

Chapter 2

Modelling of Transmission Systems Under Unsymmetrical Conditions and Contingency Analysis Using DIgSILENT PowerFactory

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Abstract DIgSILENT PowerFactory is a powerful software which includes a power system analysis function designed to cope with large power system power flows, and it handles both DC and AC lines, including all phase combinations (3ph, 2ph and single phase), with/without neutral conductor and ground wires, for both single circuit and mutually coupled parallel circuits. Although power systems are designed and normally operated in balanced (symmetrical) three-phase sinusoidal conditions, there are certain situations that can cause undesired conditions, namely the unbalanced conditions. Uneven distribution of single-phase loads is one of the main unbalanced conditions in distribution level. The objective of this chapter is to provide an extensive review of the main features of steady-state analysis which are included in PowerFactory. Steady-state analysis in PowerFactory covers the normal

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operation (*ComLdf*) and the contingency analysis (*ComSimoutage*). This chapter has been divided into three distinct parts. The first part presents the main features of modelling overhead transmission lines (*ElmTow*, *TypTow*, *TypGeo*). Secondly, power flow analysis (*ComLfd*) under unbalanced conditions is illustrated. Finally, the third part of this chapter deals with the security assessment or contingency analysis for single time-phase contingency analysis. The deterministic assessment of failure effects under contingencies within a single period (*ComOutage*, *ComNmink*, *ComSimoutage*) is also analysed.

Keywords Contingency analysis • Distribution factors • Overhead line • Unbalanced conditions

2.1 Introduction

A classic assumption about the power systems is that they are designed to be *symmetrical* and *balanced*. A symmetrical set of three-phase voltages of three phases is a set of three voltages in which each voltage is sinusoidal and has the same amplitude, and the set is arranged in such a sequence that the angular phase difference between each member of the set and the one following it, and between the last member and the first, can be expressed as the same multiple of the characteristic angular phase difference of $2/3$ radians. Assuming a set of positive sequence voltage current applied to an electric device, symmetrical refers to the use of the same impedance per phase in that component, e.g. same stator resistance in phases *a*, *b* and *c* in a synchronous generator.

On the other hand, balance conditions refer to the symmetry in electrical quantities (voltage, current, power, etc.), i.e. a circuit in which there are substantially equal currents, either alternating or direct, in all main wires and substantially equal voltages between main wires and between each main wire and neutral (if one exists). A real power system working under normal operational conditions can be assumed symmetrical and balanced; however, there are asymmetrical and unbalanced conditions that must be included in the case of an exact model representation.

One of the intrinsic causes of asymmetric impedance is transmission lines, e.g. asymmetrical geometric configuration of transmission line without transposition is the main source of asymmetrical impedance in power systems. Terminal conditions as phase technologies (3ph, 2ph and single phase, with/without neutral conductor and ground wires) establish unbalance conditions in three-phase symmetrical power system. Uneven distribution of single-phase loads is one of the main unbalanced conditions in distribution level.

The planning, design and operation of power systems require such calculations to analyse the steady-state (quiescent) performance of the power system under various operating conditions and to study the effects of changes in equipment configuration [1, 2]. One of the most common computational procedures used in

power system analysis is the load flow calculation. A number of operating procedures can be analysed, including contingency conditions, such as the loss of a generator, a transmission line, a transformer or a load. These load flow solutions are performed using computer programs designed specifically for this purpose. DIgSILENT PowerFactory is a powerful software that includes a power system analysis function designed to cope with large power system power flows, and it handles both DC and AC lines, including all phase technologies (3ph, 2ph and single phase), with/without neutral conductor and ground wires, for both single circuit and mutually coupled parallel circuits [3].

This chapter is designed to present the main features of power flow analysis on unbalanced conditions using power system analysis function in PowerFactory (*ComLfd*).

2.2 Overhead Line Model

DIgSILENT PowerFactory is very flexible power system analysis software, and it has a very wide range of modelling features in terms of transmission lines. PowerFactory provides models from DC to AC lines over all possible phase technologies (3ph, 2ph and single phase, with/without neutral conductor and ground wires) for both single circuit and mutually coupled parallel circuits.

Table 2.1 shows an overview of all supported options and the corresponding element/type combination. The line element, *ElmLne*, is the most basic branch elements, and it is used to represent the model of the overhead transmission lines. The line element can be used to define single-circuit lines of any phase technology according to Table 2.1.

The number of parallel transmission lines without mutual coupling between each other can be adjusted using the parameter *Number of Parallel Lines*. If the mutual coupling between parallel lines is to be considered, then a line coupling element *ElmTow* has to be defined. In that case, the line element *ElmLne* points to a line

Table 2.1 Overview of line models as available in PowerFactory [3]

| System | Phase technology | Element | Type |
|-------------------------------|---------------------------------------|---------------|-------------------------------|
| DC | Unipolar | <i>ElmLne</i> | <i>TypLne</i> |
| AC, single circuit | 1-ph | <i>ElmLne</i> | <i>TypLne</i> |
| | 2-ph | <i>ElmLne</i> | <i>TypLne</i> |
| | 3-ph | <i>ElmLne</i> | <i>TypLne, TypTow, TypGeo</i> |
| | 1-ph with neutral | <i>ElmLne</i> | <i>TypLne</i> |
| | 2-ph with neutral | <i>ElmLne</i> | <i>TypLne</i> |
| | 3-ph with neutral | <i>ElmLne</i> | <i>TypLne</i> |
| AC, mutually coupled circuits | Any combination of phase technologies | <i>ElmTow</i> | <i>TypTow, TypGeo</i> |

coupling element *ElmTow*, which in turn refers to the corresponding tower type *TypTow* or tower geometry type *TypGeo*. However, models based on line types (*TypLne*) are by default *non-frequency dependent*. The user defines the electrical parameters per unit length of the line at a fixed power frequency. These parameters remain unchanged; if the frequency of the simulation changes, i.e. differs from the power frequency, then the program will adjust the reactance and susceptance of the line according to the new frequency. The inductance and capacitance remain, however, unchanged. For certain functions (harmonic load flow, frequency sweeps), the PowerFactory user still has the option to define a frequency characteristic to the parameters in the line type.

For three-phase lines (either single or multiple parallel circuits), the user can choose between two different types of models: *lumped* or *distributed parameters*.

A transmission line is defined as a short-length line if its length is less than 80 km (50 miles). In this case, the shunt capacitance effect is negligible and only the resistance and inductive reactance are considered, and a model based on lumped parameters can be used without any prejudice of the results. If the transmission line has a length between 80 km (50 miles) and 240 km (150 miles), the line is considered a medium-length line and its single-phase equivalent circuit can be represented in a nominal pi circuit configuration. Medium-length line can be modelled using the classical lumped parameters, and there is not mayor negative effect on the accuracy of the obtained results. However, if the line is larger than 240 km, the model must consider parameters uniformly distributed along the line. The appropriate series impedance and shunt capacitance are found by solving the corresponding differential equations, where voltages and currents are described as a function of distance and time. Long transmission lines require the use of distributed parameter models on its calculation, and the model is provided by PowerFactory. For long transmission lines, the distributed parameter model gives highly accurate results and should be the preferred option, while the model with lumped parameters gives accurate enough results for short lines. A line is considered long as long as its length becomes the same order of magnitude of the length of wave of the voltage/current at the grid frequency.

The main features of those models are presented in next subsections.

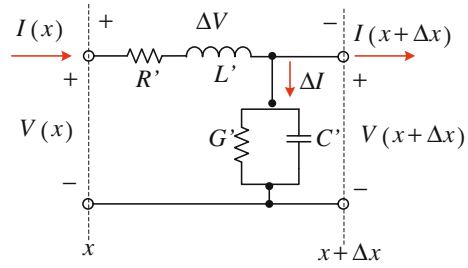
2.2.1 Distributed Parameter Model

The incremental transmission line model is shown in Fig. 2.1. In the case of sinusoidal steady state, it can be modelled by means of two equations:

$$\frac{\partial V}{\partial x} = I(x)Z' \quad (2.1)$$

$$\frac{\partial I}{\partial x} = V(x)Y' \quad (2.2)$$

Fig. 2.1 Incremental model for a line of elemental length



where Z' and Y' are the impedance and the admittance per unit length, respectively, Δx is an elemental length and V and I are the voltage and current, respectively. It must be noted that Z' and Y' are frequency-dependent parameters.

Taking second derivatives (2.1) with respect to x and rearranging the equations to separate the voltage from the current magnitudes, the system of differential can be rewritten as follows:

$$\begin{aligned} V(x) &= K_1 \cdot e^{\gamma \cdot x} + K_2 \cdot e^{-\gamma \cdot x} \\ Z_C \cdot I(x) &= -K_1 \cdot e^{\gamma \cdot x} + K_2 \cdot e^{-\gamma \cdot x} \end{aligned} \quad (2.3)$$

with

$$Z_C = \sqrt{\frac{Z'}{Y'}} \quad (2.4)$$

$$\gamma = \sqrt{Z' \cdot Y'} = \alpha + j\beta \quad (2.5)$$

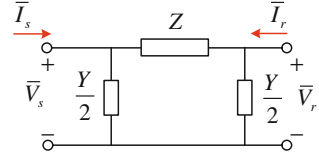
where γ is known as the *propagation factor* and Z_C is the *characteristic impedance* [1]. K_1 and K_2 are integration constants which can be determined from the border conditions at each end of the line. Following the sign convention used in Fig. 2.1, (2.3) can be expressed in the matrix form:

$$\begin{bmatrix} V_r \\ I_r \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & -Z_C \sinh \gamma l \\ \frac{1}{Z_C} \sinh \gamma l & -\cosh \gamma l \end{bmatrix} \begin{bmatrix} V_s \\ I_s \end{bmatrix} \quad (2.6)$$

where subscript r is a magnitude from the receiving end and s from the sending end. An equivalent circuit for (2.6) can be determined as shown in Fig. 2.2. The impedance and admittance of the equivalent circuit are as follows:

$$\begin{aligned} Z &= Z_C \sinh \gamma l \\ Y &= \frac{\cosh \gamma l - 1}{Z_C \sinh \gamma l} \end{aligned} \quad (2.7)$$

Fig. 2.2 Equivalent pi circuit for the line with distributed parameters



2.2.2 Lumped Parameter Model

Lumped parameter model is a simplified model of the distributed parameter model. This model is suitable to describe medium to short lines. The general formulation discussed in this section is valid for any phase configuration by appropriate dimensioning of the impedance and admittance matrices, even though the description is based on a three-phase line without neutral conductor.

