C04 - Computer aided analysis of electrical power systems

Figure 4.1 depicts a schematic representation of the Moldavian section of the Romanian transmission system. White hollow points are **buses**, 400/110 kV substations (Suceava, Roman Nord, Bacău Sud and Gutinaş) and 220/110 kV substations (Suceava, Gutinaş, Iaşi, Munteni, Dumbrava, Stejaru). Buses are points of generation or consumption. Blue lines are **branches**, 220 kV electrical lines, while red lines are 400 kV lines. Branches serve as interconnections between buses.

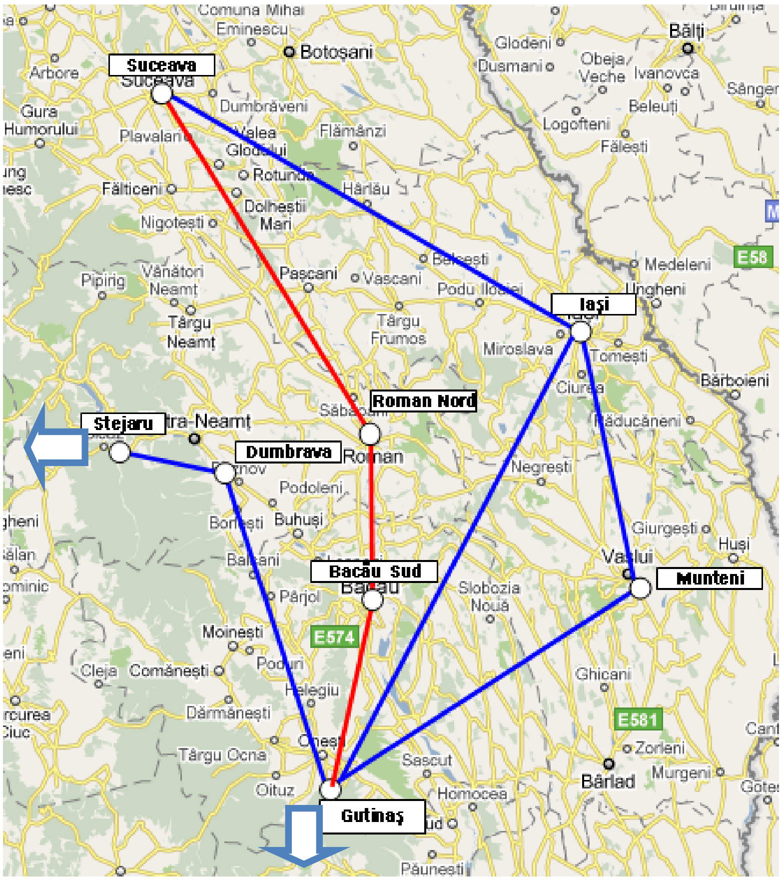


Fig. 4.1 - The transmission system in the geographical area of Moldova, Romania

This subsystem is interconnected, through other lines not represented in the graphic, with the rest of the country as follows: to the west from the Stejaru station, and to the south from the Gutinaş station, and it supplies the 110 kV HV distribution system in the Botoşani, Suceava, Neamţ, Iaşi, Vaslui and Bacău.

The dispatchers of the national transmission system are located in Bucharest. In their mission of monitoring and control, they receive real time data from the field, obtained from measuring devices and relays through the communications network built into the system, and also use SCADA archives in order to ensure at all times that the following operating requirements are met:

- supply of consumers with a guaranteed security level, defined by normatives
- keeping the main quality indicators of supply (frequency, voltage, harmonics level, phase unbalance)
- optimal operation, with minimal costs
- compliance with environmental restrictions.

From the technical standpoint, the dispatchers must:

- ensure the balance between the generated and consumed energy
- keep the bus voltages in the voltage ranges specified in normatives
- keep active and reactive generation of generation units between specified limits
- ensure that lines and transformers load do not exceed the limits for long periods of time
- take appropriate measures when accident occur, in order to prevent blackouts or limit to the minimum their effects

Dispatchers know the geographical layout of the monitored system, its network elements and their electrical parameters, and receive other data collected from the field which tell them the actual operational configuration of the network and its loading condition. All this information is processed into specialized analysis software tools, which help in taking the required decisions.

The first most used system analysis procedure is the load flow study, if it can be defined as follows (see also Fig. 4.2): knowing the EPS elements with their electrical parameters, the operational configuration and loading in all buses, at a given moment, all the bus voltages, in magnitude and angle, can be computed.

