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INTEgrated opeRation PLAnning tool towards the Pan-European Network

Work Package 4

Grid equivalenting

Deliverable D4.3

Approach for generating grid equivalents for different use cases (final version)

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Abbreviations

AC	Alternate Current
BSC	Base Showcase
CIM	Common Information Model
DC	Direct Current
DER	Distributed Energy Resource
DFIG	Double-Fed Induction Generator
DG	Distributed Generation
DPI	Dynamic Power Injectors
DSO	Distribution System Operator
EU	European Union
KPI	Key Performance Indicator
LV	Low Voltage
MV	Medium Voltage
NERC	North American Electric Reliability Corporation
P	Active Power
PCC	Point of Common Coupling
POI	Point of Interconnection
p.u.	Per unit
PV	Photovoltaic
Q	Reactive Power
REI	Radial, Equivalent and Independent
REMTF	Renewable Energy Modelling Task Force
RES	Renewable Energy Source
SC	Showcase
TSO	Transmission System Operator
UC	Use Case
V	Voltage
WECC	Western Electricity Coordinating Council
WPP	Wind Power Plant
WTG	Wind Turbine Generator
WT	WindTurbine

Executive Summary

Modern technological trends for massive RES integration into the electrical grid together with the evolution of energy storage systems and the increasing penetration of electric vehicles contribute greatly to decarbonization of the energy systems and energy efficiency improvement. This causes, however, significant challenges for the future operation of EU electricity system characterized by the wide diversity of electrical networks among EU members.

Ideally, all system operators should have full models of all grids to carry out network analysis in a digital simulation environment. However, as of today no network operator has models of the entire physical grid, in particular covering different voltage levels and all neighbouring network operators. The detailed modelling of the whole power system requires a huge input data and complex structure, and this clearly contributes to the problem. Therefore, grid equivalents adequately representing different parts of European electricity systems and at different voltage levels are needed.

During the equivalenting process, a large, branched part of the network can be substituted by a relevant simplified counterpart while keeping network characteristics at an appropriate level of accuracy. This will reduce large amount of calculations and increase the model simulation speed greatly. Generating grid equivalents instead of the detailed model has thereby a great practical significance and the grid equivalents can be convenient for different power system applications.

In deliverable D4.3, a general concept of generating grid equivalents is being introduced alongside of a classification of the generated grid equivalents. The proposed methodology is needed to generate grid equivalents that will allow an accurate analysis of the complex network, by considering local active elements in the grid. Based on the developed INTERPLAN use cases, showcases and requirements for network models and interfaces, the project provides and delivers grid equivalents to be incorporated in the integrated operation planning tool and semi-dynamic simulations environment. In a further step, the developed grid equivalents were validated during the project runtime. Using appropriate grid equivalents for the distribution grid, the complexity of such investigations can be reduced significantly and can help distribution system operators (DSOs) to identify the optimal standard parametrization of small-scale distributed energy resources (DER).

The “grid equivalenting”, is the process to generate a grid equivalent model encompassing a large part of network substituted by a smaller counterpart having the same relevant properties. To this aim, the network models of use cases were designed in numerical power system simulation environment. Then, a clustering methodology for transmission and distribution systems up to the end user level are applied, and a detailed approach for generating grid equivalents is used. To realize the transition from feeder to the network level, new grid elements have to be considered, for example transformers, generators or synchronous machines. Depending on the available data, variables dealing with these grid elements are to be examined to complete the grid representation.

The consortium provides an integrated operation planning tool to the prospective users (mainly transmission system operators (TSOs) and distribution system operators (DSOs)) where the grid equivalenting methodology can be applied. Although there are use cases where grid equivalenting cannot be used due to the need of very detailed representation of the required network model, in most of the cases, although grid equivalents are optional, usage of equivalents simplified calculations and significantly reduced time required for running simulations without discounts in the quality of results as there was no big deviation between results obtained from full grid models and corresponding grid equivalents.

1 Introduction

1.1 Purpose of the Document

During the early days of power system network analysis by digital computers, the need for network equivalents arose in order to allow the analysis of large-scale power systems to be practically possible given the limited computational speed and storage and at that time. However, due to the huge developments in computer technology, this constraint is no longer applicable and very large power systems can nowadays be analysed quickly and cost effectively on personal computers. However, power system equivalents are still required in industry. Practical examples include a distribution network company that owns and operates a distribution network and obtains its bulk power needs from a transmission company from one or several substations. The transmission network may be very large and an equivalent at one or more boundary nodes that are judiciously selected is usually sufficient for the short-circuit analysis needs of the distribution company. Similarly, the transmission company itself would not need to represent the distribution network in its entirety and an appropriate equivalent at one or more boundary nodes is usually sufficient.

Network reduction is a mathematical process that combines and eliminates network nodes and branches, so that the reduced equivalent contains smaller number of nodes and branches than the original network. The equivalent must be capable of reproducing the electrical behaviour of the original network at the boundary interface or nodes with sufficient accuracy. There are several types of power system equivalents the characteristics of which depend on the type of power system analysis being carried out. Equivalents may generally be classed as static or dynamic equivalents. The former may be used in DC (direct current) and AC (alternate current) load flow analysis, AC short-circuit analysis and harmonic analysis etc. The latter are used in power system stability and control analysis.