According to Fig. 2.3, the equations of the voltages and currents at the sending and receiving ends of the line could be formulated in terms of impedance and admittance matrices. The dimension of the matrices depends on the phase configuration. Therefore, the longitudinal voltage drop along the line (ΔV_i , $i = A, B$ and C) is given by the impedance matrix in the following form:

$$\begin{bmatrix} \bar{V}_{s,A} \\ \bar{V}_{s,B} \\ \bar{V}_{s,C} \end{bmatrix} - \begin{bmatrix} \bar{V}_{r,A} \\ \bar{V}_{r,B} \\ \bar{V}_{r,C} \end{bmatrix} = \begin{bmatrix} \Delta V_A \\ \Delta V_B \\ \Delta V_C \end{bmatrix} = \begin{bmatrix} \bar{Z}_s & \bar{Z}_m & \bar{Z}_m \\ \bar{Z}_m & \bar{Z}_s & \bar{Z}_m \\ \bar{Z}_m & \bar{Z}_m & \bar{Z}_s \end{bmatrix} \begin{bmatrix} \bar{I}_A \\ \bar{I}_B \\ \bar{I}_C \end{bmatrix} \quad (2.8)$$

Following the sign convention assumed in Fig. 2.3, the current at the sending and receiving ends of the line is calculated in terms of the *admittance matrix* as follows:

$$\begin{aligned} \begin{bmatrix} \bar{I}_{s,A} \\ \bar{I}_{s,B} \\ \bar{I}_{s,C} \end{bmatrix} &= \begin{bmatrix} \Delta \bar{I}_{s,A} \\ \Delta \bar{I}_{s,B} \\ \Delta \bar{I}_{s,C} \end{bmatrix} + \begin{bmatrix} \bar{I}_A \\ \bar{I}_B \\ \bar{I}_C \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \bar{Y}_s & \bar{Y}_m & \bar{Y}_m \\ \bar{Y}_m & \bar{Y}_s & \bar{Y}_m \\ \bar{Y}_m & \bar{Y}_m & \bar{Y}_s \end{bmatrix} \cdot \begin{bmatrix} \bar{V}_{s,A} \\ \bar{V}_{s,B} \\ \bar{V}_{s,C} \end{bmatrix} + \begin{bmatrix} \bar{I}_A \\ \bar{I}_B \\ \bar{I}_C \end{bmatrix} \\ \begin{bmatrix} \bar{I}_{r,A} \\ \bar{I}_{r,B} \\ \bar{I}_{r,C} \end{bmatrix} &= \begin{bmatrix} \Delta \bar{I}_{r,A} \\ \Delta \bar{I}_{r,B} \\ \Delta \bar{I}_{r,C} \end{bmatrix} - \begin{bmatrix} \bar{I}_A \\ \bar{I}_B \\ \bar{I}_C \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \bar{Y}_s & \bar{Y}_m & \bar{Y}_m \\ \bar{Y}_m & \bar{Y}_s & \bar{Y}_m \\ \bar{Y}_m & \bar{Y}_m & \bar{Y}_s \end{bmatrix} \cdot \begin{bmatrix} \bar{V}_{r,A} \\ \bar{V}_{r,B} \\ \bar{V}_{r,C} \end{bmatrix} - \begin{bmatrix} \bar{I}_A \\ \bar{I}_B \\ \bar{I}_C \end{bmatrix} \end{aligned} \quad (2.9)$$

Fig. 2.3 Equivalent pi circuit of the line for lumped parameters

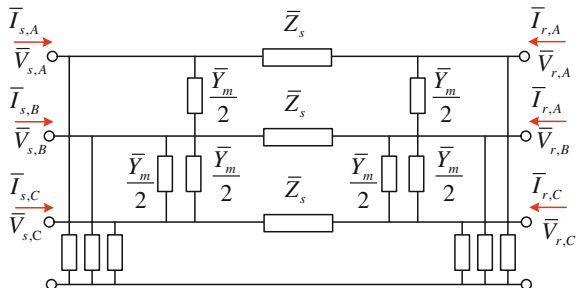
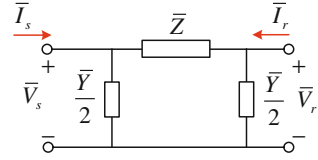


Fig. 2.4 Equivalent single-phase pi circuit for lumped parameters



Equations (2.8) and (2.9) completely define the pi model of the line for lumped parameters. \bar{Y}_s is the sum of all admittance connected to the corresponding phase, and \bar{Y}_m is the negative value of the admittance between two phases. \bar{Z}_s and \bar{Z}_m are the phase impedance and mutual impedance between two phases, respectively.

The circuit shown in Fig. 2.3 can be reduced to the single-phase pi circuit shown in Fig. 2.4.

PowerFactory includes the modelling of lumped parameter model, and it calculates the impedance (Z) and admittance (Y) of the equivalent circuit defined in the *line type* (*TypLne*) following the equations:

$$\begin{aligned} Z &= Z'_1 l = (R'_1 + j\omega L'_1)l \\ Y &= Y'_1 l = (G'_1 + j\omega C'_1)l \\ G'_1 &= B'_1 \tan \delta_1 \end{aligned} \quad (2.10)$$

where l is the length of the line in km and R'_1 , L'_1 , G'_1 and C'_1 are the line parameters per length unit. The conductance G'_1 can be defined in terms of the insulation factor $\tan \delta_1$. Sending and receiving voltages and currents can be written using the transmission matrix form as follows:

$$\begin{bmatrix} U_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} U_r \\ -I_r \end{bmatrix} \quad (2.11)$$

where

$$\begin{aligned} A &= 1 + \frac{1}{2} Z' Y' l^2 \\ B &= Z' l \\ C &= \left(1 + \frac{Z' Y' l^2}{4} \right) Y' l \\ D &= A \end{aligned} \quad (1.12)$$

This lumped parameter model is a simplified model of the distributed parameter model. It can be obtained by series expansion of the hyperbolic functions in (2.7).

The accuracy of the lumped model then depends on the weight of the truncated terms in the series expansion, which in turn depends on the factor (*frequency* \times *length*).

For overhead lines less than 250 km and power frequency, this approximation is very satisfactory and the error can be neglected. For longer lines or higher frequencies, a distributed parameter model will then give a more accurate solution.

Longer lines can be alternatively modelled connecting line sections in cascade.

In *PowerFactory*, the input parameters in the line type (*TypLne*) are defined in terms of positive and zero sequence impedance and admittance. Thus, the conversion from matrix impedance and matrix admittance (2.13) in sequence component is done by the complex transformation matrix as follows:

$$[\bar{Z}_{ABC}] = \begin{bmatrix} \bar{Z}_s & \bar{Z}_m & \bar{Z}_m \\ \bar{Z}_m & \bar{Z}_s & \bar{Z}_m \\ \bar{Z}_m & \bar{Z}_m & \bar{Z}_s \end{bmatrix} \quad [\bar{Y}_{ABC}] = \begin{bmatrix} \bar{Y}_s & \bar{Y}_m & \bar{Y}_m \\ \bar{Y}_m & \bar{Y}_s & \bar{Y}_m \\ \bar{Y}_m & \bar{Y}_m & \bar{Y}_s \end{bmatrix} \quad (2.13)$$

where

$$[\bar{T}_s] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \rightarrow [\bar{T}_s]^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \quad (2.14)$$

$$[\bar{Z}_{012}] = [\bar{T}_s]^{-1} \times [\bar{Z}_{abc}] \times [\bar{T}_s]$$

Now, the sequence parameters can be calculated as follows:

$$\begin{aligned} [\bar{Z}_{012}] &= \begin{bmatrix} \bar{Z}_0 & 0 & 0 \\ 0 & \bar{Z}_1 & 0 \\ 0 & 0 & \bar{Z}_2 \end{bmatrix} = \begin{bmatrix} \bar{Z}_s + 2\bar{Z}_m & 0 & 0 \\ 0 & \bar{Z}_s - \bar{Z}_m & 0 \\ 0 & 0 & \bar{Z}_s - \bar{Z}_m \end{bmatrix} \\ [\bar{Y}_{012}] &= \begin{bmatrix} \bar{Y}_0 & 0 & 0 \\ 0 & \bar{Y}_1 & 0 \\ 0 & 0 & \bar{Y}_2 \end{bmatrix} = \begin{bmatrix} \bar{Y}_s + 2\bar{Y}_m & 0 & 0 \\ 0 & \bar{Y}_s - \bar{Y}_m & 0 \\ 0 & 0 & \bar{Y}_s - \bar{Y}_m \end{bmatrix} \end{aligned} \quad (2.15)$$

Example 1: Comparison between distributed and lumped parameter models for transmission lines

The WSCC 3-machine system, which is well known as P.M Anderson 9-bus, is chosen as case study, and main data of this system appear in Refs. [1, 2] and widely used in the literature for testing purposes. The power system consists of 3 generators, 6 lines, 3 two winding power transformers and 3 loads totalling of 315 MW and 115 Mvar. The static and dynamic data of the system can be found in [1]. The base MVA is 100, and system frequency is 60 Hz.

The test system is depicted in Fig. 2.5, and quantities represented on it are results of classical steady-state calculations. The load flow function (*ComLdf*) is used to compare the accuracy between distributed and lumped models.

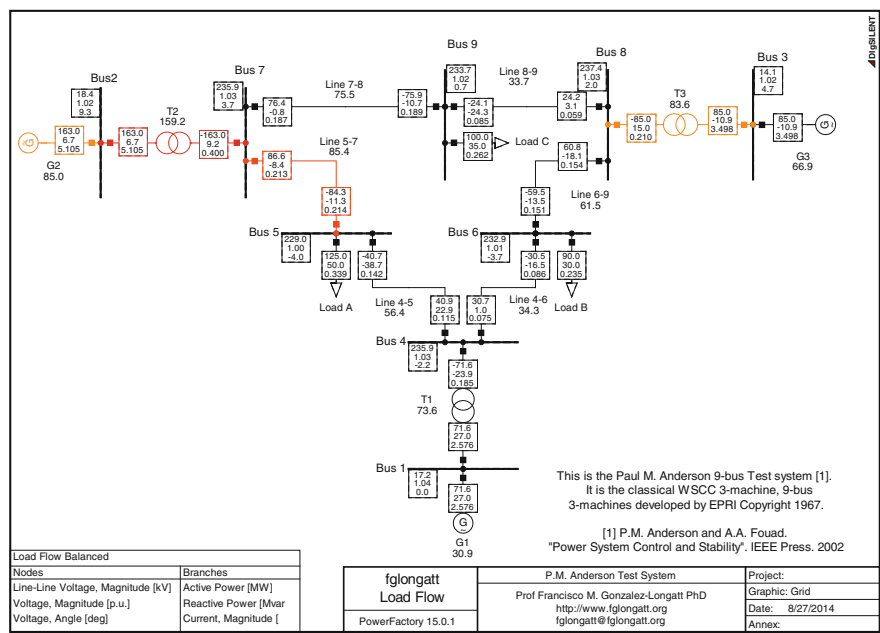


Fig. 2.5 Example 1: test system diagram and parameters

Selection between distributed and lumped models on transmission line is very simple, and it is done at the dialog box of the element transmission line (*ElmLne*). For comparison purposes, two scenarios are created where all transmission lines are using the same model: (i) lumped and (ii) distributed parameters. The calculation method is set to be classical AC load flow using balanced positive sequence and formulation based on power balance equations.