Knowing the bus voltages, other data of interest may be derived: branch power and current flows, branch power losses, branch voltage drops, element loadings.

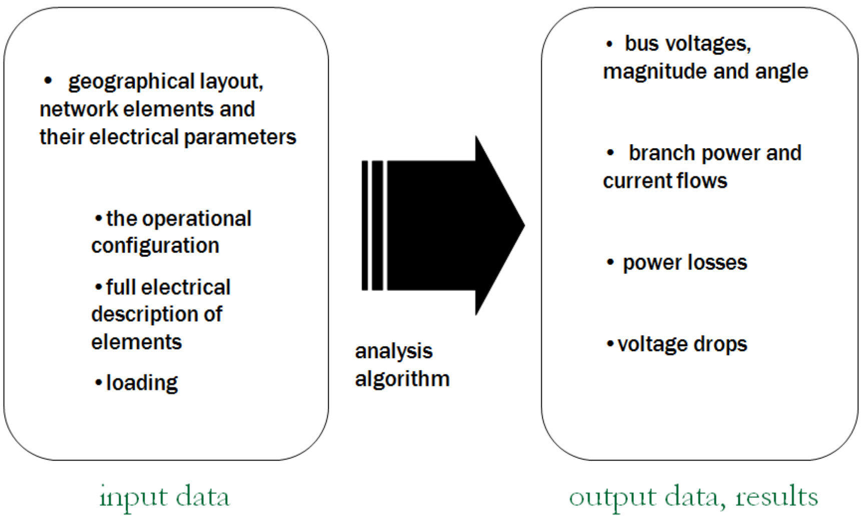


Fig. 4.2 - The principle of load flow calculation

A brief motivation on why these data are important to know is given in Table 4.1.

Table 4.1 - Load flow results and their use

load flow variable	importance
Bus voltages - magnitude	In every bus of the system, the voltage magnitude must always remain in a specified range, defined by normatives. Working at a too low or too high voltage, electrical equipment ca malfunction, wear out prematurely or become defective.
Bus voltage - angle	Voltage angle is important for stability studies. An important difference in phase angle between two ends of a branch is a sign of heavy loading. A breaker can be closed only if the voltage angles at its sides are of close values.
Branch power /current flow - active	Electrical lines and transformers have physical operating loading margins, which should not be exceeded. An overloaded line will have higher losses and, in extreme cases, can suffer of insulation damage or be taken out of service, being tripped but the protection relays. Such contingencies are a main cause for blackouts. Equipment and wires are sized for thermal limit current values.
Branch power /current flows - reactive	Voltage levels in an EPS are closely related to the amount of reactive power flows. Too much reactive power will increase the voltage, while too little reactive power will drop down the voltage.
Active power losses	Active power losses should be kept at a minimum, because lost power cannot be billed to customers and it's a waste of primary resources.
Branch loading	Under loaded equipment does not function at its optimum. Lines will generate reactive power through the capacitive effect, raising the voltage levels, and transformers no-load losses do not change. Overloaded equipment can be the cause of heavy losses or can be tripped out by protection relays, generating system instability, or can be damaged by the stress. An overloaded system can have frequency stability problems, leading to blackout.

Load flow computations are now used in offline analyses, in tasks such as the following:

- EPS extension or initial design, for proper sizing of the necessary equipment (lines, transformers, protection relays)
- the maintenance of operational systems, in approving fixes and upgrades, which should have a minimal effect on the operating conditions of the EPS
- post-mortem analyses, based on measurements taken at the occurence of blackouts or other unwanted effects, for simulating sequences of events and understanding their causes.

While load flow algorithms remain today an essential tool for dispatch centers, in real time analysis, often it is not possible to know active and reactive powers from all buses, required to perform a load flow calculation. In this case, state estimation algorithms are used, which are based on the same principles as LF algorithms, but use other and fewer input data.

There are several professional software packages oriented for power system analysis, such as EDSA/Palladin [webEDSA], ETAP [webETAP], Neplan, [webNeplan], DIGSilent Power Factory [webDIGsi], which all offer a load flow module. Regardless of the chosen LF algorithm implementation and graphical interface differences, performing a load flow computation requires several steps, described subsequently.

