C05 - EPS components modeling for load flow studies

A *load flow (LF) analysis* aims to compute the voltages, in magnitude and angle, for all buses in the studied system, using as input data the actual operating configuration of the system, its components' electrical parameters and the consumption and generation which express the system load at one given moment in time. Given the size and complexity of electrical systems and mathematical models that describe their operation, usually computer algorithms are used for this task.

The first step in performing a load flow calculation is to build in the available simulation environment an equivalent representation of the real system, in the form of an one-line diagram (one-line = on a single phase) and to attach to its components (lines, buses, transformers etc) their electrical parameters.

The system components are represented with conventional symbols, and its layout of the one-line diagram may or may not follow the real distances and placements from the real EPS. Professional EPS simulation and analysis software packages usually provide graphical user interfaces (GUIs) which allow an easy implementation of one-line diagrams. However, because graphic diagrams are built mainly for the benefit of the human operator and are not really needed for the LF computation, there are software implementations (usually those created by end-users and with limited availability) that do not use one-line diagrams, but read the input data from files instead.

Te use of one-line diagrams instead of three-phase drawings is possible because load flow algorithms use some simplifying assumptions that ease the computation effort, while giving results close to reality. The most important two of these assumptions are:

- the electric and magnetic circuits are symmetrical on all three phases, for all EPS components
- the mutual influences between neighbouring EPS elements are ignored.

A significant deviation from these assumptions can be seen only during phenomena that occur in system states that cannot be analyzed with load flow algorithms, such as short-circuits.

Thus, in steady state, EPS can be studied on a single phase only, and one-line diagrams are used. In any location within the EPS, the three-phase voltage and current systems are symmetrical and of positive sequence, and the element parameters are of positive sequence.

EPS elements found in one-line diagrams can be grouped in two main categories:

- active elements (which require or generate power: loads, generators)
- passive elements (through which electricity just flows: lines, transformers)

Next, a brief description will be given for the main elements used to build one-line diagrams in load flow simulation softwares.

1. Busbars or nodes

Nodes are EPS points where

- loads and generators are connected and draw or inject power in the grid
- interconnection points separating subsystems, where delimitations are made.

In EPS load flow analysis software, the relevant electrical parameter for nodes is the nominal voltage, based on which the real voltage achieved in operation is judged. In Romania, at 400 kV level, the allowed deviation is 5%, while at lover voltage is of 10%.

2. Synchronous generators

Generators are electrical machines used to convert the circular mechanical motion of their rotor into alternative voltage and current flow. Except wind turbines, which are asynchronous machines, electrical generators are synchronous machines (operate at tyhe same frequency thorought the system).

The input parameters required by load flow algorithms are:

- the rated active power: P_n [MW]
- the nominal power factor: $\cos\varphi_n$, *cos(phi),*
- the nominal phase-to-phase voltage: U_n [kV]
- the synchronous direct (d) and quadrature axis (q) reactances x_d, x_q [p.u.] or [%]

In Fig. 5.1, the conventional symbols for synchronous machines used in DIgSILENT Power Factory and Neplan are given.

(a) (b)

Fig. 5.1 – Synchronous machines in Neplan (a) and DIgSILENT Power Factory

There are two main mathematical representations for generators:

- as real voltage source
- as ideal current source

In the representation as real voltage source, the following values are computed:

- the three-phase rated power: $$S_n = \frac{P_n}{\cos\varphi_n} \text{ [MVA]} \tag{5.1}$$
- the rated impedance $$Z_n = \frac{U_n^2}{S_n} \; [\Omega] \tag{5.2}$$
- the generator's reactance $$x_g = x_d \cdot Z_n \; [\Omega] \; , \; x_g = \frac{x_d}{100} \cdot Z_n \; [\%] \tag{5.3}$$

Based on these equations, the equivalent representation of the synchronous generator has a real voltage source with $\underline{Z}_g$ internal impedance which generates an E_g electromotive force, connected between the g phase and the ground. The current flowing through the circuit is denoted by $\underline{I}_g$ (Fig. 5.2).