At the present time no network operator has models of the entire physical grid covering different voltage levels and all neighbouring network operators. The detailed modelling of the whole power system requires a huge input data and complex structure, and this clearly contributes to the problem. So, the grid equivalents adequately representing the parts of European electricity systems are needed.

1.2 Scope of the Document

The aim of this deliverable is to present the general concept of generating grid equivalents alongside of a classification of the generated grid equivalents. The proposed methodology is needed to generate grid equivalents that will allow an accurate analysis of the complex network, by considering local active elements in the grid. Based on the developed INTERPLAN use cases (UCs) [1], showcases (SCs) [1] and requirements for network models and interfaces [2], the project provides grid-equivalents covering all voltage levels to be incorporated in the integrated operation planning tool and quasy-dynamic simulations environment [3]. The developed grid equivalents were validated during the project runtime. Hence, a validated set of grid equivalents is provided accessible by public on the website. Using appropriate grid equivalents for the distribution grid, the complexity of such investigations can be reduced significantly and can help distribution system operators (DSOs) to identify the optimal standard parametrization of small-scale distributed energy resources (DER). Several internal reports were drafted regularly to illustrate the different iterations and improvement of the concept and are summarized in the final version of this deliverable.

1.3 Structure of the Document

The document is structured in 6 chapters. Starting with a short introduction in Chapter 1, it continues with the grid equivalents requirements in the view of INTERPLAN project in Chapter 2.

Chapter 3 presents the general concept of generating static grid equivalents. It also explains how the script for generating automated grid equivalents works and the steps it fallows. Similarly, Chapter 4 explains the general concept for generating dynamic grid equivalents focusing on the cases of connected renewable distributed energy resources.

Chapter 5 gives an overview with examples of the different grid equivalents considered during the run of INTEPLAN project. During the development of the project other tools capable of generating reduces networks were developed and in Chapter 6 the DigSilent PowerFactory network reduction tool is presented. Chapter 7 concludes the deliverable.

2 Grid equivalents requirements in the view of INTERPLAN project

2.1 General Considerations

The “grid equivalenting”, which is conceptually the successive phase of the work, is the process to generate a grid equivalent model encompassing a large part of network substituted by a smaller counterpart having the same relevant properties. To this aim, the network models of previous use cases will be designed in numerical power system simulation environment. Then, a clustering methodology for transmission and distribution systems up to the end user level will be identified, and a detailed approach for generating grid equivalents will be developed for different use cases.

As previously mentioned, the scope of the work is the development of an approach to generate simplified grid equivalents representing the original networks according to the required granularity by the individual use cases. These equivalents for instance may be two-bus grid equivalent or representative grid equivalents (with a few more nodes). If a use case does not allow such a two-bus simplification (due to result accuracy) accurate grid models will be designed.

The reduction of grids to grid equivalents requires to assign load/generation data of the replaced grid to suitable locations in the grid equivalent. In order to enable it a methodology to link end users (DER profiles) to reasonable locations in the grid equivalent is going to be developed.

Based on the experiences and results in course of the Interplan project, the grid equivalents have been iteratively improved and enhanced if required.

In order to define the grid equivalents a mapping of the requirements for grid equivalents to the developed use cases and showcases was done by the project partners.

In the project, the concepts of “base showcase (BSC)” and “showcase” were defined [4], which was the first step for defining and describing them.

The base showcase was defined as “*Presentation of base use case(s) with no planning criteria and no controllers for emerging technologies, such as renewable energy resources (RES), distributed generation (DG), demand response or storages in the frame of chosen scenario, simulation type, test model, and time-series data. The base showcase allows to analyse the operation challenges of the related use case(s) and improvements achieved through the application of planning criteria with related implementation of controllers in the associated showcase”,* while the showcase was defined as *“Presentation of use case(s) in the frame of chosen scenario, simulation type, test model, time-series data and planning criteria”* [4].

Based on these definitions and use cases developed in the project, five base showcases and five showcases have been developed:

- Low inertia systems
- Effective DER operation planning through active and reactive power control
- TSO-DSO power flow optimization
- Active and reactive power flow optimization at transmission and distribution networks
- Optimal energy interruption management

These showcases are aiming to achieve the following goals formulated as planning criteria:

- Minimize losses
- Minimize costs
- Maximize share of RES
- Assure voltage stability
- Mitigating grid congestion
- Assure transient stability
- Optimize TSO/DSO interaction
- Maximize DG/RES contribution to ancillary services
- Assure frequency stability
- Minimize energy interruptions

As already mentioned, the consortium intended to provide in the integrated tool the following features and advantages in regards to the clustering and grid equivalenting: It will include a library of grid equivalents responding to the needs of INTERPLAN project and covering all voltage levels and their active components and it will provide easy to use grid clustering techniques that are adaptive and responsive to the dynamic growth of the evolving grid thus refreshing and valid as new technologies emerge and adapted in the grid. The following flowchart shows how grid equivalenting should be integrated into the tool set.