The comparing of results command (*CommDiff*), which is included in PowerFactory, is used to compare results between the two scenarios previously defined. The comparing of results is defined on relative error using as base the scenario of lumped load. Results are presented as percentages as is shown on legend block, bottom left in Fig. 2.6. Colour legend is set in order to help identify the largest changes.

Results show the largest changes are related to power angle of bus voltages ($\phi_{iu} = -7.44\%$ at bus 9), the used of a distributed model implies an increase on the power angles and also there is an effect on the reactive power flows.

The use of lumped parameter model offers several advantages:

- It is extremely easy to be implemented and requires the lowest calculation intensity.
- It is simple and can be used in any phase configuration or number of parallel circuits (dimensions on matrices Z and Y depend on that).

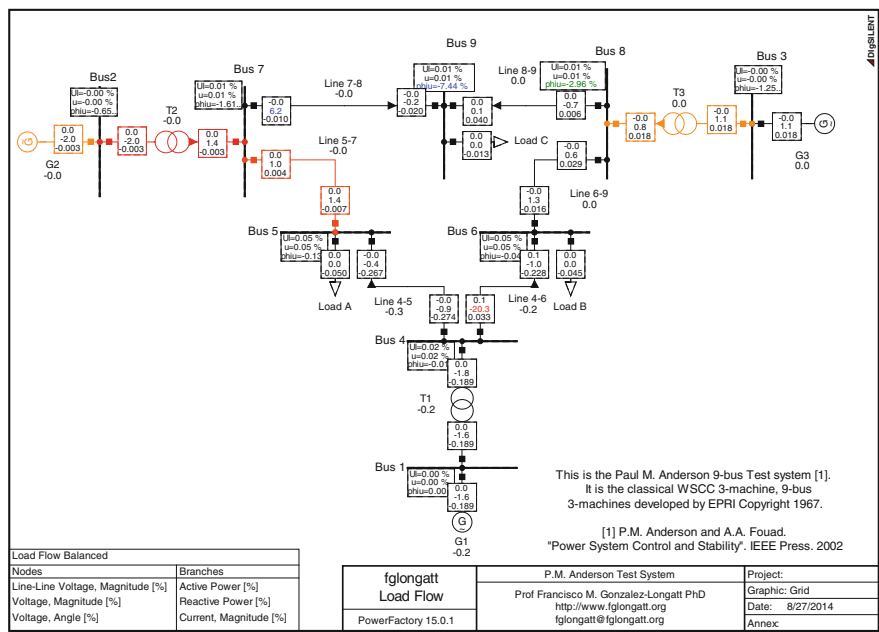


Fig. 2.6 Comparison of load flow results using lumped and distributed models on transmission lines: Example 1

- It is possible to connect several transmission lines in cascade connection (line routes).
- This model can be used on simulation related to transient or dynamic processes (with limitations).

On the other hand, this simple model has few disadvantages:

- There are considerable errors in the use of lumped parameter when the transmission line length is greater than 150 km at 50 Hz and 15 km at 600 Hz.
- Model does not represent frequency dependence on R and L in the case of studies related to frequency response or harmonics.

Model of transmission lines using distributed parameter provides the best results in calculations with overhead transmission lines, considering or not transposition and frequency dependence. Distributed model must be used in any study where frequency changes are relevant to the results, e.g. harmonic load flow and frequency response. There are two important disadvantages on the use of distributed parameter model: (i) it is computationally intensive and (ii) it cannot be used for transient simulations where frequency changes on Z' and Y' .

2.2.3 Tower Model

One important feature of PowerFactory is the way to model lines. Overhead transmission lines and cables are treated alike; they are both instances of the generalized line element (*ElmLne*). However, a simple transmission line can be modelled in very different ways, depending on type of the line selected (more details can be found in the PowerFactory user's manual [3]):

- The simplest way is the *TypLne* object type. It was used on the previous section to describe the line directly providing the electrical parameters (the user can select if the type is defined for an overhead line or a cable).
- The tower model or tower types (*TypTow* and *TypGeo*) are used where the geometrical description (coordinates) and conductor electrical parameters are clearly specified or known, and the electrical parameters are calculated from these data.

The use of one type or other depend on the data available or simulation purposes, for very simple simulations *TypLne* can be used without major difficulties or effecting results but if there is any specific phenomenon (e.g. mutual coupling) of interest, this towers type must be used.

Example 2: Comparison between line model and tower model for transmission lines A typical 230-kV, 60-Hz transmission line is considered in this example, it is named *Test System 2*, and geometrical configuration and main characteristics are indicated in Fig. 2.7.

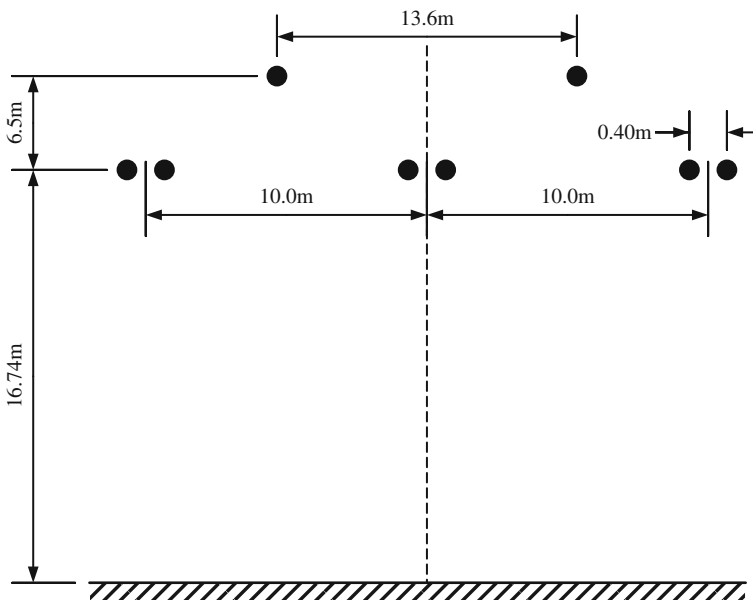


Fig. 2.7 *Test System 2* typical geometrical disposition of a 230-kV transmission line

This transmission line is used initially to evaluate the accuracy of the results provided by PowerFactory in terms of sequence impedance. The transmission line is modelled in ATP (*Alternative Transient Program*), and the routine line constant is used to obtain the sequence impedance and then compared with the results obtained from PowerFactory.

Initially, the transmission line shown in Fig. 2.7 must be modelled in PowerFactory using a tower model. This is a very simple procedure, and it is clearly and explained in detail in Sect. 9.3.4, Example Line Couplings on the PowerFactory User Manual. Here, for space limitations, the main aspects are presented and discussed.

The first step is to create the conductor types (*TypCon*) for phase and earth conductors. Phase conductor ACSR 1033.5 KCM 54/7, $r_{dc,p} = 0.0684$ Ohm/Km, $RMG_p = 1.28$ cm. Earth conductor: Alumoweld 7#9, $r_{dc,g} = 2.362$ Ohm/km, $RMG_g = 0.0567$ cm. Figure 2.8 shows all details of the created conductor types for this example.

Now, the tower geometry type (*TypeGeo*) must be defined following the dimensions provided in Fig. 2.7, and the implementation in PowerFactory is shown in Fig. 2.9.

PowerFactory is power simulation software, and it allows retrieving all the electrical parameter calculations for the transmission line in the output windows. Pressing the “Calculate” bottom, the following matrix is displayed: (i) *Natural impedance matrix*, (ii) *reduced impedance matrix* (3×3), (iii) *symmetrical impedance matrix* (sequences 0, 1 and 2), (iv) *reduced admittance matrix* (3×3) and (v) *symmetrical admittance matrix* (sequences 0, 1 and 2). For illustrative purposes, Fig. 2.10 shows symmetrical impedance and admittance matrixes (sequences 0, 1 and 2) as presented on the output window.

One of the ATP’s special features is to efficiently calculate phenomena in transmission lines. For actual multiphase overhead transmission lines, the following models are applicable: (multistage) lumped pi model, distributed parameter, untransposed-type model, distributed parameter, transposed-type model and frequency-dependent model—J. Marti model. In EMTP (Electromagnetic Transients Program) and ATP, these model data are directly calculated in the subroutine named *Line Constants*, introducing geometrical parameters of transmission lines.

Tables 2.2 and 2.3 show the comparison results between PowerFactory and ATP for sequence impedance and admittance, respectively. Relative error (%) is calculated in each case, using PowerFactory as base for comparisons.

Results provided by PowerFactory and ATP routine are quite similar in magnitudes; in fact, the largest difference is in the case of the positive sequence admittance (3.47 %).

