Francisco M. Gonzalez-Longatt
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PowerFactory Applications for Power System Analysis

Springer

Power Systems

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Printed on acid-free paper

Foreword

In 1987, the Kraftwerke Mainz-Wiesbaden, Germany (KMW AG), became the first official and registered user of the DIgSILENT software. It is not known if the fact that they were the first and single entry on the DIgSILENT PowerFactory reference list constituted apprehension on their behalf, or on behalf of the developers due to future client commitment. However, the fact that after some 27 years, KMW AG's PowerFactory installations are still maintained is a definite indicator that any possible initial doubt was unwarranted. In fact, over the past several years, the user base has grown considerably, establishing a large user community of highly qualified, experienced and creative users.

It has been the intention of the PowerFactory developers from the very beginning to provide a highly flexible power system analysis tool applicable to practically all areas of power generation, transmission, distribution and industry. Since late 1990, renewable generation based on wind and photovoltaics, along with new HVDC transmission technologies, has driven a new and fast-growing sector whose simulation needs include complex, non-traditional applications. In addition, the integration of power system analysis tasks with asset management systems and online applications (GIS, SCADA) as well as closed-loop applications (especially in Smart Grids) has increased the demand for flexible process signal interfaces and bidirectional data exchange capabilities. PowerFactory extends this flexibility even further via the provision of powerful scripting tools allowing the user to develop specific applications according to individual needs.

This first issue of the *PowerFactory Applications for Power System Analysis* serves as an impressive demonstration of the wide range of power system analysis applications that can be handled by the PowerFactory software. In addition, the solutions described for a certain analysis task will motivate and help other users to make use of the software's flexibility and give guidance regarding possible solution options.

We thank all authors who have contributed to this book, initiated by Francisco Gonzalez-Longat and José Luis Rueda, for sharing their valuable PowerFactory experiences and solutions. The topics presented are also of great interest to the PowerFactory development team in their endeavours to optimize further releases and develop even more flexible functions.

August 2014   Dr.-Ing. Martin Schmieg
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Contents

Introduction

Electric power systems have been conceived to convert energy from primary sources into electrical energy and to deliver it to industrial, commercial and residential users. The transportation of electrical power is carried out through transmission, subtransmission and distribution systems, which constitute predominantly AC facilities operating essentially at constant frequency and voltage. Nevertheless, due to transitional targets in different regions worldwide towards sustainable economies by means of large-scale incorporation of renewable energy-based generation sources, the systems are undergoing significant structural and topological changes, in which new power electronic-based technologies, such as for instance, voltage-sourced converter *high-voltage direct current* (VSC-HVDC) multi-terminal transmission links will be increasingly incorporated into the transmission networks.

The operation and planning of such complex systems requires in-depth engineering studies to understand the possible causes of threats to targeted steady-state and dynamic performance criteria as well as to devise prospective solutions from both operational and control viewpoints. So far, these studies rely largely on reliable modelling of system components and availability of suitable tools for simulation and analysis of different types of phenomena. In view of this, sophisticated software packages, such as *DIgSILENT PowerFactory*, have emerged to integrate state-of-art scientific approaches, which assist power engineers in both academic and industry-oriented research endeavours.

PowerFactory offers an amenable object-oriented platform for modelling and simulation of generation, transmission, distribution and industrial systems. Its modelling approach adopts a hierarchical scheme, which combines graphical and scripting modelling techniques. This includes a variety of standard models and the possibility of creating user defined models through *DIgSILENT Simulation Language* (DSL). The software also provides a number of functionalities for simulation, including, load flow calculation, optimal power flow calculation, estate estimation, contingency analysis, protection, RMS/EMT simulation, reliability assessment, to name a few. Besides, based on available basic functions, the

DIgSILENT Programming Language (DPL) allows defining the execution of user defined tasks, e.g. repetitive calculations and post-processing of results, in an automated manner. PowerFactory also supports a set of interfaces with other packages (e.g. MATLAB, Phyton) for data exchange and remote control.

This book aims at covering theoretical and practical aspects of the *how to's* of the development of modelling and simulation-based advanced applications for different types of power system analysis by exploiting the features of PowerFactory. Based on the experience gained throughout the last decade by top expert users and application developers of PowerFactory, the book provides a set of comprehensive guidelines, which are structured by merging innovative solution strategies. A step-by-step procedure is employed to explain the rationale behind the presented applications, which is supported by concise theoretical discussions in order to empathize physical understanding of particular phenomena involved in each case study. All implementations, outlined in the chapters, which were done using the PowerFactory version 15.1.3, are attached as complementary material of the book in pfd files in order to help the reader to follow the explanations given in each chapter and to provide a starting point for the development of additional applications. The book constitutes a valuable reference for formal instruction of power systems for undergraduate and postgraduate students as well as for engineers working in power system operation and planning in different institutions related to the power engineering field.

Chapter 1 provides a thorough review on key issues for developing load flow analysis-based applications in PowerFactory and illustrates three exemplary applications, including the study of topology changes, control of reactive power flow and frequency variation and load profiling. Chapter 2 demonstrates the main capabilities of PowerFactory on steady-state analysis under unbalanced conditions, such as asymmetrical non-transposed transmission lines and presents a discussion on its implications. Preliminary DPL-based applications are presented in Chap. 3, which deals with the implementation of Monte Carlo and Point Estimate methods for probabilistic load flow analysis, and in Chap. 4, which outlines the implementation of a generalized model to solve five-wire power flow problems in distribution systems using the TRX matrix approach.

The DPL implementation of a DC optimal power flow calculation using power transmission distribution factors is described in Chap. 5, including a comparative analysis and validation with respect to the calculations performed in MatPower environment. Chapter 6 introduces a DPL-based application for estimation of technical performance indices for assessing the impact of renewable energy sources.