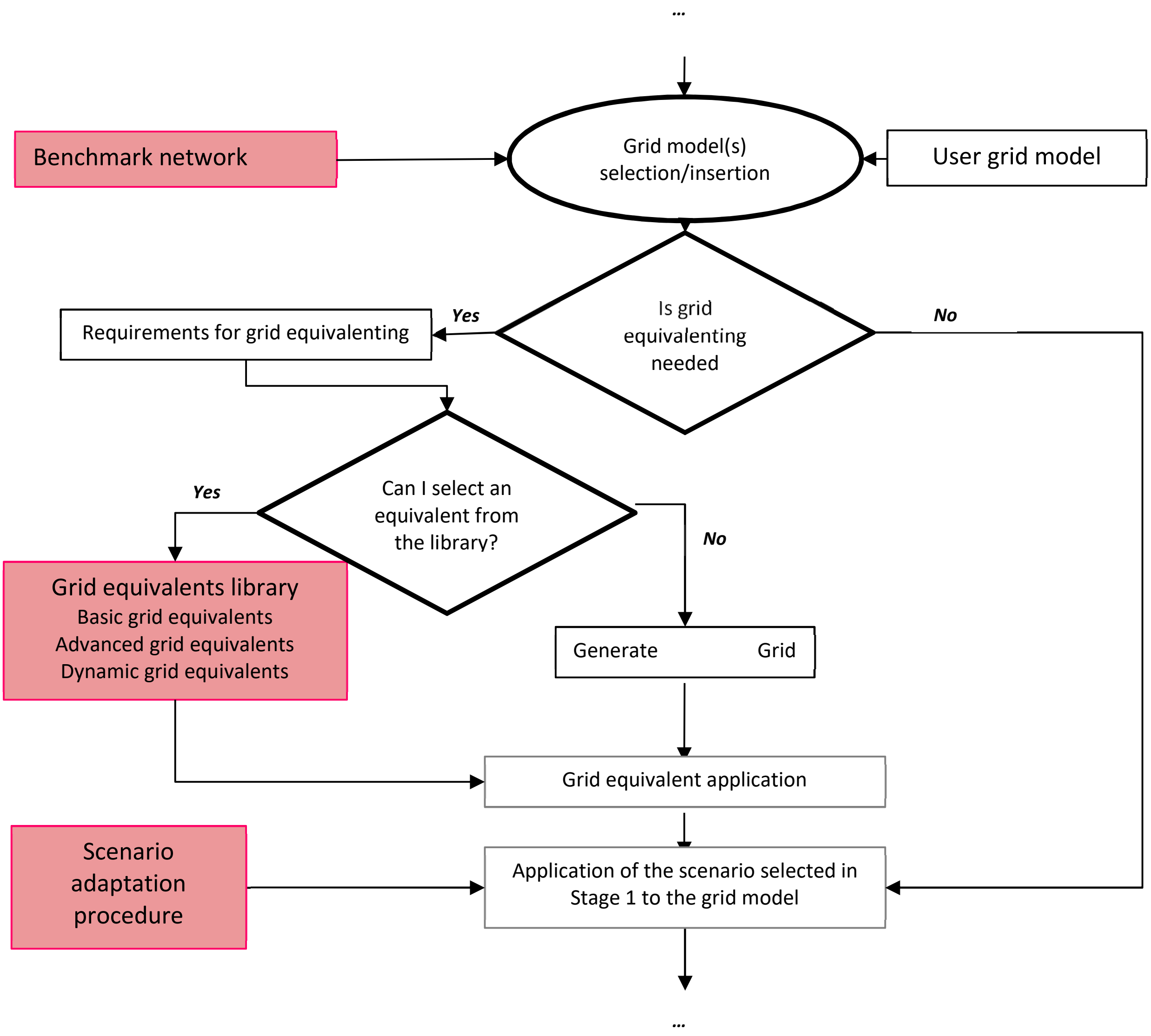


Figure 1 Section of the tool flowchart that reflects the application of grid equivalenting

2.2 Requirements of the grid equivalents

Considering the use cases and showcases the following table gathers inputs from all partners regarding the requirements of the grid equivalents.