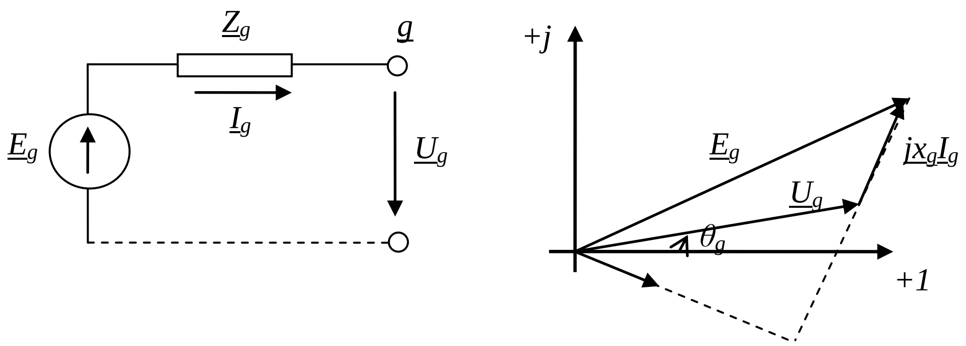


Fig. 5.2 – The equivalent and phasor diagrams of the synchronous generator seen as real voltage source, in steady state operation

Frequently, the phase stator resistance is neglected, and the generator internal impedance becomes purely inductive ($\underline{Z}_g = j \cdot x_g$).

The operating equation in steady state can be written as:

$$\underline{E}_g = \underline{U}_g + j \cdot \underline{x}_g \cdot \underline{I}_g \tag{5.4}$$

In the ideal current source representation, the current of the source is equal to the generator load current:

$$\underline{I}_g = \frac{\underline{S}_g^*}{\underline{U}_g^*} \tag{5.5}$$

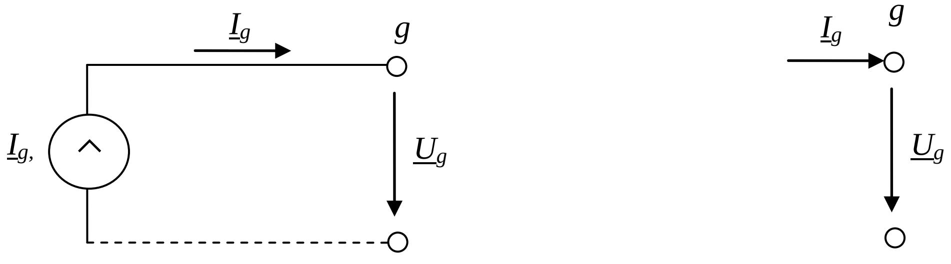


Fig. 5.3 – The equivalent and phasor diagrams of the synchronous generator seen as ideal current source, in steady state operation

In load flow calculations, because generators produce electricity at their nominal voltage, they are used for modelling PV buses, with regulated voltage. Real generators produce reactive power by varying their active/reactive output ratio (power factor). In the same manner, PV buses use a variation of the generated reactive power between set minimum and maximum limits in order to keep the bus voltage at the desired setpoint. The load flow algorithm needs as input data the generated active power, the imposed voltage magnitude and the reactive generation limits, and it will compute the voltage angle and the reactive power.

3. Loads

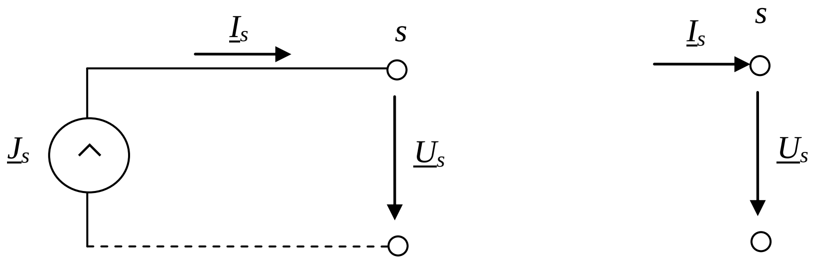
When analyzing EPS buses, loads are usually complex consumptions measured at station or substation transformers, aggregated from all consumers connected below the transformer.