1. Building of the one-line diagram of the EPS and specify electrical parameters for all elements

One-line representations are preferred because, in 3-phase load flow analysis, the system loading and parameters are considered symmetrical, so the representation of one phase is sufficient.

On an one-line diagram, the following main elements are represented using graphical conventional symbols:

- buses, which are places in the system where energy is produced or consumed. These places can be:
  - power stations or substations
  - interconnections with external systems, represented as equivalent loads
  - individual or aggregated consumers
  - generators.

In an aggregated bus, several generators and/or consumers can be connected.

- branches, which can be:
  - electrical lines on which electricity flows between buses
  - station and substation transformers
  - other series or shunt elements which affect the operating state of the EPS (reactance coils or reactors, capacitor banks, synchronous condensers or compensators).

Other network elements such as circuit breakers and protection relays are not vital in power flow calculations and they usually have a simpler representation or they are not represented at all.

To each graphical symbol, one or more of electrical parameters are attached, which are measures and types of influences that the element is exercising on the system, because of the effects induced by voltage, current or power flows through that element.

In the one-line diagram, the common grounding of all network elements is chosen as reference bus (the bus by which all variables are computed), which is often not visible on the diagram. All other buses are always visible and they are independent buses, described electrically by four parameters:

- the active power P
- the reactive power Q
- the voltage magnitude U
- the voltage angle θ.

In load flow computations, two of these parameters are known or imposed, and the other two will be computed by the load flow algorithm. From this perspective, the buses from an EPS are classified in three categories:

- PQ or consumer buses, for which the active and reactive power are known and the voltage magnitude and angle are computed; the majority of buses in the system are PQ buses.
- PV or generator buses, for which the active power and voltage magnitude are known, together with the maximum and minimum reactive power allowed: $Q_{min} \leq Q \leq Q_{max}$, and the reactive power and voltage angles must be computed. Generator buses are the buses with regulated voltage.
- slack buses (SL), usually one for an EPS, for which the voltage magnitude and angle are known, the angle being set as reference for the entire EPS with the value 0. The slack bus' active and reactive power are computed by the LF algorithm and represent the total infeed from the external system, needed to supply the local consumption and covering the power losses.

For branches, the electrical parameters

- resistance
- reactance
- conductance
- susceptance

are specified, taken from producer catalogues, and also depending on some other system specific parameters: line length, number of parallel circuits or transformers, the chosen mathematical representation. The start and end bus of each branch are usually derived from the one-line diagram, but if no graphical representation are available, they must be provided as input data.

2. Building of the bus admittance matrix $[\underline{Y}_n]$

The bus admittance matrix is a square matrix, with a number of rows equal to the number of independent buses in the system, and memorizes the EPS topology and electrical parameters for all EPS elements. It sis computed based on the input data presented above.

3. The load flow computation

Depending on the representation model for loads, load flow methods are divided in two main categories:

- Topological, linear methods, in which loads are represented using currents. These are straightforward methods and find the exact solution of the problem, but require computing the inverse of large sized complex matrices. Their use is feasible only on small, radial systems such as MV/LV distribution systems.

An example of such a method is the backward/forward sweep.

- Iterative methods, where the bus loads are considered non-linear. These start with a given approximation of the state variables and determine an approximation of the exact solution applying a series of corrections to the initial approximation of the state values or recomputing it at each step.

Iterative load flow methods are

- The Gauss-Seidel method
- The Newton-Raphson method and its variants

4. Computation of auxiliary results

All load flow algorithms compute bus voltages in magnitude and angle for all EPS buses and the reactive powers in the PV buses. These voltages are used subsequently to compute:

- branch active and reactive power flows;
- branch active and reactive power losses
- slack bus active and reactive power infeed
- branch voltage drops
- branch current flows
- element loadings

which give a complete picture of the EPS operating status for the given load conditions and EPS configuration..

Example

The one-line diagram implementation procedure for the DIGSilent Power Factory v. 14 software

The main DIGSI-PF window is depicted in Fig. 4.3. The main tool using for picking, placing, moving, connecting and resizing objects is the mouse.