Table 1 Requirements of the grid equivalent in the view of INTERPLAN project

Use Case / Showcase	Grid(s) investigated	Requirements for grid equivalent model
UC_1: Coordinated voltage/reactive power control	Transmission-distribution grid	Sub UC needs two grid equivalents one modelling TSO and the other modelling DSO. It means while studying TSO, DSO should be placed as an equivalent grid and vice versa. The grid equivalent can involve just the overall information of each connection point including voltage, active and reactive power.
UC_2: Grid Congestion Management	Transmission-distribution grid	The grid equivalent should keep the following: • number of busbars; • several sensitivities parameters (dP/dP, dV/dP, dP/dQ, etc); • lines characteristics
UC_3: Frequency tertiary control based on optimal	Transmission-distribution grid	Sub UC needs two grid equivalents one modelling TSO and the other modelling DSO. It means while studying TSO, DSO should be placed as an equivalent grid and vice versa. The grid equivalent can involve just the overall information of each connection point including voltage, active and reactive power.
UC_4: Fast Frequency Restoration Control	Transmission-distribution grid	The grid equivalent should keep following requirements: • Total grid freq. droop contribution per each control area; • Tie-line active power flow among control areas;
UC_5: Power balancing at DSO level	Transmission-distribution grid	Simple grid equivalent model for transmission network
UC_6: Inertia management	Transmission-distribution grid	Dynamic grid equivalent models should be developed for both transmission and distribution grids
UC_7: Optimal generation scheduling and sizing of DER for-energy interruption management	Transmission-distribution grid	The equivalent for the low voltage (LV) feeder and medium voltage (MV) feeder is required for the network preparation. The grid equivalent model should represent with the minimum size the properties of the original network with certain accuracy.
SC_1: Low inertia systems	Transmission-distribution grid	Dynamic grid equivalent models should be developed for both transmission and distribution grids. Grid topology can be ignored.
SC_2: Effective DER operation planning through active and reactive power control	Transmission-distribution grid	For base show case, the detailed equivalent model as result of clustering approach is not needed, rather a simplified representation should be sufficient. The sensitivity of only the critical node with respect to point of connection can be incorporated in the grid

Use Case / Showcase	Grid(s) investigated	Requirements for grid equivalent model
		equivalent.
SC_3: TSO-DSO power flow optimization	Transmission-distribution grid	SC needs two grid equivalents one modelling TSO and the other modelling DSO. It means while studying TSO, DSO should be placed as an equivalent grid and vice versa. The grid equivalent can involve just the overall information of each connection point including voltage, active and reactive power.
SC_4: Active and reactive power flow optimisation at transmission and distribution networks	Transmission-distribution grid	BSC needs two grid equivalents one modelling TSO and the other modelling DSO. It means while studying TSO, DSO should be placed as an equivalent grid and vice versa. The grid equivalent can involve just the overall information of each connection point including voltage, active and reactive power. Grid equivalenting should be possible by providing simplified Network models with aggregated values for V, P and Q
SC_5: Optimal energy interruption management	Transmission-distribution grid	The equivalent for the LV feeder and MV feeder is required for the network preparation. The grid equivalent model should represent with the minimum size the properties of the original network with certain accuracy.

2.3 Requirements analysis

After analysing the gathered information from Table 1, several conclusions can be considered:

- There is the need to have different types of grid equivalents depending on the voltage levels and model granularity
- Models should be developed for both transmission and distribution networks.
- Basic models should be simple enough to lower simulation time and maintain key characteristics of the "original" grid (e.g. voltage at connection point, active and reactive power)
- A set of grid equivalent models should consider also the grid topology and reflect different Voltage levels
- For some of the use cases / showcases dynamic grid equivalents should be developed

3 General Concept of Generating Static Grid Equivalents

To support the EU ambitious goals and the corresponding needs in power system planning and operation, a more fruitful interaction between DSOs and TSOs is expected, for which grid equivalents representing different parts of electrical networks are required. A fundamental step for this is feeder/ grid clustering, which allows to identify unique grid/ feeder clusters depending on specific network properties. Clustered electrical networks will provide the basis for the creation of a standardized reference grid model, permitting a wide range of simulations while requiring limited data input.

The networks used to determine grid clusters should be representative of the network of interest, for which a grid equivalent is to be computed, not only in terms of their electrical characteristics or topological structure, but also regarding many other aspects, such as for example, type of customers and their loads, supply areas (industrial/ urban or rural) etc. This will allow to establish the equivalent model of electrical grids more accurately.

A general approach proposed for generating grid equivalents is schematically presented in Figure 2.