In steady state operation conditions, when there is no active or reactive power deficit, and the frequency and voltage levels are closed to nominal, loads are modeled with constant active and reactive power values, for a given time interval (usually an hour):

$$P_s = const$$
$$Q_s = const \tag{5.6}$$

Other load representations:

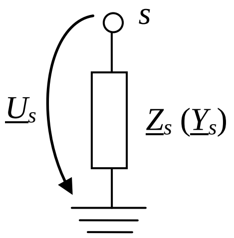
- as current source:



$$\underline{J}_s = -\underline{I}_s$$

Fig. 5.4 – The complete and simplified representation of loads as current sources

- as impedance:



$$\underline{Y}_s = \frac{1}{\underline{Z}_s}$$

Fig. 5.5. – Load representation as impedance

- as variable curves:

In some operating states with active and reactive power deficit, static load curves are used, which reflect consumption change at slow voltage and frequency variations specific to steady state operation:

$$P_s(U, f)$$
$$Q_s(U, f) \tag{5.7}$$

Frequency deviation can lead to loss of synchronism thorought the system and ultimately collapse. Thus, *f* is a closely monitored parameter in EPS, because it must be kept at all times at its nominal value or very close to it. With constant frequency, sometimes are of interest load variations when voltage varies, when usually a second degree polynomial representation is used:

$$\begin{aligned} P_{s*} &= a_P \cdot U_*^2 + b_P \cdot U_* + c_P \\ Q_{s*} &= a_Q \cdot U_*^2 + b_Q \cdot U_* + c_Q \end{aligned} \tag{5.8}$$

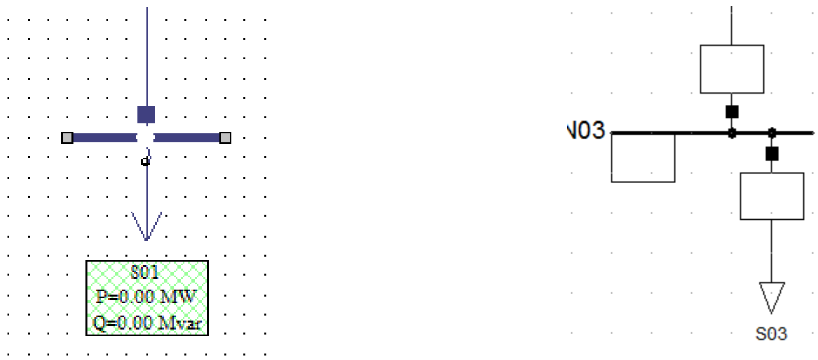
where $P_{s*} = \dfrac{P_s}{P_{S0}}; Q_{s*} = \dfrac{Q_s}{Q_{S0}}; U_* = \dfrac{U}{U_n}$, P_{s0} and Q_{s0} being the load at nominal voltage.

The polynomial coefficients from (5.8) must satisfy:

$$a_P + b_P + c_P = a_Q + b_Q + c_Q = 1 \tag{5.9}$$

and must be updated periodically, when changes in the bus load patterns occur.

The graphical representation of loads in one-line diagrams built in DIgSILENT Power Factory and Neplan is given in Fig. 5.6.



(a) (b)

Fig. 5.6 – Graphical representation for loads in Neplan (a) and DIgSILENT Power Factory (b)

4. Electrical lines

Lines are the pathways on which electricity flows from the generation sites to the consumer sites. For load flow computations, the following parameters are required for defining a line

- The electrical parameters for the 1 km length
- series
    - resistance r_0 [Ω/km] which measures the opposition to the passage of an electric current through the wire
    - reactance x_0 [Ω/km], the opposition to the passage of alternating sine wave current because of capacitance or inductance
- line-to ground
    - conductance, g_0 [S/km] which measures active power loses due to insulation flaws and the corona discharge effect
    - capacitive susceptance b_0 [Ω/km] between circuits and circuits and ground.