Preliminary DSL-based applications are given in Chaps. 7–9. A comprehensive review of frequency control and the implementation of a simplified automatic generation frequency controller are provided in Chap. 7, whereas the modelling of combined cycle gas turbine for dynamic simulation studies is presented in Chap. 8. Relevant aspects for modelling of the third order model of double fed induction generators and a dynamic equivalent for wind power plants are discussed in Chap. 9.

Chapters 10–12 introduce advanced DPL applications for the study of low frequency oscillations in power systems. Namely, Chap. 10 concerns the

implementation of a script for performing parameterized modal analysis in order to determine critical operating conditions, whereas Chap. 11 presents a probabilistic approach for risk assessment associated to the occurrence of poorly damped oscillatory modes. In Chap. 12, the theory and implementation of a novel heuristic optimization algorithm, namely the Mean-Variance Mapping Optimization, is given.

Chapters 13–16 illustrate the integration and communication of PowerFactory with other software and simulations programs. Special emphasis on the use of Matlab/Simulink interface and co-simulations, real-time simulation and controller hardware-in-the-loop application for testing are presented.

Chapters 17–19 provide advanced applications of DSL on modelling of very specific components in power systems. DSL implementation of Flexible AC Transmission Systems (FACTS) devices is presented in Chap. 17. Chapter 18 describes the main modelling aspects of active and reactive power controllers combining DSL and Matlab/Simulink. Multi-terminal High voltage Direct current will be an important technology in future transmission systems, thus, important aspects of modelling and simulation are presented in Chap. 19.

Finally, Chap. 20 overviews a couple of good contributions for researchers: the use of one not-well-known PowerFactory analysis function, namely the Parameter Estimation function, and reading data from text files using ElmFile. These elements are used for model parameter identification in the case of one wind farms.

Committed readers will notice that there is some overlap between the chapters, which has been intentionally kept to illustrate how some approaches could share some common implementation steps, despite of being conceived for different purposes. We hope that the book proves to be a useful source of information on the use of PowerFactory and, at the same time, provide the basis for discussion among readers and users with diverse expertise and backgrounds. Given the great variety of applications, which could not be completely covered in a single edition, it is expected that a second edition of the book will be made available soon.

We would like to thank all authors and invited reviewers of the individual chapters for their continuous and valuable support in the different stages of the preparation of this book. A especial website, www.pf4powersystemsapp.com, will be made available from 1 January 2015 to foster active discussions and the possibility of receiving feedback on the book content. Potential collaboration, organization of scientific workshops and exchange of ideas for future works on power system modelling and simulation can also be conducted through this website.

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Chapter 1
Load Flow Calculation and Its Application

Muhammad Raza

Abstract This chapter demonstrates the application of load flow analysis using electrical power system planning software. PowerFactory is used as a software tool for network planning, designing, and application of load flow analysis. Description about the load flow command and different components available in PowerFactory for modeling are given, and how to model the power system network is explained. Furthermore, project planning principle is explained through three case studies. In first case study, network topology for low-voltage network is explained and how to select the network component to fulfill the network constraints is demonstrated. In second case study, medium-voltage network is developed and different power control options are demonstrated to determine the power and voltage operating point of the sources. In addition, method of controlling reactive power flow and frequency variation due to imbalance in power have been simulated. In third case study, application of a load profiling has been developed for low-voltage distribution network. In this study, variation of the load throughout a year has been analyzed.

Keywords Load flow tools and application · Newton–Raphson method · Power flow equation · PowerFactory · Distribution network · Electrical networking planning and designing · Load profiling

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1.1 Introduction

Power flow calculation is a steady-state analysis of electrical power system to calculate the voltage magnitude and angle at all busbars, and power flow in all branches. Load flow analysis is an essential tool in the process of planning, designing, and operation of power systems under different operating conditions and equipment configuration. Based on load flow calculations, different results can be predicted, such as line losses, transformer loading, power exchange between two or more grids, and required voltage control range of transformers and generators. Load flow results are usually required as initial state for other calculations such as RMS simulation and harmonic analysis; also multiple load flow calculation is required for contingency and reliability analysis.

The derivation of power flow equation is based on admittance of the network. In [1], method of formulating admittance matrix is covered in detail. Generally, power flow equation can be expressed using (1.1) and (1.2).

$$P_l = U_l \sum_{m=1}^{n} U_m \{G_{lm} \cdot \cos(\delta_l - \delta_m) + B_{lm} \cdot \sin(\delta_l - \delta_m)\} \qquad (1.1)$$

$$Q_l = U_l \sum_{m=1}^{n} U_m \{G_{lm} \cdot \sin(\delta_l - \delta_m) - B_{lm} \cdot \cos(\delta_l - \delta_m)\} \qquad (1.2)$$

To solve the system, the number of unknown variables is reduced to number of equation by categorizing network buses into three types. These types are so-called load bus (also known as PQ bus), generator bus (commonly known as PV bus), and slack bus (also called as SL bus). Known and unknown parameters associated with buses are defined in Table 1.1. In the next section, how these categorization in PowerFactory can be made are explained.

- **Load Bus**: All the busbars at which voltage magnitude and angle are not controlled or undefined are called PQ bus. At load bus, fixed power to be injected or consumed is given; unknown quantity voltage magnitude and angle are then calculated. Usually, bus connected with load is defined as PQ bus.
- **Generator Bus**: Busbar at which voltage magnitude is controlled or kept constant is called a PV bus. At generator bus, only active power and voltage magnitude is given as known quantity; thus, power equation is solved for voltage angle and reactive power. A busbar connected with active source is usually defined as PV bus.