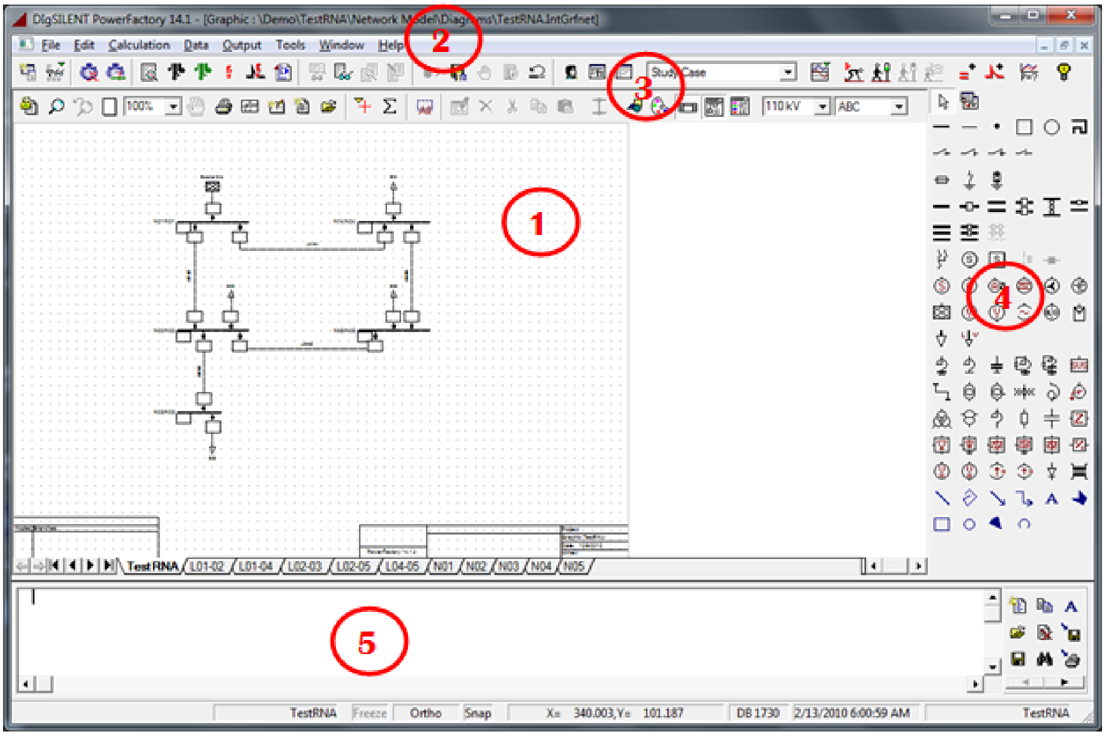
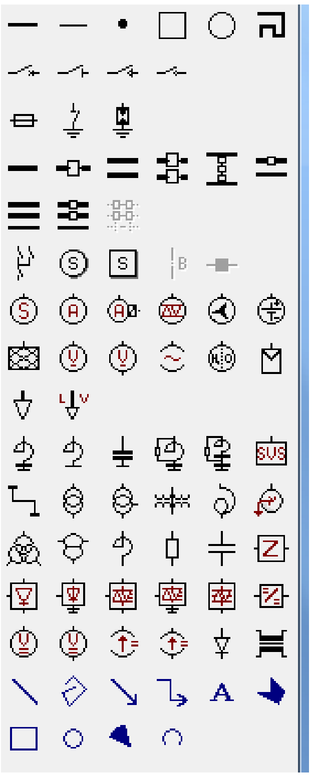


Fig. 4.3. – The main DIGSilent Power Factory v. 14 window
1 – main working area, where diagrams are drawn; 2 – Menu bar;
3 – Toolbars; 4 – Components panel; - 5 – Message area

The complete palette of objects that can be placed in an one-line diagram, together with a selection of the most used ones, is given in Fig. 4.4.

An element can be selected from the components panel by clicking on it with the mouse (normal left click). The selection is cancelled by pressing the mouse right button or the **Esc** key. While the selection is active, the mouse cursor will be followed by a small icon of the selected item (Fig. 4.4).

The element is placed on the working diagram by clicking with the mouse. If the element is to be connected on a busbar, a supplementary window opens when clicking on that busbar, and the element must be connected to a free cubicle (new ones are created automatically when all available are full) (Fig. 4.5).