Now, the typical 230-kV transmission line presented in Fig. 2.7 is used to substitute all transmission in the *Test System 1*, WSCC 3-machine system. Classical load flow function in PowerFactory are calculated in order to compare results between the use of *TypLne* object type and tower type (*TypTow*). Figure 2.11 shows changes (%) on the load flow solution; bus voltage angles exhibit the largest

Conductor Type - Equipment Type Library\ACSR 1033.5 KCM 54/7.TypCon *

| Category | Parameter | Value | Unit |
|-----------------|-------------------------|---|--------|
| Basic Data | Name | ACSR 1033.5 KCM 54/7 | |
| | Nominal Voltage | 230. | kV |
| | Nominal Current | 1.047 | kA |
| | Number of Subconductors | 2 | |
| | Bundle Spacing | 0.4 | m |
| (Sub-)Conductor | DC-Resistance (20°C) | 0.0648 | Ohm/km |
| | GMR (Equivalent Radius) | 128. | mm |
| | Outer Diameter | 523.7 | mm |
| | Conductor Model | <input checked="" type="radio"/> Solid Conductor <input type="radio"/> Tubular Conductor | |

☐ Skin effect

Conductor Type - Equipment Type Library\Alumoweld 7#9.TypCon

| Category | Parameter | Value | Unit |
|-----------------|-------------------------|---|--------|
| Basic Data | Name | Alumoweld 7#9 | |
| | Nominal Voltage | 230. | kV |
| | Nominal Current | 0.2 | kA |
| | Number of Subconductors | 1 | |
| | Conductor Model | <input checked="" type="radio"/> Solid Conductor <input type="radio"/> Tubular Conductor | |
| (Sub-)Conductor | DC-Resistance (20°C) | 2.362 | Ohm/km |
| | GMR (Equivalent Radius) | 5.67 | mm |
| | Outer Diameter | 11.44 | mm |

☐ Skin effect

Fig. 2.8 Conductor types (TypCon) for phase and earth conductors of a typical 230-kV transmission line

changes together with the reactive power flows. *TypTow* provided a more detailed and realistic model as consequence is expected to provide less optimistic results. The use of the tower-type model is a computationally efficient calculation providing more realistic results. Authors suggest the use of this model as much as known data allow.

Tower Type - Equipment Type Library \ Tower Type 230 kV.TypTow

Basic Data

Load Flow

VDE/IEC Short-Circuit

Complete Short-Circuit

ANSI Short-Circuit

IEC 61363

RMS-Simulation

EMT-Simulation

Harmonics/Power Quality

Optimal Power Flow

Reliability

Generation Adequacy

Description

General Geometry

Name: Tower Type 230 kV

Nominal Frequency: 60 Hz

Number of Earth Wires: 2

Number of Line Circuits: 1

Transposition: none

Input Mode

☒ Geometrical Parameter

☐ Electrical Parameter

Earth Resistivity: 100 Ohmm

Types of Earth Conductors:

| | Conductor Types | TypCon |
|-------------------|-----------------|--------|
| Earth Conductor 1 | Alumoweld 7#3 | |
| Earth Conductor 2 | Alumoweld 7#3 | |

Conductor Types of Line Circuits:

| | Conductor Types | TypCon | Num. of Phases | Transposition |
|-----------|----------------------|--------|----------------|---------------|
| Circuit 1 | ACSR 1033 5 KCM 54/7 | | 3 | |

Coordinate of Earth Conductors [m]:

| | X | Y |
|-------------------|------|-------|
| Earth Conductor 1 | 3.2 | 23.54 |
| Earth Conductor 2 | 16.8 | 23.54 |

Coordinate of Line Circuits [m]:

| | X1 | X2 | X3 | Y1 | Y2 | Y3 |
|-----------|----|----|----|-------|-------|-------|
| Circuit 1 | 0 | 10 | 20 | 16.74 | 16.74 | 16.74 |

OK

Cancel

Calculate

Fig. 2.9 Tower geometry types (TypGeo) of a typical 230-kV transmission line *Test System 2*

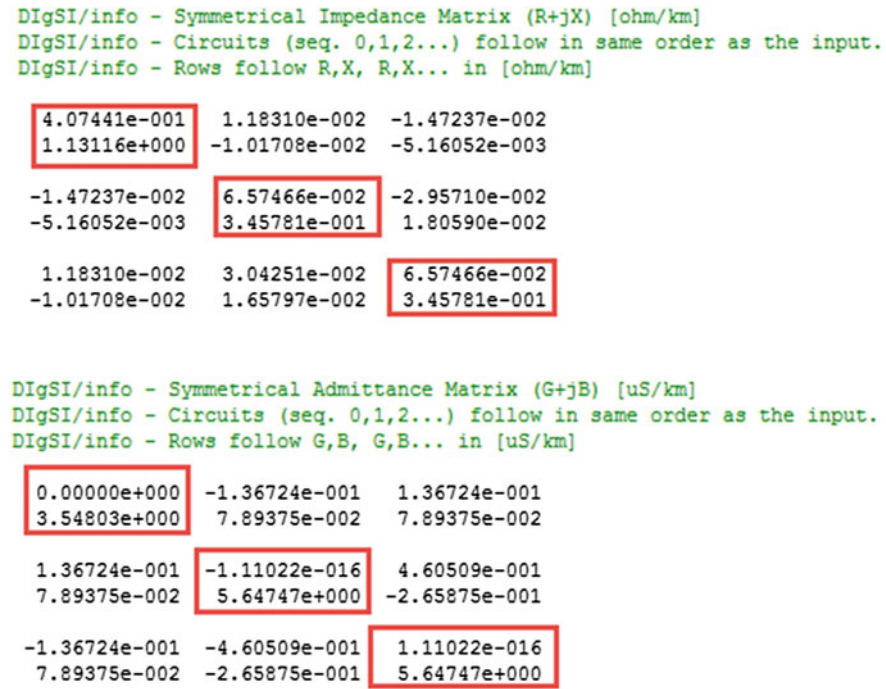


Fig. 2.10 Illustrative results of symmetrical impedance and admittance matrix *Test System 2*

Table 2.2 Results comparison: sequence impedance (Z)

| | PowerFactory | | ATP line constant | | Error | |
|----------|--------------|----------|-------------------|----------|---------|---------|
| | R [Ω/km] | X [Ω/km] | R [Ω/km] | X [Ω/km] | R [%] | X [%] |
| Seq 0 | 0.40744 | 1.13115 | 0.40861 | 1.14514 | 0.28750 | 1.23700 |
| Seq 1, 2 | 0.06574 | 0.34578 | 0.06663 | 0.35092 | 1.35500 | 1.48700 |

Table 2.3 Results comparison: sequence admittance (Y)

| | PowerFactory | ATP line constant | Error |
|----------|--------------------------|--------------------------|--------|
| | Y [μΩ ⁻¹ /Km] | Y [μΩ ⁻¹ /Km] | Y [%] |
| Seq 0 | 3.5480 | 3.4648 | 2.3456 |
| Seq 1, 2 | 5.6475 | 5.4512 | 3.4758 |

2.3 Power Flow Analysis Under Unbalanced Conditions

The load flow function in PowerFactory allows several features, AC systems, unbalanced, 3-phase (*abc*). This analysis function performs load flow calculations for a multiphase network representation. It can be used for analysing unbalances of 3-phase systems, e.g. introduced by unbalanced loads or non-transposed lines, or

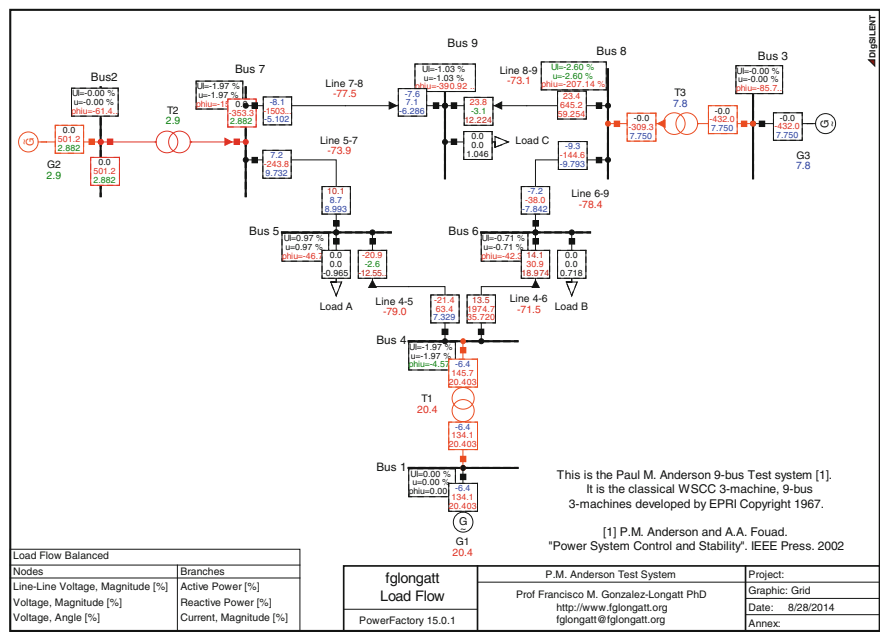


Fig. 2.11 Comparison of load flow results using *TypLne* object type and *TypTow* on transmission lines: Example 1

for analysing all kinds of unbalanced system technologies, such as single-phase or two-phase systems (with or without neutral return).

In PowerFactory, the nodal equations used to represent the analysed networks are implemented using two different formulations, *Newton–Raphson with current equations* or *Newton–Raphson with power equations*. The selection of the method used to formulate the nodal equations is user-defined and should be selected based on the type of network to be calculated. The standard Newton–Raphson algorithm using the power equation formulation is typically used for large, meshed transmission systems with a relatively high *X/R* ratio, especially when heavily loaded, and typically, this formulation usually converges best. However, distribution systems are very different to transmission system. “Current Equations” formulation usually allows a better convergence in distribution systems, especially unbalanced distribution systems. It must be noticed, this is not a general rule, each specific case of no convergence must be specifically analysed.

The unbalanced AC load flow could be performed for a multiphase network representation. It can be used in order to analyse unbalances of 3-phase systems, e.g. introduced by unbalanced loads or non-transposed lines, or for analysing all kinds of unbalanced system technologies, such as single-phase or two-phase systems (with or without neutral return). This option is available only for AC load flow calculations.

Example 3: Magnetically Coupled transmission lines The line coupling element (*ElmTow*) can be used to simulate magnetically coupled transmission lines. Transmission lines in multiple circuits sharing the same support structure (tower) or with very short distance between them are magnetically coupled. In this example, an academic, three-phase, double-circuit, 230-kV, non-transposed transmission system is shown in Fig. 2.12 (*Test System 3*), as distances. Distances shown in Fig. 2.12 are only for academic purposes and should not be taken as rule, and that configuration is designed in order to increase the magnetic and electric coupling between circuits. *Test System 1*, WSCC 3-machine system, has six transmission lines operating at 230 kV, and in this example, tower shown in Fig. 2.12 is issued in order to provide coupling between circuits.

A very simple procedure is followed in PowerFactory to create a *Line Couplings Element* (ElmTow) and the *TypLne* object type, and illustrative information is presented in Figs. 2.13 and 2.14. More details of the process to be followed can be found in PowerFactory user’s manual [3].