Table 1.1 List of known and unknown variables according to bus type

Bus type	Given parameter	Unknown parameter
Slack bus	U, δ	P, Q
Generator bus	P, U	Q, δ
Load bus	P, Q	U, δ

- **Slack Bus**: Any busbar at which voltage magnitude and angle kept constant at defined value is called SL bus. The angle of slack node acts as a reference angle in the network. Slack bus in a network acts as a balancing bus; where missing or excess power is generated or consumed by the active source.

Power flow Eqs. (1.1) and (1.2) are nonlinear function; therefore, numerical iteration method is required to find the solution. There are different methods available for solving nonlinear equation [2–4], but for load flow calculation two approaches are well known: Gauss–Seidel method and Newton–Raphson method [1, 5, 6]. In PowerFactory, Newton–Raphson method is implemented for calculating load flow solution.

1.2 Network Models in PowerFactory for Load Flow

PowerFactory is one of the prominent computer aid engineering software for planning, designing, and operation of power system. It has a vast range of library to model electrical power component and different tools for detail analysis. In this section, transformation of the load flow problems into PowerFactory and performing steady-state analysis with different options and design criteria are explained. There are many possibilities to model electrical component either in detail or in simple form in PowerFactory, but only basic modeling component and those options that are necessary for load flow analysis are covered here. For detail, it is recommended to consult the software user manual [7].

In general, from modeling point of view, PowerFactory electrical component model can be categorized into four categories.

- **Busbar**: It is a fundamental electrical network component at which voltage magnitude and angle are calculated. It is also commonly referred as terminal and junction node. In addition, it is possible to model the busbar as a station in detail that includes the different arrangement of terminals and switches such as single-bus system with tie breaker and double-busbar system with bypass busbar. In PowerFactory, it is identified by the class called *ElmTerm*.
- **Source/Generator**: Generators are modeled as voltage-controlled sources that control the voltage magnitude and active power injection into the busbar. The busbar connected to the generator is commonly referred as PV bus. In the network, at least one of the generators must be configured as reference machine, i.e., control the voltage magnitude and angle. The busbar connected to the reference machine is set as SL bus. Most common generator/source models in PowerFactory are synchronous machine (*ElmSym*), double-fed induction machine (*ElmAsmsc*), static generator (*ElmGenstat*), external grid (*ElmXnet*), AC voltage source (*ElmVac*), and AC current source (*ElmIac*).

- **Shunt Filter/Load**: These electrical network components supply schedule active and reactive power, and the busbar connected with it is known as PQ bus. Generally, a load is modeled in PowerFactory using class *ElmLod*, but additionally, there are other models available depending upon network voltage level such as MV load (*ElmLodmv*) and LV load (*ElmLodlv*). Shunt filter (*ElmShnt*) can be modeled as resistive (R), inductive (L), and capacitive (C) filter either or combination of them. In PowerFacotry, asynchronous machine (*ElmAsm*) model is used for motor representation. Motor can either be modeled as single- or double-cage motor.
- **Series Branches**: Series branches are the electrical components that connect the two terminals to form the network. It includes lines (*ElmLne*), transformers (*ElmTr**), series reactance (*ElmSind*), series capacitance (*ElmScap*) and filters (*ElmSfilt*), and power control devices. Each of them has subcategories for detail modeling of the network.

  Most common elements in PowerFactory for the development of the network to formulate the load flow problem and required input data are listed below:
- **Busbar**: Input data for busbar for load flow calculation are rated line-to-line voltage, e.g., 10 kV. Beside that in PowerFactory, other network informations are also required such as system type (AC), and phase technology (ABC, i.e., three-phase balance network). All these informations defined the network basic property.
- **Line**: Transmission line is modeled as PI-network for calculation, and input data required by line are series resistance, series inductance, and shunt capacitance. Usually, these values are given in per km of length. In addition, derating factor and number of parallel line also affect the current-carrying capacity and total impedance of line.
- **Load**: Load can be modeled in different ways such as constant impedance, constant current, or constant power. Constant power load is voltage-independent model and represented with stiff voltage characteristics. This method is mostly used in load flow calculation, and it is suitable for medium- to high-voltage network analysis but not for low-voltage network as load power depends on voltage variation. For the representation of the active power demand of motor, load must be modeled as constant current that changes linearly with voltage. For low-voltage load such as lighting or household electrical equipment, constant-impedance model of load is required that changes proportionally to the square of the voltages. For detail analysis, either of load models individually does not cover all the aspect of consumer load. Characteristics of all models can be combined by using the ZIP model of load [7]. In PowerFactory, load type (*TypLod*) must be defined for load ZIP modeling. Input parameters are inserted on load flow page of load type as shown in Fig. 1.1.

Fig. 1.1 PowerFactory setting for voltage dependency load modeling on load flow page of load type

- **Shunt Filter**: It is a representation of R, L, and C or combination of these filters. Usually, shunt filter is modeled as admittance for load flow calculation and the value can be given either directly as layout parameters or calculated from design parameters such as rated voltage, rated power, quality factor, and resonance frequency.

- **Generator**: For load flow calculation, generator is modeled as current-injected source. It is important to define voltage controller scheme for generator, i.e., droop characteristic (DV), fixed set point (PV), or uncontrolled (PQ). If the busbar connected with the generator set to PV mode, then only one generator can control the voltage of that busbar; on the other hand, if the voltage controller scheme is set as droop control, more than one generator can control the voltage of the busbar. Active dispatch and voltage set point must be defined according to input mode. Additionally, to investigate the loading and operation limit violation, it is required to set the active and reactive power maximum and minimum limits. In PowerFactory, it is also possible to implement external station controller and power–frequency controller to control the reactive and active power of the generator. Station control system is used to simulate the behavior as supervisor control system of generators' reactive power. Similarly, power–frequency controller controls the frequency at a busbar by controlling one or more generators' active power flow. Load flow page of a static generator (*ElmGenstat*) is shown in Fig. 1.2.