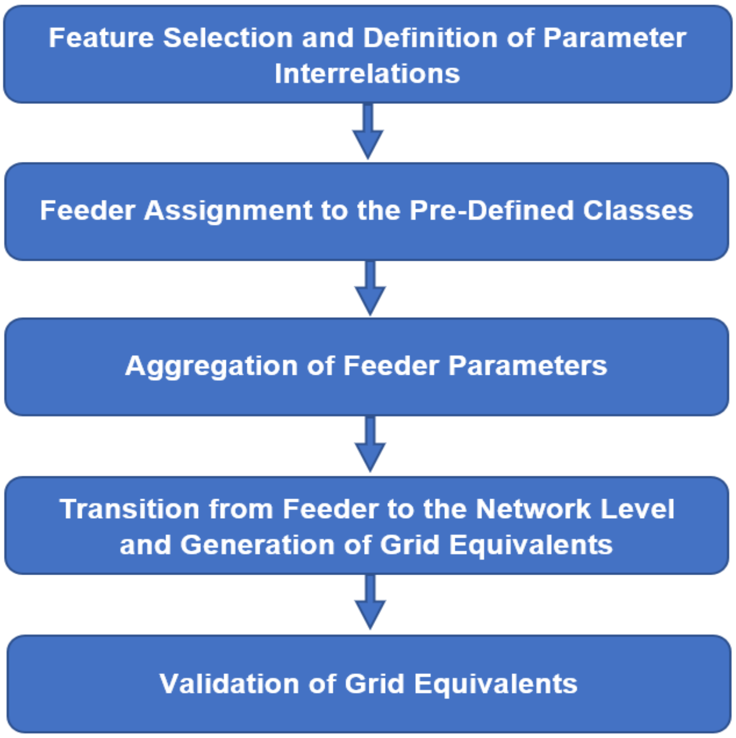


Figure 2: Basic algorithm for generating grid equivalents

3.1 Feature Selection and Definition of Parameter Interrelations

As a starting point for the computation of grid equivalents, it is considered that grid clusters [5] have already been identified. Hence, those equivalents would be built upon predefined clusters, by assigning subsets of a network to their corresponding clusters, and merging feeders belonging to the same cluster first. As a final step, feeders corresponding to heterogeneous clusters will be combined to obtain a simple grid equivalent. In order to merge homogeneous and heterogeneous feeders, it is necessary to identify the relationship between Key Performance Indicators (KPIs) and network parameters defined in [2]. Such relationships or maps indicate how the parameters of the grid equivalent would look like. The proposed methodology could be applied to the use cases, whose objectives are mainly based on maintaining the set voltage limits and coordination of power flows.

▪ Feature selection and Definition of Parameter Interrelations

Before starting an equivalenting process the most appropriate KPIs should be identified. In an ideal case, all characteristics related to the KPI calculation must be already implemented into a preceding clustering procedure. If the functional relationship between the KPI-variables and common clustering parameters cannot be directly observed or computed, it is recommended to specify the model of dependence among the characteristics by using regression analysis.

In the case of linear regression, the model, that relates the dependent variable to the given features, can be defined as follows:

$$y = Xw + \varepsilon \tag{1}$$

where y is a vector of the dependent variable;

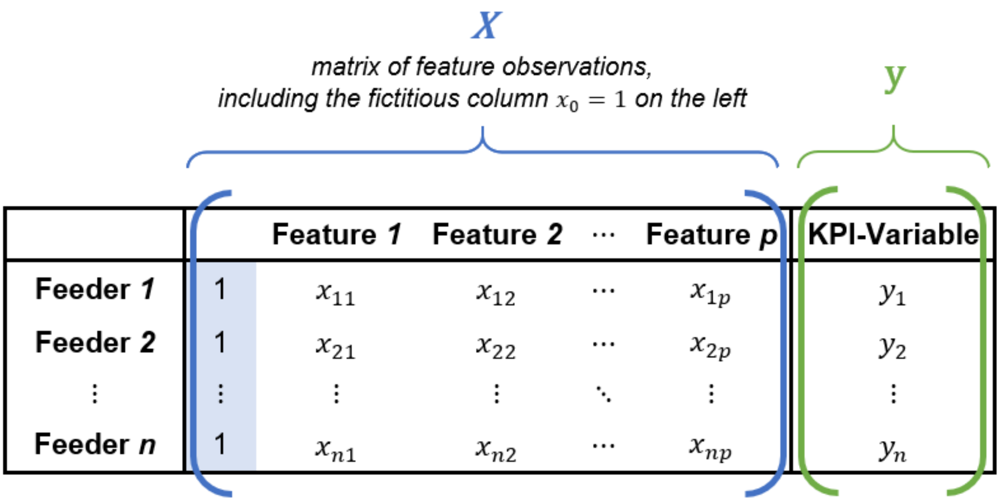
ε is an error term, corresponding to the random, unpredictable model error;

X is a matrix of feature observations, sized *n* rows by (*p*+*1*)-columns*,* where *n* represents the number of observations and *p* represents the number of parameters;

w is a (*p*+*1*)-dimensional parameter vector; its elements are often referred to as “weights”.

Thus, the problem of determining the relationship between the chosen KPI-variable and feeder features used for clustering has the main task in finding the optimal weights w_i from the given data set.

For a better understanding of linear regression models the matrix form of equation (1) is visualized on Figure 3.



		Feature *1*	Feature 2	⋯	Feature *p*	KPI-Variable
Feeder *1*	1	x_{11}	x_{12}	⋯	x_{1p}	y_1
Feeder *2*	1	x_{21}	x_{22}	⋯	x_{2p}	y_2
⋮	⋮	⋮	⋮	⋱	⋮	⋮
Feeder *n*	1	x_{n1}	x_{n2}	⋯	x_{np}	y_n

Figure 3: Matrix representation of the linear regression model

3.2 Feeder Assignment to the Pre-Defined Classes

Figure 4 schematically illustrates an example of a distribution grid with *n* radial feeders connected to the substation terminal. The given grid is to be substituted by a simplified equivalent grid model.