- number of parallel circuits n_c
- line length l [km]

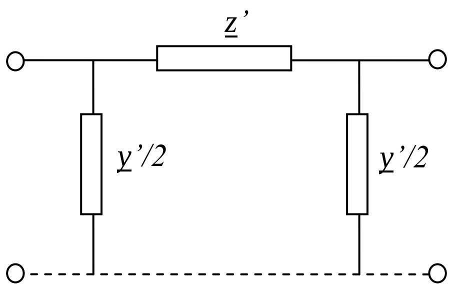
Based on these values, the line parameters are computed, the impedance $\underline{z}$ and admittance $\underline{y}$:

$$\underline{z} = l \cdot (r_0 + j \cdot x_0) / n_c$$
$$\underline{y} = l \cdot (g_0 + j \cdot b_0) \cdot n_c \tag{5.10}$$

These values differ according to the wire material used (copper, aluminum, steel of different cross-sections) and types of poles. Electrical parameters values for 1 km of wire are given by wire manufacturers in catalogues.

There are several types of line mathematical models used by software applications

- for OHL short lines (length up to 80 km), the conductance and capacitive susceptance can be neglected, and only the impedance z is used.
- for medium and long lines, two models can be used:
  - PI with lumped parameters (Fig. 5.7)



$$\underline{z}' = \underline{z} \cdot \underline{k}_z$$
$$\underline{y}' = \underline{y} \cdot \underline{k}_y \tag{5.11}$$

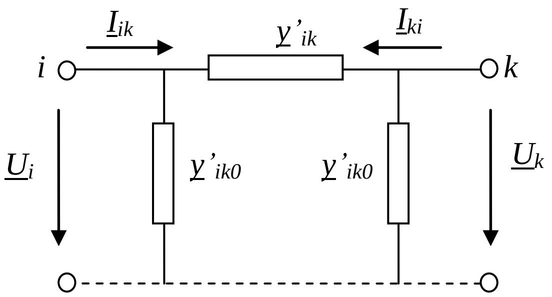
Fig. 5.7 – The PI model for electrical lines

$\underline{k}_z$ and $\underline{k}_y$ are correction coefficients. For OHLs up to 100 km in length and ground cables up to 50 km, the $\underline{k}_z = \underline{k}_y = 1$ approximations are allowed . For OHLs with length up to 250 km, the following expressions are used

$$\underline{k}_z \approx 1 + \frac{\underline{z} \cdot \underline{y}}{6}, \quad \underline{k}_y \approx \frac{1 + \frac{\underline{z} \cdot \underline{y}}{12}}{1 + \frac{\underline{z} \cdot \underline{y}}{6}} \tag{5.12}$$

For higher length lines, the exact values of $\underline{k}_z$ and $\underline{k}_y$ are used. Frequently, the PI quadrupole in which all elements are expressed with admittances is used. In Fig. 5.8 and (5.13-5.14), its equivalent circuit and mathematical equations are given, in which the r_{ik}, x_{ik}, b_{ik} parameters are the same as in (5.10).

$$\begin{bmatrix} \underline{I}_{ik} \\ \underline{I}_{ki} \end{bmatrix} = \begin{bmatrix} \underline{y}_{ik} + \underline{y}_{ik0} & -\underline{y}_{ik} \\ -\underline{y}_{ik} & \underline{y}_{ik} + \underline{y}_{ik0} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_i \\ \underline{U}_k \end{bmatrix} \tag{5.13}$$