- **External Grid**: As explain earlier, there must be at least one slack busbar in the network. In PowerFactory, busbar type is defined by the element connected to it. To set a busbar as slack, mode type of generation unit connected to it must be set to SL. Voltage magnitude and angle values are required as input data.

Fig. 1.2 Load flow setting page of PowerFactory static generator model
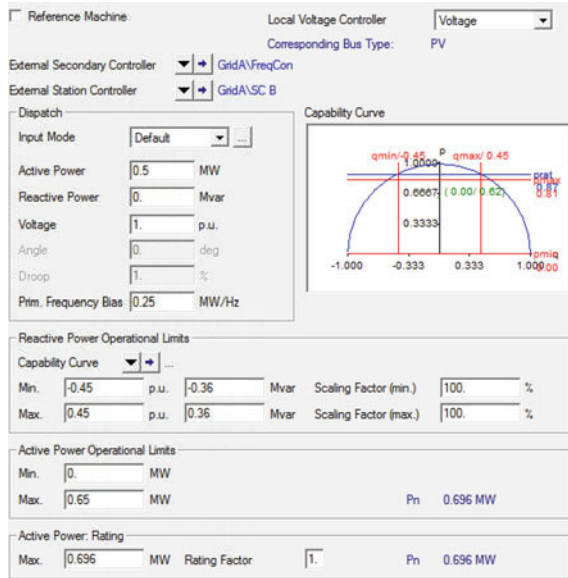
1.3 Project Planning Using Load Flow Calculation

Generally, power system transmission network is subdivided into three systems for planning, designing an operational point of view. This categorization based on transmission voltage levels, i.e., high-voltage (HV), medium-voltage (MV), and low-voltage (LV) network. Voltage level associated with each network category is listed in Table 1.2. High-voltage network system is used for transferring large electrical power over long distance from city to city or one country to another and connects large power stations. Medium-voltage network usually distributes power within urban and rural area and supplies power to industries having large motors. Low-voltage network supplies power to household customer and small industries [8]. Foremost step in network planning is to construct the single line diagram which is based on geography, and it shows the distribution of load, generation, and layout of the network. Topologically, power systems are constructed and operated as radial, ring-main, and meshed system. Each of these network topologies has some advantages and disadvantages; network design is usually chosen according to the planning criteria such as cost, reliability, and contingency. More detail can be found in [8].

1.3.1 Case Study: Low-Voltage Network

Radial system is the simplest configuration of electrical network. In radial system, there is only one feeding point and usually it is employed at low-voltage-level network. The advantage of this configuration is low investment cost and simple operation, but as a disadvantage, this configuration does not support n − 1 criterion;

Table 1.2 Power system network level

Name	Nominal voltage
High voltage	380 kV (400 kV)
	220 kV
	110 kV
Medium voltage	30 kV
	20 kV
	10 kV
	6 kV
Low voltage	400/230 V

that is, in case of failure of a line, the downstream load of that line cannot be restored. On the other hand, radial ring-main topology which is obtained by connecting the line end back to same station as shown in Fig. 1.3 provides reserves for outage of each sections.

PowerFactory project of this case study is available, having title "Load Flow Case LV Network.pfd." All the required equipment types and necessary data are included in the project. Network configuration is set as the final solution of the project. Six feeders are defined in the project. To activate the coloring according to the feeder, on menu, click "View → Diagram Coloring." Standard coloring dialog box will open; select option "Other" on basic page. Choose from the list box "Topology" and "Feeders" and press OK.

The list of feeders can be seen by clicking on toolbar option "Edit Relevant Objects for Calculation" and then "Feeders (*.ElmFeeder)." List of other elements can also be displayed in a similar manner. In this configuration, there are six
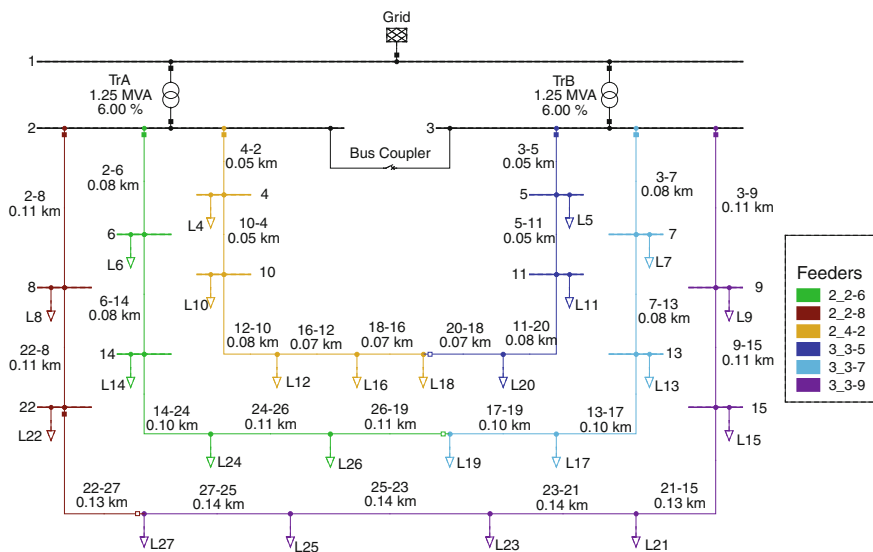

Fig. 1.3 Single line diagram of LV network

outgoing feeders, i.e., line 2–8, 2–6, 4–2, 3–5, 3–7, and 3–9. The term feeder is referred to the outgoing connection from MV or LV substation such as overhead line or cables. Power is transferred via two distribution transformers from MV to LV network. Thus, it provides possibility to continue supply to the customer via one transformer by closing coupling switch in case other transformer is malfunctioning or in schedule services. This means that the thermal loading of each transformer must be at 50 % in average in normal operation. External grid represents the MV distribution system with an ability to withstand load variation of LV network; thus, busbar 1 acts as a slack bus.