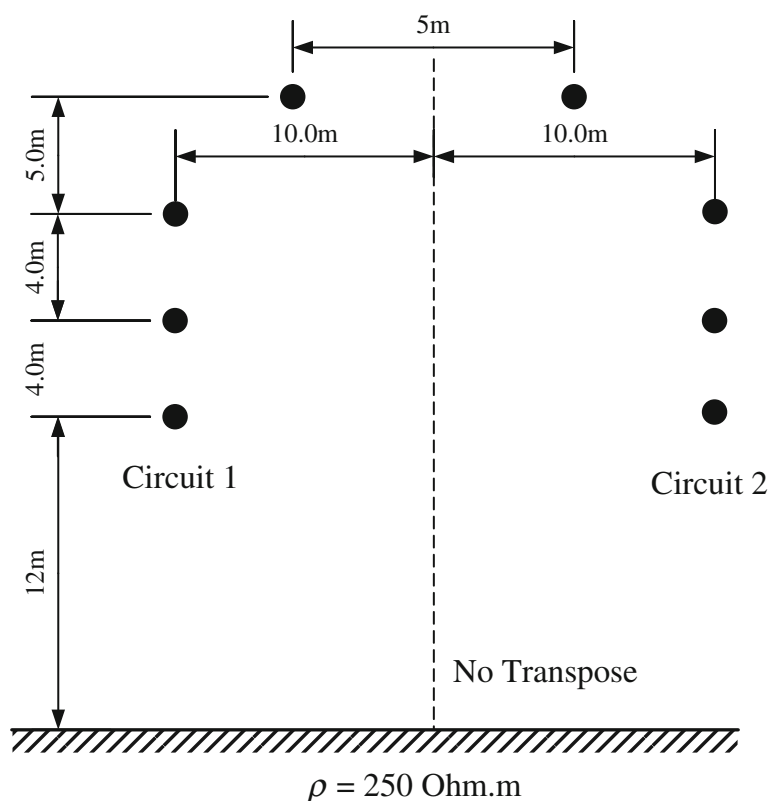


Fig. 2.12 *Test System 3* Illustrative case of a double-circuit, 230-kV transmission line

Tower Type - Equipment Type Library\Tower Type Double Circuit.TypTow

General | Geometry

Name: Tower Type Double Circuit

Nominal Frequency: 60 Hz

Number of Earth Wires: 2

Number of Line Circuits: 2 Transposition: none

Input Mode:
☒ Geometrical Parameter
☐ Electrical Parameter

Earth Resistivity: 250 Ohmm

Types of Earth Conductors:

| | Conductor Types | TypCon |
|-------------------|-----------------|--------|
| Earth Conductor 1 | Alumoweld 789 | |
| Earth Conductor 2 | Alumoweld 789 | |

Conductor Types of Line Circuits:

| | Conductor Types | TypCon | Num. of Phases | Transposition |
|-----------|----------------------|--------|----------------|---------------|
| Circuit 1 | ACSR 1033.5 KCM 54/7 | | 3 | |
| Circuit 2 | ACSR 1033.5 KCM 54/7 | | 3 | |

Geometry

Coordinate of Earth Conductors [m]:

| | X | Y |
|-------------------|----|----|
| Earth Conductor 1 | 5 | 25 |
| Earth Conductor 2 | 15 | 25 |

Coordinate of Line Circuits [m]:

| | X1 | X2 | X3 | Y1 | Y2 | Y3 |
|-----------|----|----|----|----|----|----|
| Circuit 1 | 0 | 0 | 0 | 12 | 16 | 20 |
| Circuit 2 | 20 | 20 | 20 | 12 | 16 | 20 |

Fig. 2.13 Tower types (*TypTow*) used on double-circuit, 230-kV transmission line *Test System 3*

All transmission in the *Test System 1*, WSCC 3-machine system, is using the double-circuit transmission systems as shown in Fig. 2.12. Unbalanced load flow function in PowerFactory is used to calculate the magnitude of line-to-neutral

Line Couplings - GridLine Couplings 4-5 and 4-6.ElmTow

Name: Line Couplings 4-5 and 4-6

Route: ...

Basic Data

EMT-Simulation

Description

☐ Out of Service

Line Model

☒ Lumped Parameter (PI)

☐ Distributed Parameter

Number of Overhead Line Systems: 1

Geometries:

| Type | TypTow | TypGeo | Distance | m |
|------|---------------------------|--------|----------|---|
| G1 | Tower Type Double Circuit | | 0 | |

Earth Wires:

| Type | TypCon | Max Sag | m |
|-------|--------------|---------|---|
| G1/E1 | Aluminum 795 | 0 | |
| G1/E2 | Aluminum 795 | 0 | |

Line Names:

| Circuit | ElmLine | ElmRoute | Polarity | Type | TypCon | Max... | Transposition | Phasing |
|---------|----------|----------|------------|----------------------|--------|--------|---------------|---------|
| G1/C1 | Line 4-5 | | Terminal i | ACSR 1033.5 KCM 54/7 | 0 | | | A-B-C |
| G1/C2 | Line 4-6 | | Terminal i | ACSR 1033.5 KCM 54/7 | 0 | | | A-B-C |

OK

Cancel

Calculate

Fig. 2.14 Tower element (*ElmTow*) used on double-circuit, 230-kV transmission line *Test System 3*

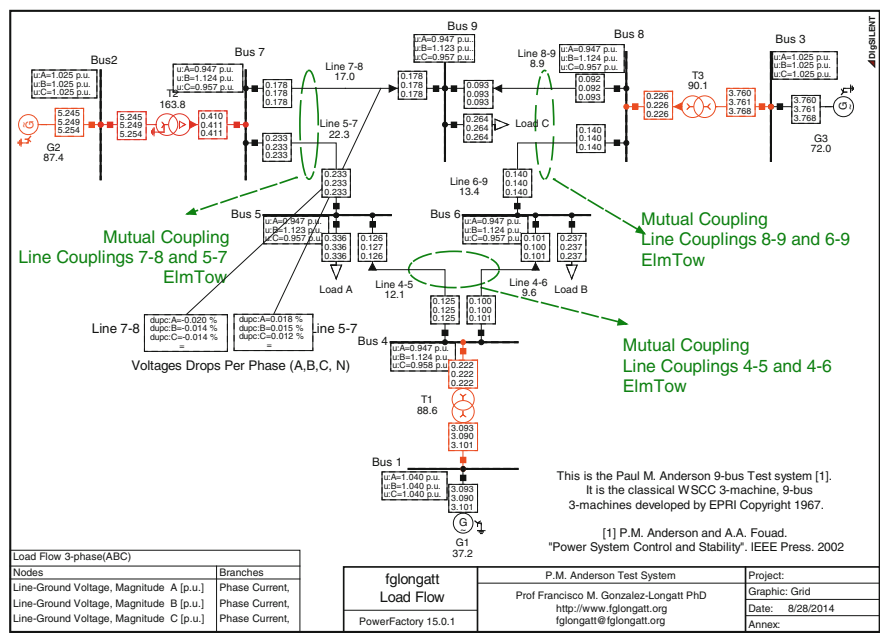


Fig. 2.15 Unbalanced load flow results considering magnetic coupling between transmission systems: Example 3

voltages (p.u) in all nodes and magnitude of phase currents (kA). Figure 2.11 shows the results of the unbalanced load flow solution; bus voltage magnitudes exhibit a considerable unbalance where phase *B* has the highest line-to-neutral voltage ($u_B = 1.124$ p.u.).

The detected voltage imbalance is caused by the shunt currents created by the capacitive coupling with earth and grounding wires. On the other hand, magnetic coupling is providing a relatively low unbalance; voltage drops per phase are presented in Fig. 2.11 where phases A and B show the largest voltage drop across the series impedance (Fig. 2.15).

2.4 Contingency Analysis

In general terms, *contingency analysis* can be defined as the evaluation of the security degree of a power system. Contingency analysis is generally related to the analysis of abnormal system conditions. This is a crucial problem, both in planning and in daily operation. A common criterion is to consider contingencies as a single outage of any system element (generator, transmission line, transformer or reactor) and evaluate the post-contingency state. This is known as the $N - 1$ security criterion. Other contingencies to be taken into account are simultaneous outages of

double-circuit lines that share towers in a significant part of the line path. The outage of the largest generator in an area and any of the interconnection lines with the rest of the system is another contingency to be analysed.

Contingency analyses are used to determine the state of the network after an outage of one ($N - 1$) or multiple elements ($N - k$). Therefore, a load flow must be performed for each selected contingency. This chapter deals with the most basic but typically used contingency analysis: deterministic contingency analysis. PowerFactory contingency analysis module offers two contingency analysis methods [3].

- **Single Time-Phase Contingency Analysis:** The deterministic assessment of failure effects under given contingencies, within a single time period. Here, only one post-fault load flow is analysed per contingency case.
- **Multiple Time-Phase Contingency Analysis:** Deterministic assessment of failure effects under given contingencies. It is performed over different time periods, each of which defines a time elapsed after the contingency occurred. It allows the definition of user-defined post-fault actions.

In both cases, the prefault and post-fault load flows are compared to the specified loading and voltage limits and the reports are generated from the comparison between prefault and post-fault load flows. In PowerFactory, the term *Fault Case* is used to define a contingency. Two concepts must be defined in order to understand the functionality of this module [3]:

- **Contingencies:** These are objects in PowerFactory of the class *ComOutage* which are used to represent contingencies. They are defined by a set of events which represent the originating faults over time and the following fault clearing and post-fault actions.
- **Time Phases:** These represent points in time at which the steady-state operational point of the network under analysis is calculated. Each time phase is defined via a user-defined post-contingency time. The post-contingency time defines the end of a phase, that is, the point in time at which the steady state of the network is calculated.

As mentioned before, the single time-phase contingency analysis function first performs a *prefault load flow*. Following this, it performs a corresponding post-contingency load flow for a single time phase and contingency [3]. The function calculates the initial consequences of the contingencies, regardless of the operational measures to mitigate violations in the system. Moreover, automatic transformer tap changer and switchable shunts can be considered as long as their time constants are smaller than the current *post-contingency time*. The results of the contingency analysis with multiple time phases correspond to the steady-state operational point of the network being studied, at every post-contingency time for each of the defined contingencies. Compressive details about procedure to perform a contingency analysis using PowerFactory can be found in the PowerFactory user's manual [3].

The *Contingency Analysis* command (*ComSimoutage*) performs a load flow calculation to determine the operational point of the network under no-fault

conditions. The command contains *Contingency Cases* (*ComOutage* objects) which define one or more elements that are taken out of service simultaneously. Following the calculation of the base load flow, a contingency load flow for each of these contingencies is calculated. This calculation considers the post-fault thermal ratings of branch elements, transformer tap changer controller time constants and automatic shunt compensators [3].