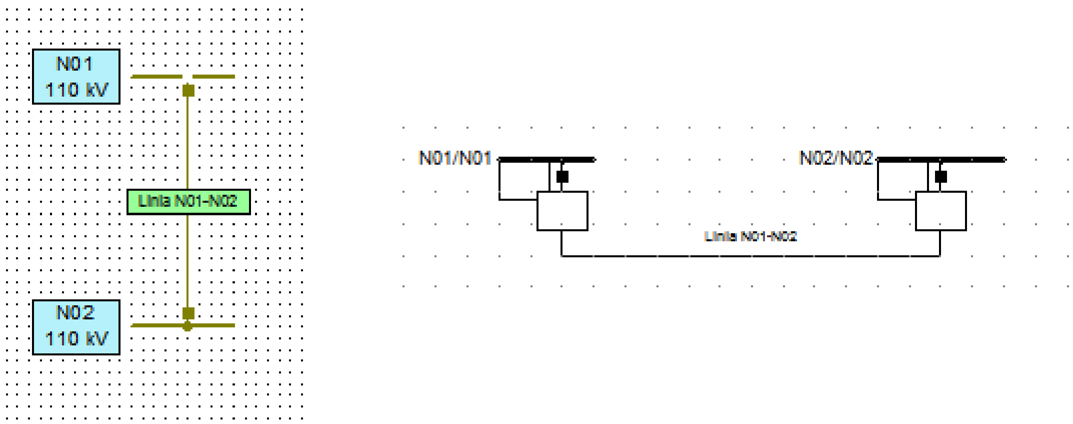


$$
\underline{y}'_{ik} = \frac{1}{\underline{z}'_{ik}} = \frac{1}{r'_{ik} + j \cdot x'_{ik}}
$$
$$
\underline{y}'_{ik0} = \underline{y}'_{ki0} = j \cdot \frac{b'_{ik}}{2} \tag{5.14}
$$

Fig. 5.8 – The PI model with admittances for electrical lines

- the distributed parameters model (the telegrapher's equations).

The graphical representation of lines in one-line diagrams built in DIgSILENT Power Factory and Neplan is given in Fig. 5.9.



(a) (b)

Fig. 5.9 – Graphical representation for lines in Neplan (a) and DIgSILENT Power Factory (b)

5. Transformers

Transformers used in EPS can be

- power transformers, through which electricity flows to the consumer and are used for stepping up or stepping down the voltage in transmission and distribution systems
- measurement transformers, used in substations for measurement devices, which need the transformation of high voltages and currents.

Three-phase power transformers can be

- 2-winding transformers
- 3-winding transformers
- auto-transformers

For load flow computations, the following parameters are needed for 2-winding transformers, provided by producers in equipment catalogues and given on transformer factory plates:

- the rated power S_n [MVA]

- the nominal voltage on the HV winding U_n^{IT} [kV]
- the nominal voltage on the LV winding U_n^{JT} [kV]
- the short-circuit voltage u_{sc} [%]
- the no-load current i_o [%]
- load or copper losses ΔP_{sc} [kW]
- no-load or iron losses ΔP_0 [kW]
- tap changer ratios and steps
- the vector groups of windings (Y, d or Z)

Using as reference one of the nominal voltages, denoted in (5.15) with U_n , the four electrical parameters are computed:

$$R_T = \frac{\Delta P_{sc} \cdot U_n^2}{S_n^2} \cdot 10^{-3} \quad [\Omega] \qquad X_T = \frac{u_{sc} \cdot U_n^2}{100 \cdot S_n} \quad [\Omega]$$
$$G_T = \frac{\Delta P_{Fe}}{U_n^2} \cdot 10^{-3} \quad [S] \qquad B_T = \frac{i_0 \cdot S_n}{100 \cdot U_n^2} \quad [S] \tag{5.15}$$

Some software applications, such as EDSA/Paladin Design Base require directly these parameters.

Taking as reference the direction in which power flows through the transformer, the windings are named "primary" and "secondary". When the HV winding is the primary, the transformer is of step down type. When the primary winding is the LV winding, the transformer is of step up type.

Transformers are modelled in load flow algorithms with equivalent circuits with electrical parameters computed with one of the nominal voltages. For simplifying the calculus, it is recommended the use of non-tapped winding (usually, the LV winding). Otherwise, the (5.15) parameters should be recomputed at each tap change.

The most common equivalent representation is the Γ circuit (Fig. 5.10), which has a longitudinal impedance $\underline{Z}$ made from the resistance R_T and reactance X_T, and a $\underline{Y}$ shunt admittance of conductance G_T and susceptance B_T. On the longitudinal branch, an ideal transformer is series coupled, described by its complex $\underline{N}$ turns ratio, with the magnitude computed as the ratio of the windings' voltages at no load operation, and with the angle determined by the transformer's vector group.