Feeders in radial ring-main configuration offer reserves in case of fault from another feeder which is connected to the same substation via open switches as demonstrated in Fig. 1.3. Therefore, it is necessary to keep the loading of each line section lower than its maximum permissible loading to be able to supply the extra load during fault.

Also, system losses and voltage drop can be minimized by changing the location of open switch within the loop. For network planning, total number of consumers, load per consumer, and geographical distance between loads must be known. Also, different line types for selections must also be available. Line types of different cross section are listed in Table 1.3. Also, line types are available in global library of PowerFactory. Network is planned for 50 Hz three-phase balance AC system.

Similarly, transformer specifications are given in Tables 1.4 and 1.5. Additionally, some distribution transformer may equip with tap changer. Through tap changer, additional winding can be added either at HV or LV side, which leads to rise or drop in the voltage level and/or produces phase shift. Here, same type is assigned to both transformers.

Using load and line data that are given in Tables 1.6 and 1.7, respectively, LV network can be established in PowerFactory. In normal operation, switches at

Table 1.3 Line type input data for low-voltage network

Cross section (mm^2)	Rated voltage (kV)	Rated current (kV)	Resistance (Ohm/km)	Reactance (Ohm/km)	Susceptance (μS/km)
50	1.0	0.185	0.3908	0.0785	223.0531
70	1.0	0.230	0.2703	0.0754	245.0442
95	1.0	0.275	0.1950	0.0754	257.6106
120	1.0	0.315	0.1556	0.0723	282.7433
150	1.0	0.355	0.1264	0.0723	285.8849
185	1.0	0.400	0.1013	0.0723	285.8849
240	1.0	0.465	0.0787	0.0723	301.5929
300	1.0	0.525	0.0636	0.0723	314.1593
400	1.0	0.600	0.0494	0.0723	339.2920

Table 1.4 Transformer type data for low-voltage network

Power (MVA)	HV voltage (kV)	LV voltage (kV)	Short-circuit voltage (%)	X/R	Vector group	No load current (%)	No load losses (kW)
1.25	10.0	0.4	6.0	7.073	Yy0	0.192	2.4

Table 1.5 Transformer tap setting

Type	Side	Additional voltage per tap (%)	Phase shift	Tap min. position	Tap neutral position	Tap max. position
Asymmetrical phase shifter	LV	2.5	0.0°	−2	0	+2

Table 1.6 Input data for all loads

Input mode	Active power (MW)	Power factor (inductive)	Technology
P, cos(phi)	0.04	0.98	3Ph-D

Table 1.7 Line input data for low-voltage network

Name	Busbar		Rated voltage (kV)	No. of parallel line	Length (km)	Derating factor
	From	To				
3–5	3	5	1.00	1.00	0.05	1.00
5–11	5	11	1.00	1.00	0.05	1.00
3–7	3	7	1.00	1.00	0.08	1.00
7–13	7	13	1.00	1.00	0.08	1.00
13–17	13	17	1.00	1.00	0.10	1.00
17–19	17	19	1.00	1.00	0.10	1.00
27–25	27	25	1.00	1.00	0.14	1.00
25–23	25	23	1.00	1.00	0.14	1.00
23–21	23	21	1.00	1.00	0.14	1.00
21–15	21	15	1.00	1.00	0.13	1.00
3–9	3	9	1.00	1.00	0.11	1.00
9–15	9	15	1.00	1.00	0.11	1.00
22–8	22	8	1.00	1.00	0.11	1.00
2–8	2	8	1.00	1.00	0.11	1.00
2–6	2	6	1.00	1.00	0.08	1.00
6–14	6	14	1.00	1.00	0.08	1.00
14–24	14	24	1.00	1.00	0.10	1.00
24–26	24	26	1.00	1.00	0.11	1.00
26–19	19	26	1.00	1.00	0.11	1.00
11–20	11	20	1.00	1.00	0.08	1.00
20–18	20	18	1.00	1.00	0.07	1.00
18–16	18	16	1.00	1.00	0.07	1.00
16–12	16	12	1.00	1.00	0.07	1.00
12–10	12	10	1.00	1.00	0.08	1.00
10–4	10	4	1.00	1.00	0.05	1.00
4–2	4	2	1.00	1.00	0.05	1.00
22–27	22	27	1.00	1.00	0.13	1.00

Fig. 1.4 PowerFactory load
flow command basic setting

busbars 18, 19, and 27 and bus coupler are open, thus operating all the feeders in
radial configuration. All loads are modeled as constant power system. Initially,
assign the line type of minimum cross-section (low-priced) to all lines so that the
amount of current flowing through the lines is according to loads and loading of each
lines can be determined. Select load flow command from the toolbar or from menu
by clicking "Calculation → Load Flow → Load Flow". Command class is referred
as *ComLdf*. Adjust the option as shown in Figs. 1.4 and 1.5, and execute the load
flow calculation. These settings execute the balance AC load flow calculation with
no reactive power control and using reference machine as an active power control.

Load flow results will be shown in single line diagram. Overloaded cables and
low-voltage busbars can be identified via diagram coloring feature. Losses in the
network in initial calculation would be high, as many of lines will be overloaded
and voltage drop at the end of the feeders might be greater than limits.

In low-voltage network, voltage drop at the end of the feeder must be within the
tolerance of ±10 % of rated voltage. One of the criteria of the network planning is
the consideration of utilization factor which can be directly measured via compo-
nent loading.