Contingency cases can be generated by two means: the *Contingency Definition* command (*ComNmink*) or via the definition and use of fault cases and fault groups. In the first case, the contingencies can be created using the *Contingency Definition command* available in its toolbar icon. Another way is by right clicking on a selection of elements in the single line diagram and selecting the option:

Calculate/Contingency Analysis comSimoutage. The corresponding dialog is shown in Fig. 2.16.

In the second case, contingency cases can be created using references to user-defined *fault cases* and *fault groups* from the *Operational Library*.

Either an $N - 1$ or $N - 2$ outage simulation for the selected elements can be prepared. Additional $n - k$ outage for mutually coupled lines/cables is available. Moreover, the Contingency Definition command optionally allows selecting lines/cables, transformers, series reactors, series capacitors and/or generators so as to create contingencies.

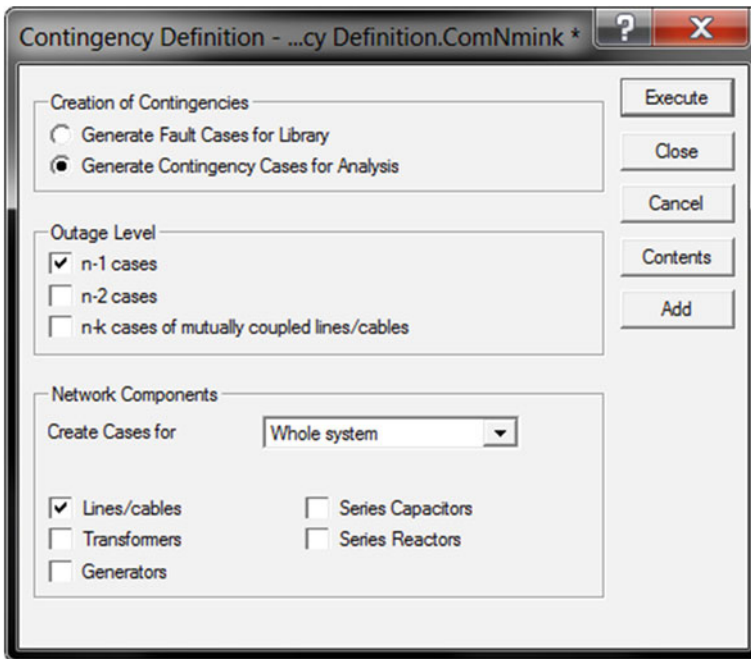


Fig. 2.16 Contingency definition command (*ComNmink*)

2.4.1 Single Time-Phase Contingency

When the command contingency analysis is executed, the dialog shown in Fig. 2.17 is displayed. The contingency analysis limits can be set individually for each terminal and branch element (in the load flow page of the element's dialogue) or globally in the limits for recording field of the contingency analysis command. The calculated result is stored in the result file whenever one of the constraints (individual or global) is violated. The following options can be selected: (i) *AC Load Flow Calculation*: The classical AC load flow analysis to calculate the state of the power system after each contingency. (ii) *DC Load Flow Calculation*: With this option the linear DC load flow method is used to calculate the power system state after each contingency. (iii) *DC Load Flow + AC Load Flow for Critical Cases*: The contingency analysis will perform two runs. First, it will use a linear DC load flow method to calculate the active power flow per contingency case. If for certain contingencies, loadings are detected to be outside a certain threshold, then for these cases, the contingency analysis will recalculate the post-fault load flow using the iterative AC load flow method [3].

The parameters in this section set the global threshold used to determine whether a calculated result is recorded in the *Results object*.

Contingency cases can be displayed by clicking on *show* button or add by *Add Cases/Groups*. This second button is used to create the contingency cases (*Com-Outcome* objects) based on fault cases and/or fault groups. A fault case contains

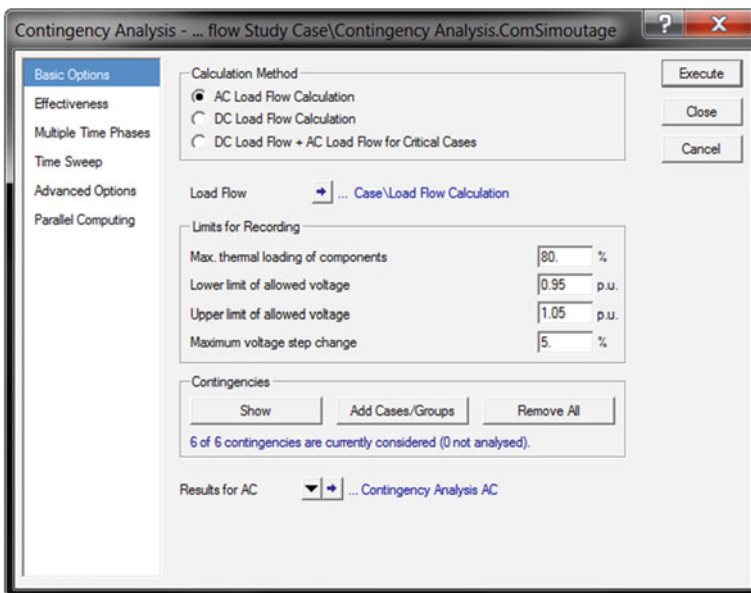


Fig. 2.17 Basic options of contingency analysis command

events: the fault location and (optionally) others (post-fault actions). Fault groups contain a set of references to fault cases. In order to use the *Add Cases/Groups* option, the fault cases and/or groups must have been previously defined in the Operational Library. If these have been defined, then the Add Cases/Groups button can be pressed. As a result, a data browser list of the available fault cases/groups pops up [3].

Depending on the calculation method selected, the reference to the corresponding result file object (*ElmRes*) is defined. The results stored in this file are filtered according to the global threshold set in *Limits for Recording* section of the Basic Data tab and also according to the individual limits defined within each component's respective dialogue.

Example 4: DC Contingency Analysis In power systems, it is possible to use approximate linear model. The method known as contingency analysis with distribution factors is based on *DC load flow*. This model is based on the assumption that the node voltages are $V_i = 1.00$ p.u. at all nodes and losing in this way the capability to track reactive power flows or node voltage. The DC load flow provides a linear relation between active power injections and phase angles of nodal voltages.

$$P_i = \sum_j P_{ij} = \sum_j \frac{V_i V_j}{x_{ij}} \sin \theta_{ij} \approx \sum_j \frac{\theta_i - \theta_j}{x_{ij}} \quad (2.16)$$

where P_i is the net active power injected to bus i , obtained in the general case as the difference between the active power injected by generating elements, S_{Gi} , and the active power absorbed by loads, S_{Li} . P_{ij} and x_{ij} are the branch active power flows and branch reactance, respectively, and θ_i is the bus phase angle.

The Eq. (2.16) can be written as follows:

$$\mathbf{P_I} = \mathbf{B}\boldsymbol{\theta} \quad (2.17)$$

$\mathbf{P_I}$ is net active power injected vector, $\boldsymbol{\theta}$ is the bus phase angle vector and \mathbf{B} is a matrix with the same structure (sparse and symmetrical) of the bus admittance matrix, but its values being computed only in terms of branch reactance. Matrix \mathbf{B} can be expressed by means of the *branch-to-node incidence matrix* \mathbf{A} and the diagonal reactance matrix \mathbf{X} as shown in (2.18):

$$\mathbf{B} = \mathbf{A}\mathbf{X}^{-1}\mathbf{A}^T \quad (2.18)$$

The relationship between the active power injected vector and the branch active power vector can be expressed by means of the branch-to-node incidence matrix \mathbf{A} (matrix reduced by removing the slack row):

$$P_i = \sum_j P_{ij} \Rightarrow \mathbf{P_I} = \mathbf{A} \mathbf{P_f} \quad (2.19)$$

The relationship between the branch active power flow and the phase angle vector can be written using the incidence matrix:

$$P_{ij} = \frac{\theta_i - \theta_j}{x_{ij}} \Rightarrow P_f = [\mathbf{X}^{-1} \mathbf{A}^T] \theta \quad (2.20)$$

Combining (2.17), (2.19), (2.20), an expression to obtain the branch active power vector from the active power injected vector is found:

$$\mathbf{P_f} = [\mathbf{X}^{-1} \mathbf{A}^T \mathbf{B}^{-1}] \mathbf{P_I} = \rho \mathbf{P_I} \quad (2.21)$$

If the system is considered to be linear, the principle of superposition can be applied, and consequently, power flows after a change in the injected powers can be obtained as follows:

$$\mathbf{P_f} = \mathbf{P_f^0} + \rho \Delta \mathbf{P_I} \quad (2.22)$$

where ρ is known as *distribution factor* and represents the flow increase in an element mn (line or transformer) after a unitary increase in the power injected in bus i Eq. (2.23).

$$\rho_{mn}^i = \frac{\Delta P_{mn}^i}{\Delta P_i} \quad (2.23)$$

The flow increase in a branch element, P_{mn} , after the outage of a generator in bus i will be obtained as follows:

$$\Delta P_{mn} = \rho_{mn}^i \Delta P_i = \rho_{mn}^i (-\Delta P_{G_i}) \quad (2.24)$$

where ΔP_{G_i} is the active power generation before the outage.

The WSCC 3-machine system (*Test System 1*) is used to illustrate a comparison between PowerFactory contingency tools and the simplified method of the distribution factors. The test system is depicted in Fig. 2.5, and quantities represented on it are results of classical steady-state calculations.