$$\underline{N} = N \cdot e^{j\theta} \tag{5.16}$$

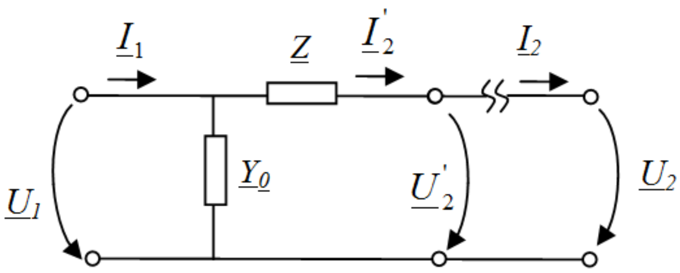


Fig. 5.10 – The Γ representation of the 2-winding transformer

The actual turns ratio is defined as the ratio between the non-tapped winding and tapped winding.

$$N = \frac{U^{nt}}{U^{t}} \tag{5.17}$$

The tapped winding voltage is given by its nominal voltage and actual tap setting:

$$U^{t} = U_{n}^{t}\left[1 + (w_{n} - w)\cdot\frac{\Delta U}{100}\right] \tag{5.18}$$

where U_n^{nt}, U_n^{t} - the nominal non-tapped and tapped winding voltage; w – actual tap setting; w_n – the nominal tap; ΔU – tap changer ratio. The U^{nt} *and* U_n^t values correspond to nominal tap setting, w_n, operation, which usually is the median tap, while U^t is the voltage value corresponding for the w tap setting.

In Figures 5.11 and 5.12 and eqs. (5.19) and (5.20), the Γ representations and operational equations for step up and step down 2-winding transformers are given.

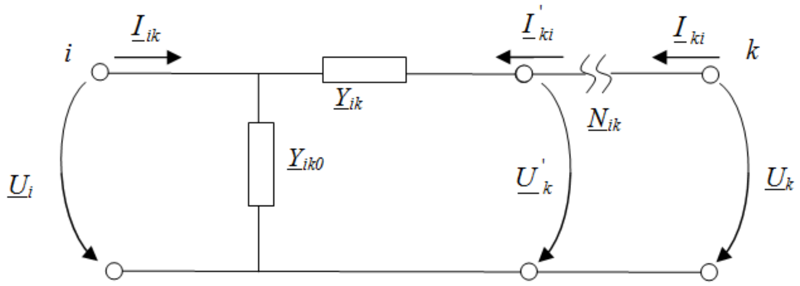


Fig. 5.11 – The Γ representation of the step up transformer

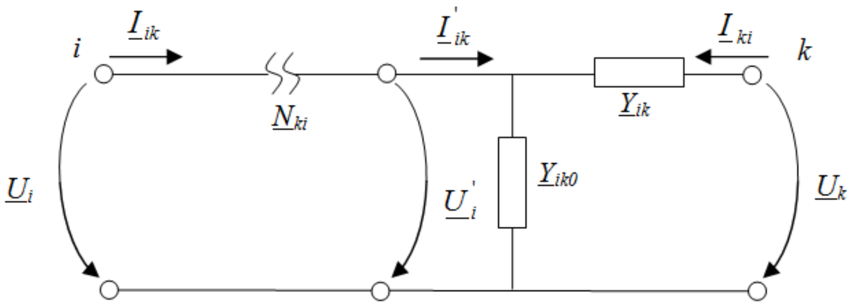
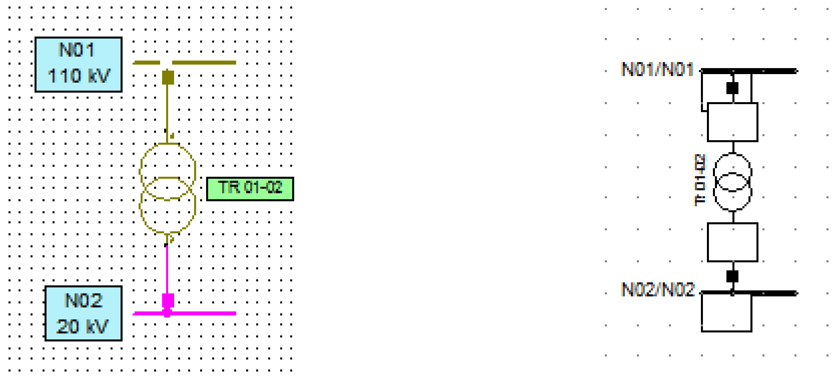