For example, if the line transformer loading is near 20 %, then it considers as
overdesign as transformer with higher rated power is installed which leads to
unnecessary higher cost. Similarly, a cable can be operated with 100.0 % loading
and for short duration of time at higher loading but excess heat and stress on the
cable lead to shortening of cable life, which is then considered as underdesign.
Generally, loading of the components near 70 % is preferable. PowerFactory

Fig. 1.5 PowerFactory load flow command power control setting
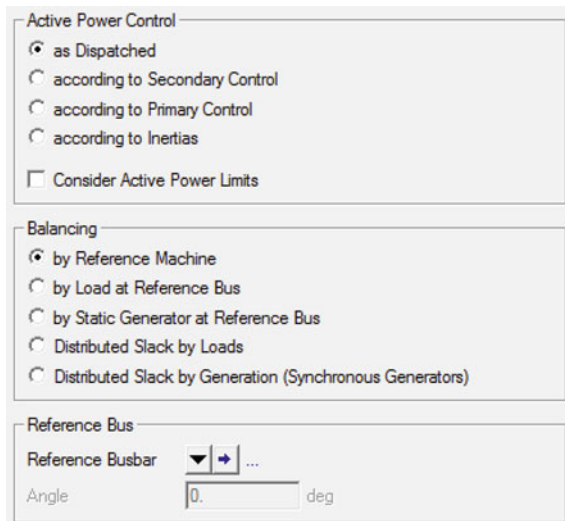
provides many data-handling tools that can be used for defining filters according to custom criteria.

Display the list of lines, on flexible data page of the list, define custom variable by clicking "Define Flexible Data", and choose loading variable (c:loading). Sort the list of lines in descending order by clicking on the loading column header. Note down lines that have loading above 70 %. Similarly, list of busbars (*.ElmTerm) can be displayed and sorted in ascending order according to voltage magnitude by defining variable (m:u). List of overloaded lines and low-voltage busbars is shown in Table 1.8. It can be noticed that there are lines that are above 100 % loading, and maximum voltage drop at busbars is up to 60 % of rated voltage. Limit violations can be mitigated by choosing cables of higher cross section for overloaded lines; this may improve the voltage drops as well.

It is not only sufficient to select the cable according to normal operational current, but also it is important to consider the worst-case scenario. Worst case in the design would be if either busbar 2 or busbar 3 goes out of service; in this situation, total load has to be supplied by only one transformer. The criteria for lines and transformer would be not to exceed their thermal limit; that is, loading must not be higher than 100 % and voltage drop at feeders end busbar must not drop below 0.8 p.u.

According to these criteria, cable types with the recommended cross-section are listed in Table 1.9. To study worst-case scenario, set busbar 3 to out of service and close switches at busbars 18, 19, and 27. Execute the load flow with same setting and observe the results. With recommended setting in worst case, transformer loading would be 86.4 % and all the lines will have less than 100 % loading. Maximum voltage drop will be up to 0.841 p.u. When the fault is not on the main supplying busbars (bus 2 or 3), there are multiple options via disconnector (i.e., bus coupler, switches at busbars 18, 19, and 27, and feeder switches) to reroute the supply of the consumers that are on the fault branch. For self-exercise, find the

Table 1.8 List of cables above 70 % thermal limits and busbars above 10 % voltage drop limits

Line	Loading (%)	Max. current (kA)	Busbar	Rated voltage (kV)	Measured voltage (kV)	Measured voltage (p.u.)	Voltage drop (%)
3–9	272.49	0.5041	27	0.400	0.235	0.588	−41.200
9–15	236.84	0.4382	25	0.400	0.245	0.612	−38.792
21–15	197.55	0.3655	23	0.400	0.264	0.659	−34.067
4–2	172.79	0.3197	21	0.400	0.291	0.728	−27.189
23–21	153.86	0.2846	15	0.400	0.324	0.810	−18.989
10–4	139.76	0.2586	18	0.400	0.356	0.891	−10.892
3–7	138.65	0.2565	19	0.400	0.357	0.893	−10.732
2–6	138.23	0.2557	9	0.400	0.357	0.893	−10.670
12–10	105.96	0.1960	26	0.400	0.358	0.895	−10.525
25–23	105.68	0.1955	16	0.400	0.360	0.899	−10.093
7–13	105.26	0.1947					
6–14	104.94	0.1941					
3–5	99.18	0.1835					
16–12	71.16	0.1316					
13–17	70.90	0.1312					
14–24	70.69	0.1308					

Table 1.9 Recommended cross-section of cable types for lines

Line name	Cable type
	Cross section (mm^2)
3–9, 2–8	400
3–5, 3–7, 9–15, 22–8, 2–6, 4–2	300
5–11, 7–13, 21–15, 22–27, 6–14, 10–4	240
13–17, 14–24, 11–20, 12–10	185
17–19, 27–25, 23–21, 24–26, 20–18, 16–12	150
25–23	120
26–19, 18–16	95

recommended switches' states in order to supply all the loads when transformer TrB and line 26–19 both are out of service.

As explained earlier, for low-voltage network, preferable load model is constant impedance. In constant-impedance model, actual amount of power consumed by the load depends on voltage level of the connected busbar. If voltage drops, power consumed by the load would be lower than rated value. Besides accuracy of consumer load representation at LV network, constant-impedance model is also useful for solving load flow algorithm when the losses in the network are too high.

In this case study, initially while planning network, same cable type (i.e., 50 mm^2) to all lines was assumed.

Table 1.10 Feeder load scaling setting

Name	Load scaling	Scale factor	Power factor
2_2–8	Manual	1.0	No scaling
2_2–6	Manual	1.1	No scaling
3_3–5	Manual	1.2	No scaling
3_3–7	Manual	1.3	No scaling
3_3–9	Manual	1.4	No scaling
2_4–2	Manual	1.5	No scaling

If load flow command is executed for worst-case scenario with initial setting, load flow will not converge. The solution can be found by modeling all loads as constant impedance. In the project, load type with the setting shown in Fig. 1.1 is assigned to all loads. Enable load flow option "Consider Voltage Dependency of Load" on basic page as shown in Fig. 1.4. Execute the load flow command; process will converge. It is to be noticed that power consumption by loads is reduced and it depends upon the connected busbar voltage. Detailed report of the network can be created by executing "Output of Result (*ComSh*)" command. Click "Output Calculation Analysis" icon from the toolbar, and execute the command with option "Grid Summary".