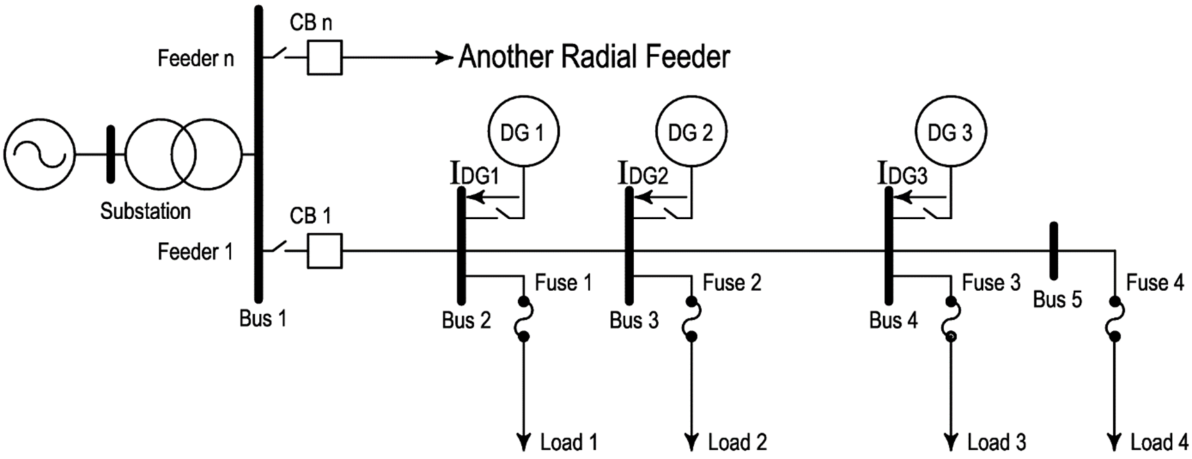


Figure 4: Schematic diagram for typical radial distribution system

The relevant characteristics of each new feeder have to be analysed thoroughly to correctly assign the feeder to one of the already identified classes. This could be performed automatically through computing the distances from each new object, i.e. feeder, to the obtained cluster centres according to the specified distance metric (for more details see Deliverable D4.1 “Method for clustering distributions grid” [5]). In this concrete case the Euclidean metric should be used to measure the similarity between feeder objects, since it was defined for distance computation at the stage of clustering. The Euclidean distance represents the straight-line distance between two data points p_i and q_i in the n-dimensional space of Euclidean geometry:

$$D_e = \sqrt{\sum_{i=1}^{n} (p_i - q_i)^2} \tag{2}$$

Minimum distance value would serve as a criterion for belonging to the nearest class of feeders.

Alternatively, determination of feeder classes could be realized by implementing a classification approach, such as for example, the Nearest Neighbours method [6]. The class membership of each object will be defined by the most frequent class among its k nearest neighbours. Following this approach, it is necessary to apply the identical distance measure previously used for K-means clustering.

3.3 Aggregation of Feeder Parameters

After identification of class membership all the feeders belonging to the same class can be aggregated to a representative feeder unit, representing the spectrum of properties for the whole feeder group. In this case, the above-mentioned requirements for parameter interrelations should be considered.

The resulting equivalent grid can be designed based on the set of *m* feeders presenting each feeder class (see Figure 5) or the equivalent grid can be shown as a single equivalent element combining electrical and topological characteristics of feeders belonging to different classes (see Figure 6), e.g. total cable length, total number of nodes, total impedance.

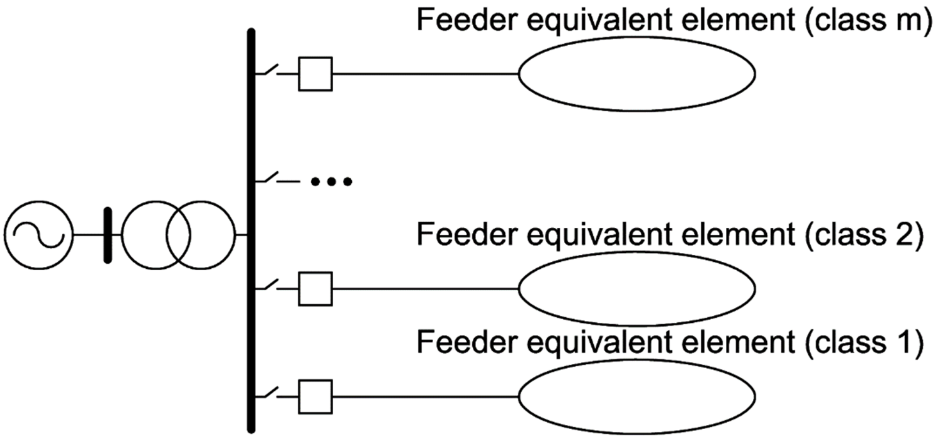


Figure 5: Equivalenting of the population of feeder classes

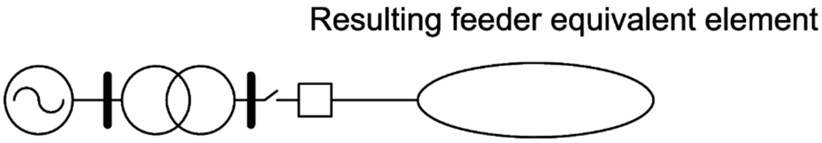


Figure 6: Single grid equivalent representation

Depending on the KPIs, defined for evaluating project use cases, the equivalent element can be represented by a broad set of relevant properties, such as for example:

- the sum of parameter values resulting from specific characteristics of representative feeders, e.g. the sum of power losses (corresponds to the KPI#1: Level of losses and KPI#7: Power losses)
- an extremum value of the parameter of interest, e.g. the maximum voltage drop/ rise (corresponds to the KPI#10: Voltage Quality: Voltage magnitude variations)
- an average parameter value, e.g. average loading (corresponds to the KPI#15: Utilization of electricity grid elements)
- any other representative parameter value.

More detailed description of project KPIs is presented in Deliverable D3.2: “INTERPLAN use cases” [1]. In this context, the developed equivalents are addressing particular KPIs and therefore, they cannot be interpreted as equivalents fully representing the original networks in all aspects.

3.4 Equivalent grid impedance

As a particular case of the grid equivalenting process, if the focus of the study lies on defining the equivalent grid impedance, it is recommended to apply the method of equal power losses. The proposed method is based on the principle, that total power losses are equal to the sum of branch losses. Active power losses in the given electrical grid ΔP_{grid} are to be divided into two main components: active power losses in lines ΔP_L and active power losses in transformers ΔP_T. The same is true for the reactive part of power losses.

The equivalent grid impedance $Z_{eq\ Grid}$ can be represented by equivalent line impedance $Z_{eq\ L}$ and equivalent transformer impedance $Z_{eq\ T}$ connected in series (see Figure 7).

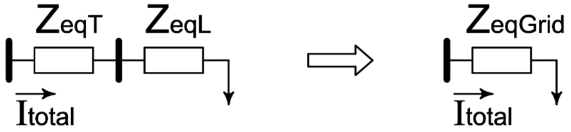


Figure 7: Concept of grid equivalenting based on equivalent impedance

The equivalent line impedance is the sum of the individual line losses divided by square of the total current. For each of *m* line segments with impedance Z_{Li} and current I_{Li} the equivalent impedance can be calculated as follows:

$$Z_{eq\ L} = \frac{\sum_{i=1}^{m} I_{Li}^2 \cdot Z_{Li}}{I_{total}^2} \tag{3}$$

Similarly, for equivalent impedance of *n* transformers:

$$Z_{eq\ T} = \frac{\sum_{j=1}^{n} I_{Tj}^2 \cdot Z_{Tj}}{I_{total}^2} \tag{4}$$

3.5 Transition from Feeder to the Network Level and Generation of Grid Equivalents

The evaluation of unique features derived from sets of feeder clusters is used as a basis for the network exploration. The preceding clustering approach could be initially performed at the network level. As a feeder-based cluster analysis is expected to yield more accuracy, the equivalenting process focuses on the feeder level.

Feeder equivalent can be considered as a grid element represented by a single line and the load connected at the end terminal. The equivalent load must be equal to the total active and reactive power consumed by the load of the original feeder. The feeder line element is assumed to have the set of attributes specific to the type of the main line of the corresponding representative feeder. The line length is initially defined to be equal to the total length of the representative feeder. The number of parallel lines is to be set so, that the line loading would be quite close to the loading of the main line of the real feeder.

The assumptions made in setting feeder attributes might lead to certain inconsistencies, such as deviations of equivalent impedance values from the original ones. To compensate for these undesirable effects, different feeder parameters can be appropriately modified. At the first stage of the equivalenting process the feeder parameter optimization can be performed: the feeder line length will be corrected accordingly to achieve a minimal difference between the values of equivalent impedance for the original feeder and its equivalent.

To meet the requirements for keeping voltage values within acceptable limits, the load distribution can be activated at the second stage of the equivalenting process. Figure 8 illustrates schematically the concept of load distribution: if any voltage drop higher than 5% occurs, the main feeder line will be automatically split in two parts and some amount of the feeder load will be shifted from the end node to the splitting point so, that the total feeder load will remain the same and the permissible voltage will be set at the feeder end terminal. The main principle here is, that the minimum amount of the load is to be distributed at the minimum necessary distance from the feeder end terminal. This will cause, however, some decrease of feeder related parameters, such as for example, equivalent impedance. So, applying the concept of load distribution could be useful for the correction of small voltage deviations from the set limits.

