformer (MVA) | 60 |
| | $Z_n$ | Rated Transformer Impedance (%) | 10 |
| | $R_n$ | Rated Resistance of Transformer (%) | 1 |
| | $k$ | Secondary Used Tap Voltage (pu) | 1,025 |
| | $P_G$ | Total Power Passing Through the Transformer (MVA) | 89,85 |
| | $FP$ | Total Generation Power Factor | 0,97 |
| | $V_{Gn}$ | Rated Generation Voltage (kV) | 13,8 |
| | $V_{SE}$ | Voltage at the Associated Substation (kV) | 141 |

| $V_G$ | 14,59 |
|---|---|
| **Generation Voltage (kV)** | |

| $V_G$ | 105,72 |
|---|---|
| **(% de $V_G$)** | |

In this condition, the voltage of the two generating units will be 14.59kV, i.e. 105.72% of the rated voltage.

With the first unit is synchronized and charged, the second unit should be synchronized, at the 13.8kV bar, with a voltage of 14.26kV and, with the load of 40MVA and power factor 0.98, the voltage of the two units will reach the value of 14.59kV.

### 7.3 - Exceptional Conditions

Depending on the characteristics of the components of the installation and their operating conditions, it may occur that some limits are exceeded and, still, can be circumvented. These simulations can be done with the help of the spreadsheet.

For example, considering that the substation associated voltage is at the maximum precarious voltage limit of 107%, with the step-up transformer at the tap of -5%, the without load voltage of the first unit should be 12.63% above the rated voltage. If we consider this example, the final voltage of the generation will be 16.26kV, that is, 17.80% above the rated voltage of the generating units.

| SYSTEM DATA | | | |
|---|---|---|---|
| Generation, Substation and Step-up Transformer Data | $VP_{TEn}$ | Rated Primary Voltage of Transformer (kV) | 13,8 |
| | $VS_{TEn}$ | Rated Secondary Voltage of Transformer (kV) | 138 |
| | $P_{TEn}$ | Rated Power of Transformer (MVA) | 60 |
| | $Z_n$ | Rated Transformer Impedance (%) | 10 |
| | $R_n$ | Rated Resistance of Transformer (%) | 1 |
| | $k$ | Secondary Used Tap Voltage (pu) | 0,95 |
| | $P_G$ | Total Power Passing Through the Transformer (MVA) | 89,85 |
| | $FP$ | Total Generation Power Factor | 0,97 |
| | $V_{Gn}$ | Rated Generation Voltage (kV) | 13,8 |
| | $V_{SE}$ | Voltage at the Associated Substation (kV) | 147,66 |

| $V_G$ | 16,26 |
|---|---|
| ***Generation Voltage (kV)*** | |

| $V_G$ | 117,80 |
|---|---|
| *(% de $V_G$)* | |

In addition to the generators not being designed to operate at this voltage, the installation components (potential transformers, auxiliary relays, instruments, etc.) also do not support these overvoltage values.

The solution to this specific problem can be use another secondary tap of the step-up transformer, such as +2.5% or +5%.

| SYSTEM DATA | | | |
|---|---|---|---|
| Generation, Substation and Step-up Transformer Data | $VP_{TEn}$ | Rated Primary Voltage of Transformer (kV) | 13,8 |
| | $VS_{TEn}$ | Rated Secondary Voltage of Transformer (kV) | 138 |
| | $P_{TEn}$ | Rated Power of Transformer (MVA) | 60 |
| | $Z_n$ | Rated Transformer Impedance (%) | 10 |
| | $R_n$ | Rated Resistance of Transformer (%) | 1 |
| | $k$ | Secondary Used Tap Voltage (pu) | 1,025 |
| | $P_G$ | Total Power Passing Through the Transformer (MVA) | 89,85 |
| | $FP$ | Total Generation Power Factor | 0,97 |
| | $V_{Gn}$ | Rated Generation Voltage (kV) | 13,8 |
| | $V_{SE}$ | Voltage at the Associated Substation (kV) | 147,66 |

| $V_G$ | 15,19 |
|---|---|
| ***Generation Voltage (kV)*** | |

| $V_G$ | 110,08 |
|---|---|
| ***(% de $V_G$)*** | |

With the tap +2.5%, the generation voltage will be 14.41kV (4.39% above the rated voltage) for the synchronization of the first unit and, 15.19kV (10.08% above the rated voltage) with the total load set.

| SYSTEM DATA | | | |
|---|---|---|---|
| Generation, Substation and Step-up Transformer Data | $VP_{TEn}$ | Rated Primary Voltage of Transformer (kV) | 13,8 |
| | $VS_{TEn}$ | Rated Secondary Voltage of Transformer (kV) | 138 |
| | $P_{TEn}$ | Rated Power of Transformer (MVA) | 60 |
| | $Z_n$ | Rated Transformer Impedance (%) | 10 |
| | $R_n$ | Rated Resistance of Transformer (%) | 1 |
| | $k$ | Secondary Used Tap Voltage (pu) | 1,05 |
| | $P_G$ | Total Power Passing Through the Transformer (MVA) | 89,85 |
| | $FP$ | Total Generation Power Factor | 0,97 |
| | $V_{Gn}$ | Rated Generation Voltage (kV) | 13,8 |
| | $V_{SE}$ | Voltage at the Associated Substation (kV) | 147,66 |

| $V_G$ | 14,87 |
|---|---|
| ***Generation Voltage (kV)*** | |

| $V_G$ | 107,78 |
|---|---|
| ***(% de $V_G$)*** | |

With the tap +5%, the generation voltage will be 14.06kV (1.90% above the rated voltage) for the synchronization of the first unit and, 14.87kV (7.78% above the rated voltage), with the total load set.

With the help of the spreadsheet can be analyzed alternatives, depending on the needs of the user and facilities resources.