In normal operation with recommended cable types, total active and reactive power including demand and losses that must be supplied by medium network grid can be determined from external grid model connected to slack busbar.

According to simulation, total demand of low-voltage network is 985.1 kW and 235.2 kVar. During planning, it is also sometimes essential to study the future load increment. Future loads usually are not given as definite value, and it is not necessary to change the load value manually. Scale factor can be introduced for all feeders, and it will be applied on all corresponding loads. In PowerFactory, on feeder load flow page, assign the value according to Table 1.10. To consider the feeder load scaling during load flow calculation, select the option "Feeder Load Scaling" on basic page of load flow command. After execution of load flow, it can be noticed that power flow from each feeding point increases proportionally. Furthermore, due to the increase in power flow, voltage drop increases within the feeders and at feeding busbars too (buses 2 and 3).

As explained earlier, distributed transformer may also have tap setting and usually it increases or decreases tap value automatically according to the set point and voltage range. Adjust the transformer tap control setting on both transformers load flow page according to Fig. 1.6. To enable the automatic transformer control during load flow calculation, select option "Automatic Tap Adjust of Transformer" on basic page of load flow command. After calculating load flow, it can be noticed that voltages at feeder busbar has improved, consequently improving voltage level at all load busbars. Shunt filter is not modeled in the project, but similar to transformer tap control, shunt auto-tap control can be activated by selecting option "Automatic Shunt Adjustment".

Fig. 1.6 Automatic transformer tap control setting

1.3.2 Case Study: Medium-Voltage Network

Most of the medium-voltage networks are in ring-meshed configuration as shown in Fig. 1.7. Often, small generators are connected to the network at medium-voltage level. Here, "Grid A" is set as slack generation and "Grid B" is set in PQ mode to represent the equivalent model of low-voltage network level with negative active and reactive power of 985.1 kW and 235.2 kVar, respectively.

Here, network level is 10 kV. PowerFactory project for this case study is available having title "Load Flow Case MV Network.pfd." Lines and its type parameters as well as transformer and it types parameters are defined in the project. Generator settings are listed in Table 1.11. An additional load is connected at "busbar 36" having value 3,000.0 kW and 1,700.0 kVar. Calculate the three-phase balance load flow calculation with active power control option as dispatch and power balancing by reference machine. Disable all reactive power control options. It can be observed that all the lines and generators loading are less than 100 %. Active power supplies by generators are according to the set points, and all the busbars' voltage levels are within the range of ±3 % of nominal voltage, but generators are consuming relatively high reactive power, and network reactive power demand is only fulfilled by "Grid A." Therefore, here, the planning objective is to determine the appropriate voltage set points for the generator so that reactive power becomes positive and improves the power factor of "Grid A." Load flow results without power control are shown in
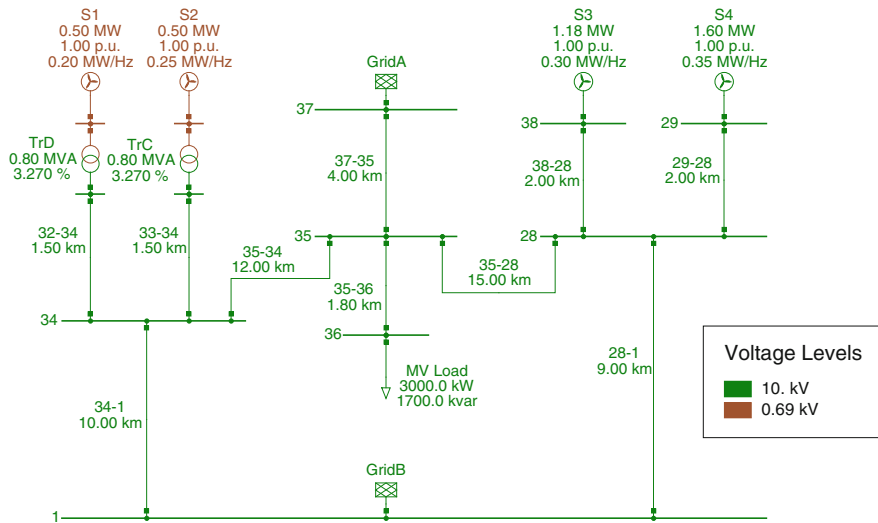
Fig. 1.7 Medium-voltage network in ring-meshed configuration

Table 1.11 Generator setting for medium-voltage network

Name	Bus type	Power (MVA)	Power factor	Active power (MW)	Voltage set point (p.u.)	Pri freq. Bias (MW/Hz)	Reactive power operational limits (MVar)		Active power operational limits (MW)	
							Min	Max	Min	Max
S1	PV	0.8	0.93	0.50	1.0	0.20	−0.38	0.38	0.0	0.70
S2	PV	0.8	0.87	0.50	1.0	0.25	−0.36	0.36	0.0	0.65
S3	PV	1.5	0.95	1.18	1.0	0.30	−0.90	0.90	0.0	1.40
S4	PV	2.0	0.97	1.60	1.0	0.35	−1.12	1.12	0.0	1.90

**Table 1.12** Power flows of sources in medium-voltage network

Source	Active power (kW)	Reactive power (kVar)	Busbar voltage (p.u.)
Grid A	389.99	2,960.29	1.0
S1	500.00	−59.36	1.0
S2	500.00	−59.36	1.0
S3	1,180.00	−505.19	1.0
S4	1,600.00	−949.14	1.0

Table 1.12. One way to achieve this is by assuming and changing voltage set points of generators manually and recalculating the load flow. This process is repeated and inefficient. In PowerFactory, external station controller (*ElmStactrl*) can be defined to automate this process (Fig. 1.8).