The power generation in this system in per unit is represented as follows:

$$\begin{aligned} \mathbf{P_I} &= [P_{g2} \ P_{g3} \ 0 \ P_{LA} \ P_{LB} \ 0 \ P_{LC} \ 0]^T \\ &= [1.63 \ 0.85 \ 0 \ -1.25 \ -0.9 \ 0 \ -1 \ 0]^T \end{aligned} \quad (2.25)$$

The active power flow limits ($\mathbf{P_{lim}}$) considered are shown in:

$$\mathbf{P}_{\text{lim}} = \begin{bmatrix} P_{14}^{\text{lim}} & P_{27}^{\text{lim}} & P_{39}^{\text{lim}} & P_{45}^{\text{lim}} & P_{46}^{\text{lim}} & P_{57}^{\text{lim}} & P_{69}^{\text{lim}} & P_{78}^{\text{lim}} & P_{89}^{\text{lim}} \end{bmatrix}^T$$

$$\mathbf{P}_{\text{lim}} = [2 \quad 2 \quad 2 \quad 1.5 \quad 1.5 \quad 1.5 \quad 1.5 \quad 1.5 \quad 1.5]^T \quad (2.26)$$

Taking into account the topology and the network parameters, matrices \mathbf{A} , \mathbf{X} , \mathbf{B} and $\boldsymbol{\rho}$ can be calculated:

$$\begin{aligned} \text{Bus} \quad & \begin{bmatrix} 1-4 & 2-7 & 3-9 & 4-5 & 4-6 & 5-7 & 6-9 & 7-8 & 8-9 \end{bmatrix} \\ & \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & -1 & 0 & 0 & 0 & -1 & 0 & -1 \end{bmatrix} \\ & \mathbf{A} = \\ & \begin{bmatrix} 0.0576 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.03125 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0586 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.085 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.092 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.1610 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.170 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.072 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1008 \end{bmatrix} \\ & \mathbf{X} = \\ & \begin{bmatrix} 32 & 0 & 0 & 0 & 0 & 0 & -32 & 0 & 0 & 0 \\ 0 & 17.065 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -17.065 \\ 0 & 0 & 39.995 & -11.765 & -10.870 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -11.765 & 17.975 & 0 & -6.211 & 0 & 0 & 0 & 0 \\ 0 & 0 & -10.870 & 0 & 16.751 & 0 & 0 & 0 & -5.882 & 0 \\ -32 & 0 & 0 & -6.211 & 0 & 52.100 & -13.889 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -13.889 & 23.810 & -9.9206 & 0 & 0 \\ 0 & -17.0648 & 0 & 0 & -5.882 & 0 & -9.9206 & 32.868 & 0 & 0 \end{bmatrix} \\ & \mathbf{B} = \\ & \begin{bmatrix} -1.0000 & -1.0000 & -1.0000 & -1.0000 & -1.0000 & -1.0000 & -1.0000 & -1.0000 & -1.0000 \\ 1.0000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.0000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.6387 & -0.3848 & 0 & -0.8751 & -0.1351 & -0.6387 & -0.5329 & -0.3848 & 0 \\ -0.3613 & -0.6152 & 0 & -0.1249 & -0.8649 & -0.3613 & -0.4671 & -0.6152 & 0 \\ -0.6387 & -0.3848 & 0 & 0.1249 & -0.1351 & -0.6387 & -0.5329 & -0.3848 & 0 \\ -0.3613 & -0.6152 & 0 & -0.1249 & 0.1351 & -0.3613 & -0.4671 & -0.6152 & 0 \\ 0.3613 & -0.3848 & 0 & 0.1249 & -0.1351 & 0.3613 & -0.5329 & -0.3848 & 0 \\ 0.3613 & -0.3848 & 0 & 0.1249 & -0.1351 & 0.3613 & 0.4671 & -0.3848 & 0 \end{bmatrix} \\ & \boldsymbol{\rho} = \end{aligned}$$

Now, the distribution factors are used to study generator outages. If the lost generation is assumed by the slack bus,

$$\Delta P_{mn} = \rho_{mn}^i \Delta P_i$$

where $\Delta P_i = -P_{Gi}$, the active power generation before outage. In case of G2 outage, the power flows can be calculated from (2.22):

$$\begin{aligned} \mathbf{P}_f &= P_f^0 + \rho \cdot [-1.63 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T \\ \mathbf{P}_f &= [P_{14} \quad P_{27} \quad P_{39} \quad P_{45} \quad P_{46} \quad P_{57} \quad P_{69} \quad P_{78} \quad P_{89}] \\ \mathbf{P}_f &= [2.3 \quad 0 \quad 0.85 \quad 1.42 \quad 0.88 \quad 0.17 \quad -0.02 \quad 0.17 \quad -0.83]^T \end{aligned}$$

The results show that transformer T1 is overloaded (2.30 p.u.) when the generator 2 is out of service. It can be achieved the same results by means of PowerFactory. Firstly, the contingency definition function must be defined by selecting *N-1 cases* and *Create cases for generators* (see Fig. 2.17) and *ComSimoutage* function (Fig. 2.17). If the contingency analysis function (*comSimoutage*) is executed using a DC and AC load flow as calculation method, tables as shown in Fig. 2.18 can be obtained (*report contingencies function*). As can be seen, DC load flow provides enough accuracy in this case.

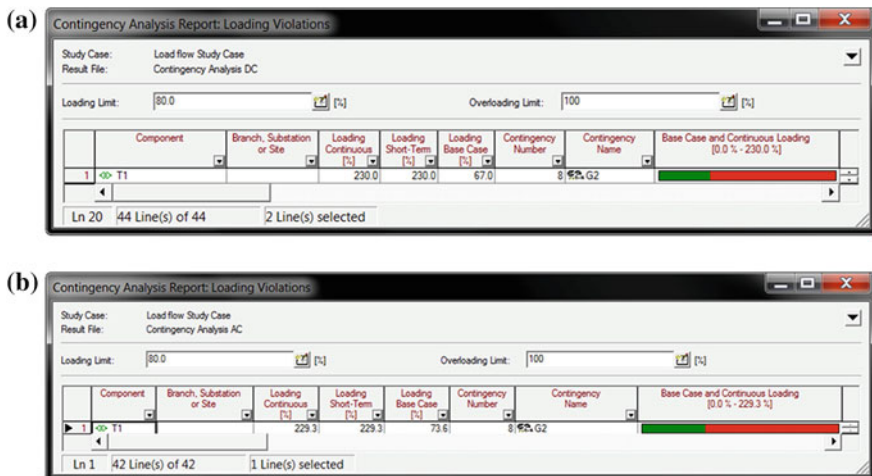


Fig. 2.18 Contingency report, generator 2 outage: **a** DC load flow and **b** AC load flow. **a** Calculation method: DC load flow and **b** calculation method: AC load flow

2.5 Using Distribution Factors to Study the Outage of a Transmission Line

The distribution factors calculated above can be used in order to get the new active power flows when a transformer/line is out of service. Post-contingency flows can be obtained replacing the branch out of service by two fictitious active power injections as depicted in Fig. 2.19. The fictitious injections must coincide with the power flow after the outage:

$$\begin{aligned} P_{ij} &= P_{ij}^0 + \rho_{ij}^i \Delta P_i + \rho_{ij}^j \Delta P_j = P_{ij}^0 + (\rho_{ij}^i - \rho_{ij}^j) P_{ij} \\ P_{ij} &= \Delta P_i = -\Delta P_j = \frac{P_{ij}^0}{1 - \rho_{ij}^i + \rho_{ij}^j} \end{aligned} \quad (2.27)$$

This approach allows us to avoid modifying matrix **B** and consequently matrix ρ . Then, the active power flow through a branch nm after ij outage is obtained as follows:

$$P_{mn} = P_{mn}^0 + \rho_{mn}^i \Delta P_i + \rho_{mn}^j \Delta P_j \quad (2.28)$$

Using (27) and (28), power flow through the nm branch is as follows:

$$P_{mn} = P_{mn}^0 + \frac{\rho_{mn}^i - \rho_{mn}^j}{1 - \rho_{ij}^i + \rho_{ij}^j} P_{ij}^0 = P_{mn}^0 + \rho_{mn}^{ij} P_{ij}^0 \quad (2.29)$$

ρ_{mn}^{ij} is known as the branch nm distribution factor when the branch ij is out of service. In the nine-bus system, suppose that lines fail, active power flows can be estimated using the distribution factors for each case. The distribution factors considering the line outages are as follows:

$$\rho_{\text{lines}} = \begin{matrix} & \begin{matrix} \rho_{mn}^{45 \text{ off}} & \rho_{mn}^{46 \text{ off}} & \rho_{mn}^{57 \text{ off}} & \rho_{mn}^{69 \text{ off}} & \rho_{mn}^{78 \text{ off}} & \rho_{mn}^{89 \text{ off}} \end{matrix} \\ \begin{matrix} 4-5 \\ 4-6 \\ 5-7 \\ 6-9 \\ 7-8 \\ 8-9 \end{matrix} & \begin{bmatrix} 7.0 & 1.0 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 6.4 & 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 3.23 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 3.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 8.5 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 & 1.0 & 5.8 \end{bmatrix} \end{matrix}$$

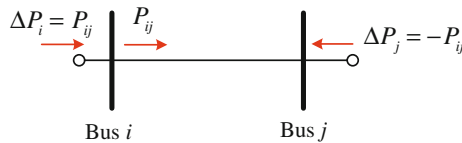


Fig. 2.19 Modelling a branch outage using fictitious injections

Table 2.4 Post-contingency power flow after line outage

| | Outage line | | | | | |
|------------|-------------|-------|-------|-------|-------|-------|
| Power flow | 4–5 | 4–6 | 5–7 | 6–9 | 7–8 | 8–9 |
| 4–5 | N/A | 0.67 | 1.25 | −0.23 | −0.38 | 0.62 |
| 4–6 | 0.67 | N/A | −0.58 | 0.9 | 1.05 | 0.05 |
| 5–7 | −1.25 | −0.58 | N/A | −1.48 | −1.63 | −0.63 |
| 6–9 | −0.23 | −0.9 | −1.48 | N/A | 0.15 | −0.85 |
| 7–8 | 0.38 | 1.05 | 1.63 | 0.15 | N/A | 1 |
| 8–9 | −0.62 | 0.05 | 0.63 | −0.85 | −1 | N/A |

The diagonal elements have not to be taken into account as they represent the flow increase in a line after the outage of the same line. The analyses of the transformer outage have not been performed since they correspond to radial branch connected with generators. Therefore, the outages of those transformers are comparable to analysing the generator outage.

Then, multiplying the line distribution factors by the preoutage flow before the line fault, the post-contingency flow changes are obtained (Table 2.4). As can be seen, there are *two power flow violations*. If the contingency analysis is executed selecting the mentioned lines, similar results are obtained compared with the distribution factor methodology (Fig. 2.20).