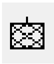
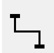
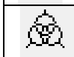
	bus (Single Busbar System)
	External Grid, used to define the slack bus
	Electrical line (Line)
	2-Winding Transformer
	3-Winding Transformer
	Synchronous Machine, used for defining PV buses
	load

Fig. 4.4 – The components panel in DIGSilent Power Factory

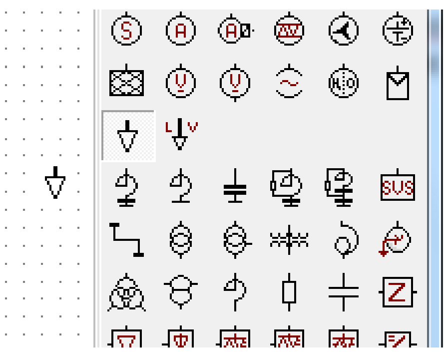


Fig. 4.5 - The selection of a load element

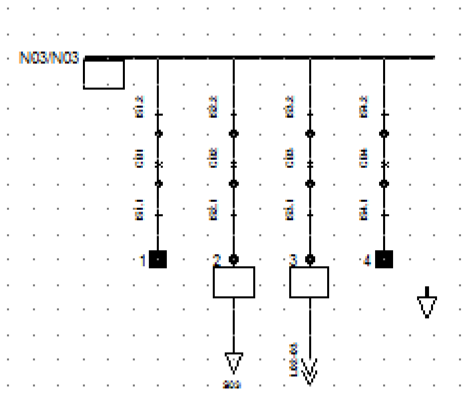


Fig. 4.6. - Connecting a load on a busbar

The one-line diagram from Fig. 4.3 has 5 buses, 5 lines, 4 loads and one external grid. Electrical parameters must be defined for these elements, and they are given in Tables 4.2 and 4.3.

Table 4.2 – Branch data for the test system in Fig. 4.3

Name	IN bus	OUT bus	Conductor cross-section	Length km	
L01-02	N01	N02	150 mm^2	20	R_0=0.198 Ω/km X_0=0.433 Ω/km B_0=2.66 µS/km
L01-04	N01	N04	150 mm^2	40	
L02-03	N02	N03	150 mm^2	60	
L02-05	N02	N05	150 mm^2	40	
L04-05	N04	N05	150 mm^2	20	

Table 4.3 – Bus data for the system in Fig. 4.3

Bus	Bus type	Nominal voltage kV	Pi MW	Qi MVAr
N01	slack	110		
N02	PQ	110	17	3
N03	PQ	110	12	1
N04	PQ	110	8	1
N05	PQ	110	8	1

An one-line diagram built in DIGSI-PF for the EPS presented in Fig. 4.1 is depicted in Fig. 4.7. Electrical parameters of elements are witheld because of confidentiality clauses.

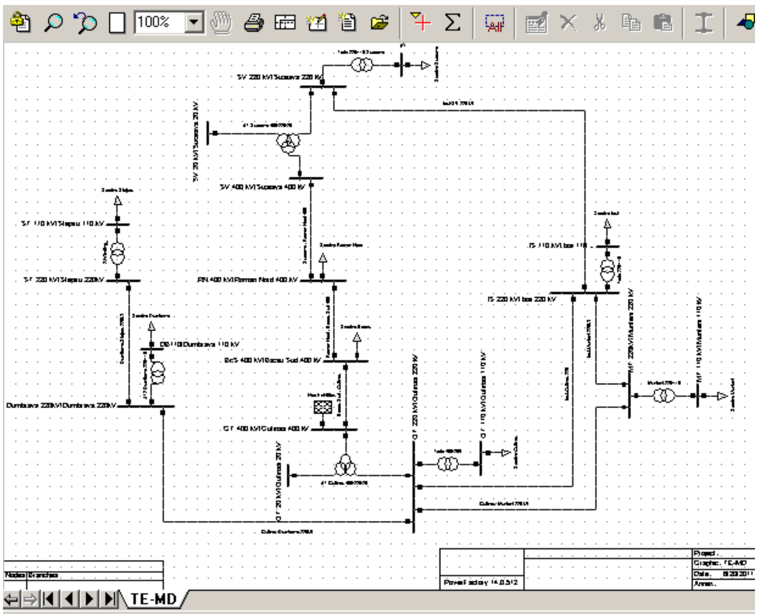


Fig. 4.7 - The one-line diagram for the EPS in Fig, 4.1, implemented in DIGSilent Power Factory.

References

[webEDSA] http://www.poweranalytics.com/
[webETAP] http://etap.com/
[webNeplan] http://www.neplan.ch/
[webDIGsi] http://www.digsilent.de/