Station controller acts on sources to control the reactive power flow according to the desired characteristic. The objective of station controller can be to control the

Fig. 1.8 PowerFactory
station controller "SC A"
setting
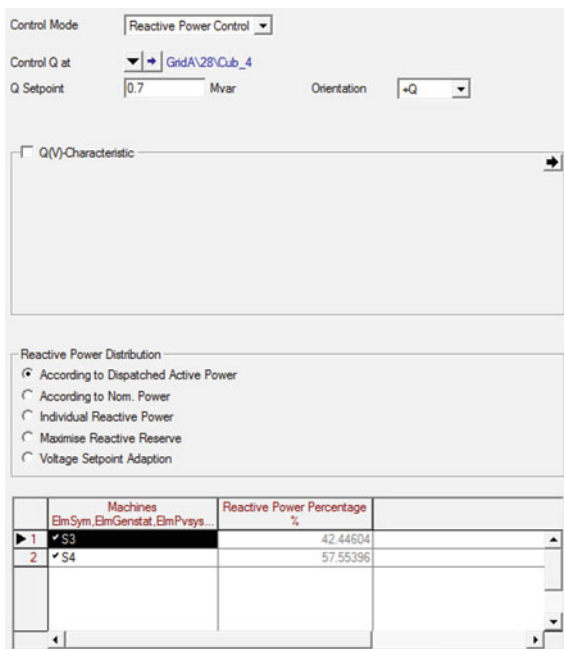
voltage level at a busbar, maintain power factor, or control reactive power flow in a branch. In the example, two station controllers "SC A" and "SC B" are defined. "SC A" controls generators S3 and S4, and "SC B" controls generators S1 and S2. New station controller can be created by selecting S1 and S2 and then press "Right click → Define → Station Control;" adjust the setting as shown in Fig. 1.9, and press OK. If station controller already exists, you can assign generators to it by selecting generators and pressing "Right click → Add → Station Control." Setting for station controller "SC A" is shown in Fig. 1.8.

Note "SC A" is controlling reactive power flow through line "35–28" at the side of "busbar 28" and "SC B" is controlling power factor at "busbar 34" at the line "35–34." In this setting, reactive power flow is enforced from generators toward load connected at "busbar 36" and reducing the amount of reactive power supply from the "Grid A."

After calculating load flow with the station controllers, it can be seen from Table 1.13 that the demand of reactive power required by the load is now fulfilled by the generators and power factors of all sources are improved. Results also provide the required voltage set points for the generators as well. Results can be verified by disabling the station controllers and assigning the voltage set points to the corresponding generators.

In above example, power is balanced by slack node and generation unit connected to that bus is assumed to have infinite power, but in reality all generation units have active power limits and usually power is balanced by increasing or

Fig. 1.9 PowerFactory
station controller "SC B"
setting
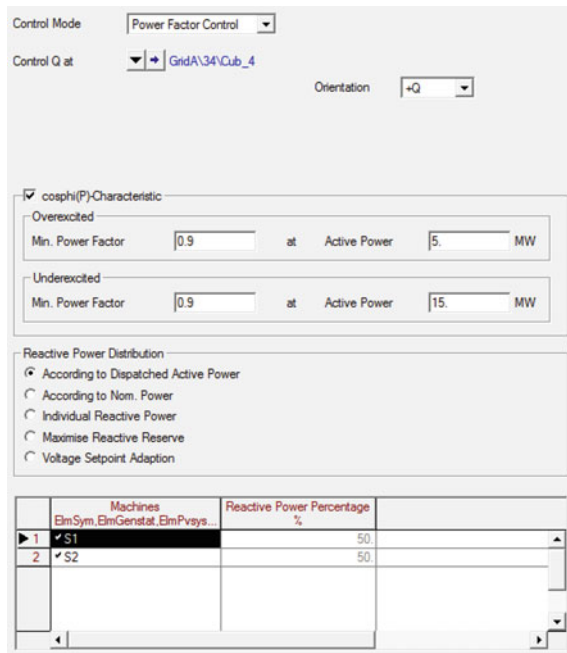
decreasing individual generator power. If in the network, generation is more than the load, then the grid frequency rises, and if generation is less than demand, then overall network frequency drops. This phenomenon can be studied in PowerFactory using Load Flow (*ComLdf*) active power control options "According to Secondary Control" and "According to Primary Control." Power control option can be changed on load flow page of load flow command. See Fig. 1.5 for detail.

In power balancing by primary control, all generators contribute in balancing the power according to their gain K_{pf} defined on load flow page (*ElmXnet*, *ElmSym*, *ElmGenstat,* etc.); for details see Fig. 1.2. Here, it is important to set the reference machine (*ElmXnet*) into other than SL mode, and it must have nonzero primary frequency biasing. Disable all the station controllers and assign the 0.1 MW/Hz primary frequency biasing to the external grid "Grid A" (*ElmXnet*). Generators parameters are set according to Table 1.11 except voltage set points which are taken from Table 1.13. Enable "Out-of-Service" flag for "Grid B," and connect load (*ElmLod*) to busbar 1 of value 985.1 kW and 235.2 kVar.

From Table 1.13, it can be noticed that the load demand in the network is 345.58 kW higher than total generation. Thus, change in grid frequency and contribution of each source is calculated using (1.3) and (1.4). After calculating load flow with primary frequency control, the resulting generation from all sources is listed in Table 1.14. Simulation results may differ due to network losses which vary according to power flow direction. Load flow calculation with "According to Secondary Control" active power control option has same principle of balancing the power as of