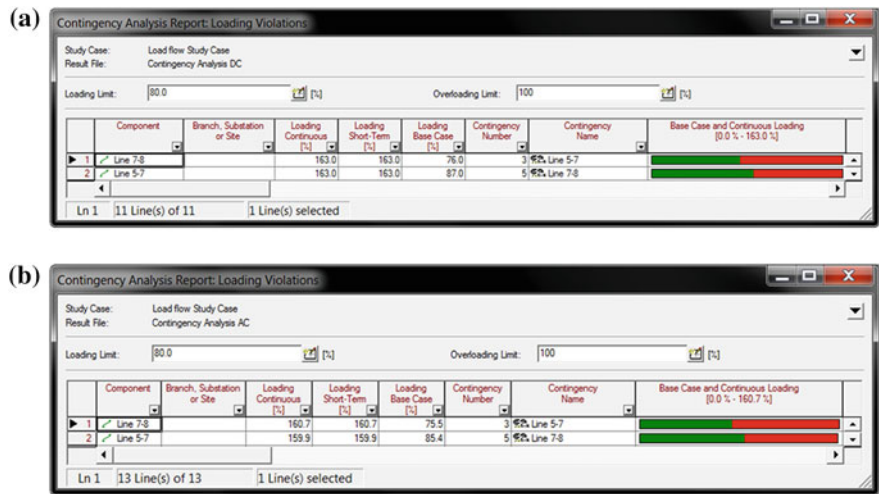


Fig. 2.20 Contingency report, lines outage: **a** DC load flow and **b** AC load flow. **a** Calculation method: DC load flow and **b** calculation method: AC load flow

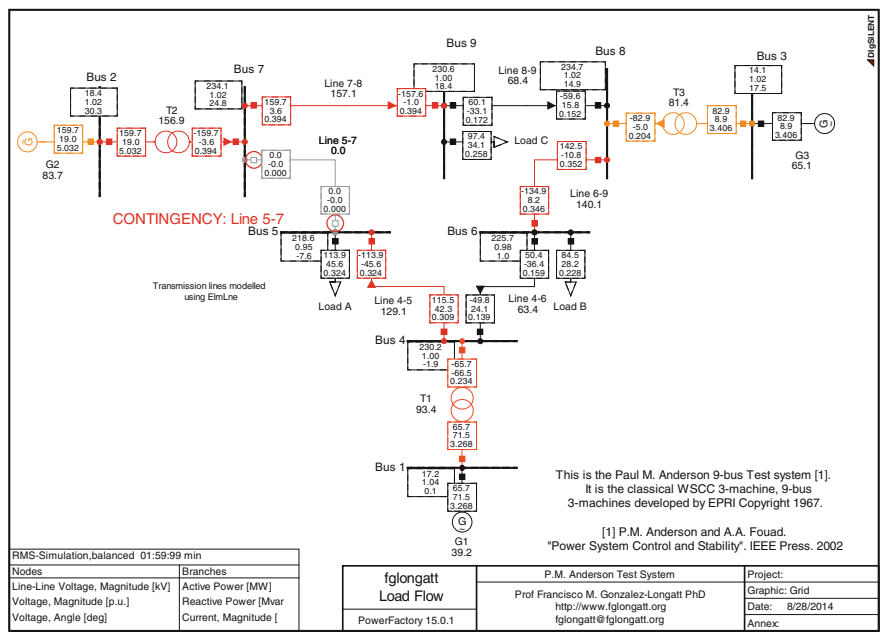


Fig. 2.21 State of test system 1 120s after sudden disconnection of transmission line 5–7

RMS simulation in PowerFactory is used to evaluate the loading of transmission line 7–8 considering an outage in line 5–7. Figure 2.21 shows all voltages and power at 120 s after the sudden disconnection of line 5–7, it can be seen that loading on transmission line 7–8 reaches 157.1 %, which is near to the calculated value (163 %) in Table 2.4, and contingency analysis results are presented in Fig. 2.21. It must be noticed that there is a small discrepancy between the loadings using different methods. Results presented at Fig. 2.21 are just a snapshot of the dynamic situation taken at 120 s; in order to get a full picture about the loading condition during the contingency, a time-domain plot is shown in Fig. 2.22.

Figure 2.3 shows oscillatory behaviour in the loading conditions immediately after the sudden disconnection of line 7–8, and the maximum loading condition (199.274) is reached 0.452 s after the contingency. Oscillations are overdamped, the amplitude of the oscillation decreases over the time, and it is easy to see an asymptotic behaviour around a loading condition of 160 % as was predicted in the previous calculations.

Figure 2.22 includes plot of the frequency in each generator and the calculation of the frequency of inertia centre. The contingency, outage of line 5–7, produces a change in the system topology which triggers a sudden power imbalance in this

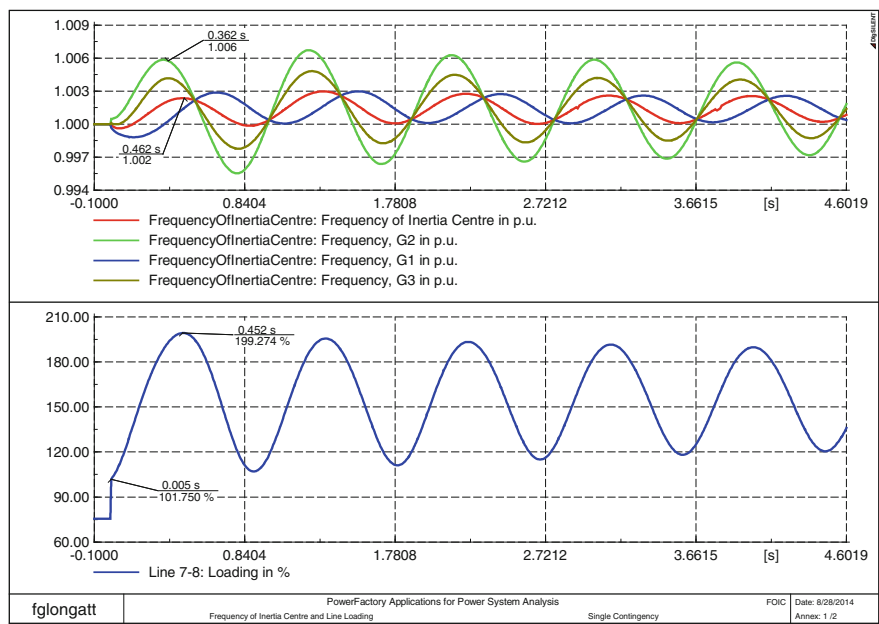


Fig. 2.22 Dynamic response of the system frequency and loading at line 7–8 after sudden disconnection of transmission line 5–7

system, causing a frequency response of the system. During a system frequency disturbance, the frequency created by each generator is related to the generator's inertia; however, the *frequency of centre of inertia* (FOIC) can be used as indicator of the systemic system frequency response. PowerFactory is able to provide individual measurements of frequency using the PLL element (*ElmPhi_pll*); however, to obtain the FOIC, few calculations are performed during the simulation following the equations presented on [4]. *DIgSILENT Simulation Language* (DSL) has been used to calculate of FOIC during RMS simulations, this implementation is shown in Fig. 2.23, and results are shown in Fig. 2.22.

Plot of FOIC shows how the system frequency oscillates after the disconnection of line 5–7, generators modify its rotational speed to reach a new equilibrium point, and during this oscillation process, individual frequencies are changing and the FOIC as well. It can be noticed how the FOIC is slowly returning to the nominal frequency (1.00 p.u.).

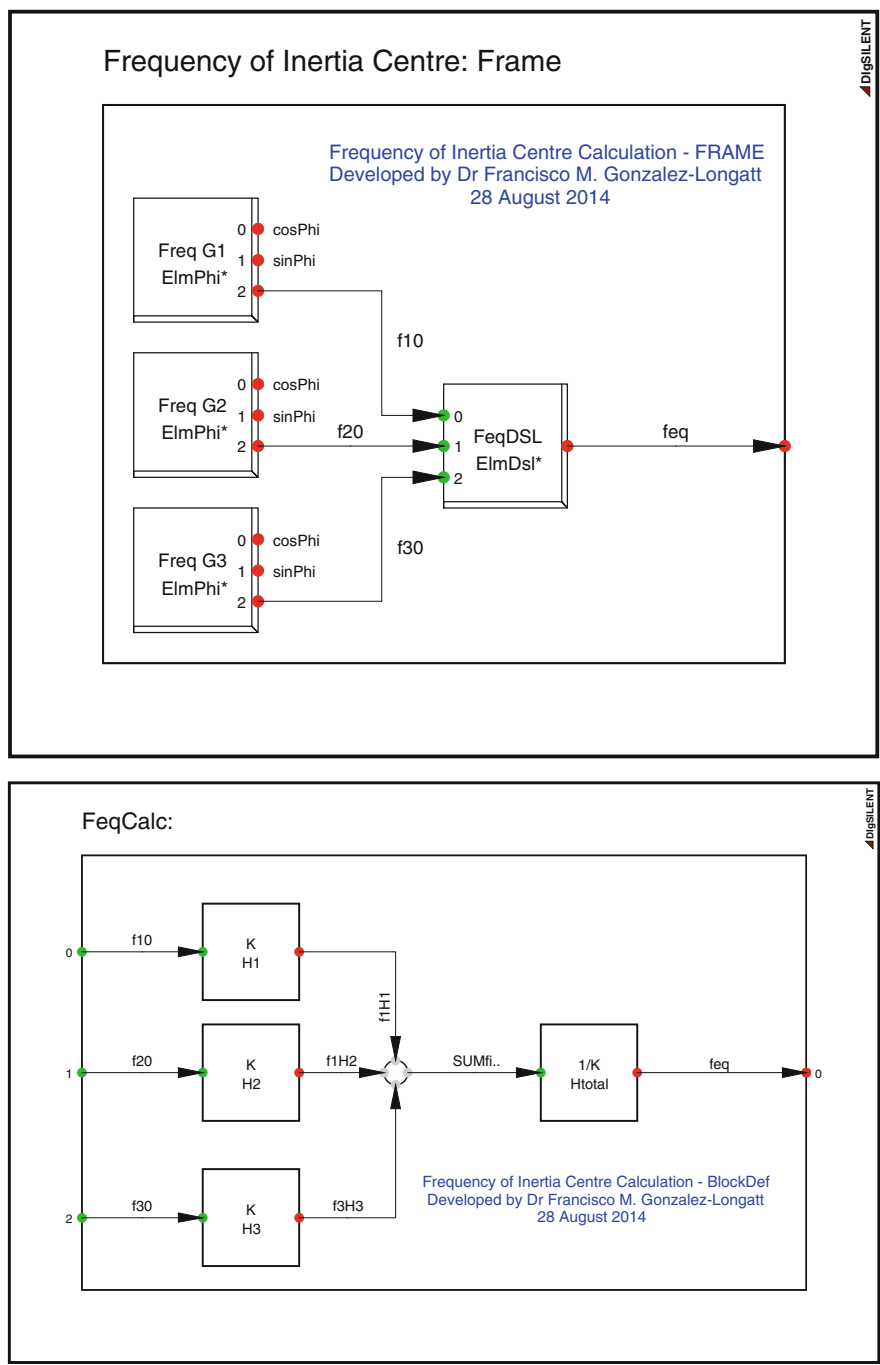


Fig. 2.23 DSL implementation to calculate frequency of inertia centre

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