Fig. 5.12 – The Γ representation of the step down transformer

$$\begin{bmatrix} \underline{I}_{ik} \\ \underline{I}_{ki} \end{bmatrix} = \begin{bmatrix} \underline{y}_{ik} + \underline{y}_{ik_0} & -\underline{N}_{ik}\cdot\underline{y}_{ik} \\ -\underline{N}_{ik}^{*}\cdot\underline{y}_{ik} & \underline{N}_{ik}^{2}\cdot\underline{y}_{ik} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_{i} \\ \underline{U}_{k} \end{bmatrix} \tag{5.19}$$

$$\begin{bmatrix} \underline{I}_{ik} \\ \underline{I}_{ki} \end{bmatrix} = \begin{bmatrix} (\underline{y}_{ik} + \underline{y}_{ik_0})\cdot\underline{N}_{ki}^{2} & -\underline{N}_{ki}^{*}\cdot\underline{y}_{ik} \\ -\underline{N}_{ki}\cdot\underline{y}_{ik} & \underline{y}_{ik} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_{i} \\ \underline{U}_{k} \end{bmatrix} \tag{5.20}$$

The graphical representation of 2-winding transformers in one-line diagrams built in DIgSILENT Power Factory and Neplan is given in Fig. 5.13.



(a) (b)

Fig. 5.13 – Graphical representation for 2-winding transformers in Neplan (a) and DIgSILENT Power Factory (b)

The approach is similar for the 3-windings transformer. Its conventional symbol and equivalent Γ representation are given in Fig. 5.14.

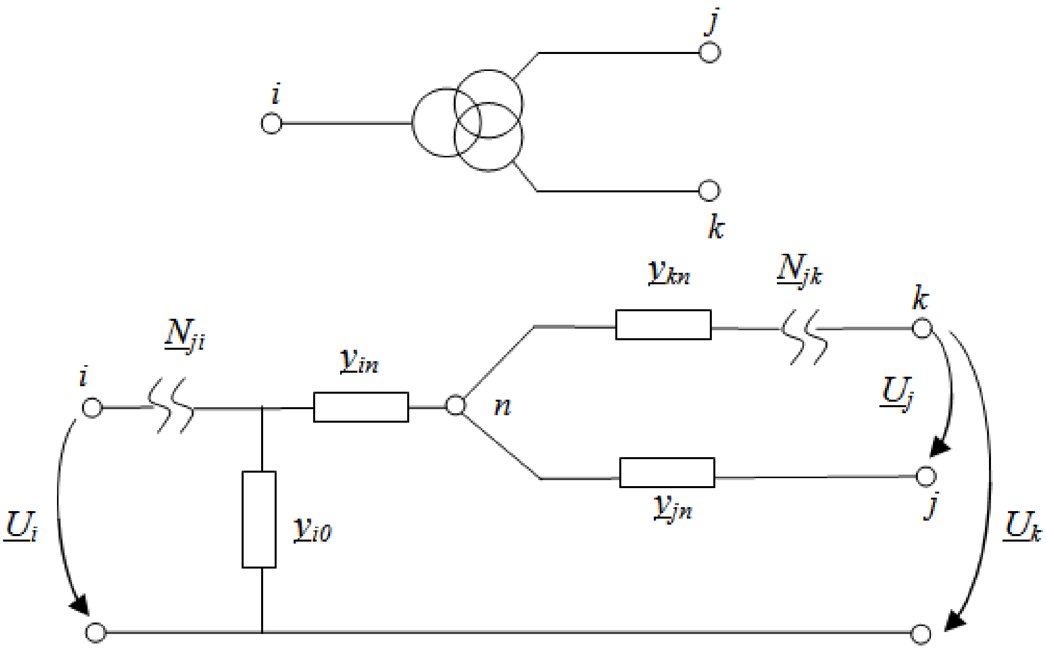


Fig. 5.14 – Conventional symbol and equivalent Γ representation for 3-winding transformers