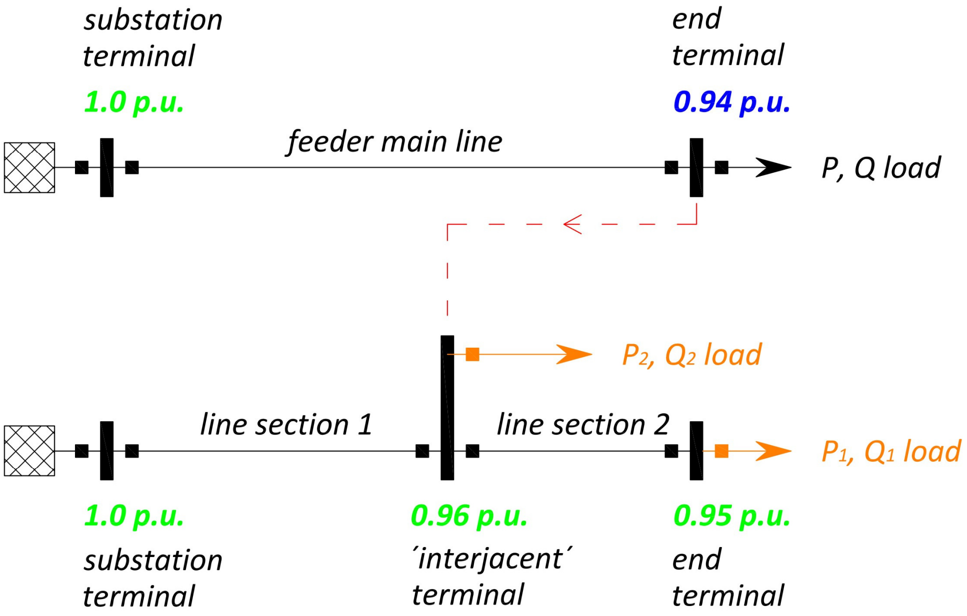


Figure 8: schematic representation of the load distribution concept

The next steps of the equivalenting process involve consideration of the network related data. This allows to create grid equivalents able to represent the key properties of real electrical networks for individual use cases and showcases of the INTERPLAN Project. To realize the transition from feeder to the network level, new grid elements must be considered, for example transformers, generators or synchronous machines. The corresponding values of attributes dealing with these grid elements are to be set to complete the grid representation.

3.6 Validation of Grid Equivalents

The proposed concept for generating grid equivalents has to be evaluated under real grid conditions and against full models. In order to modify and improve the developments, the equivalent models are went through a validation process in simulation environments based on representative use cases of the INTERPLAN project. After verifying the results, the developed models were implemented into the grid equivalents library able to cover the relevant use cases [7].

4 General Concept of Generating Dynamic Grid Equivalents for RES

As wind and photovoltaic (PV) generation continuously increase their share in the overall generation portfolio, they have growing influence on power system behaviour. Power system has to be prepared for all possible scenarios resulting from the intermittent nature of these resources, from system adequacy in the long run to day-ahead and intraday operation planning in the short term. Therefore, it is necessary to support planners with convenient and effective methods for considering RES in operation planning. The main prerequisite for it are the models of renewable generation prepared keeping in mind the purpose and characteristics of system operation planning.

These models should represent the right level of details so that a balance between accuracy and ease-of-use is achieved. Because power system operation planner is focused predominantly on the grid corresponding to a single voltage level (e.g. high voltage (HV) network), generation aggregation and grid equivalenting have to be used, so that the effect of operation of these resources is visible to the planner, but irrelevant phenomena taking place far from this grid are neglected. Aggregation and equivalenting also helps to decrease computational requirements and problems related to data maintenance.

Along with increasing RES in the power system its controllability decreases. Therefore, in order to account for the most stressed operation conditions, not only static operation planning is necessary, but also dynamic phenomena must be considered. Dynamic simulation requires dynamic models that fit into the aggregated and equivalented power flow representation of RES and the interconnecting grid. In this respect, accuracy and ease-of-use can be assured by utilisation of standard dynamic models, such as the second generation of RES models proposed by Western Electricity Coordinating Council (WECC) [8]. These models are available in most of simulation programmes, which facilitates data exchange between different owners, common understanding of how the models work and continuous development of these models. For example, these models are well prepared to represent all requirements resulting from the European Network Codes, so that planners are only asked to fill the right parameters corresponding to their power system.

The methodology for creating dynamic equivalents consists of two steps presented in Figure 9.

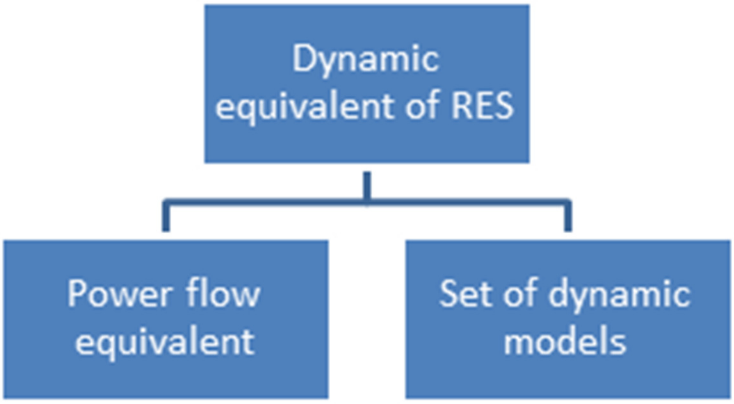


Figure 9 Methodology for creating dynamic equivalents

4.1 Preparation of power flow equivalent for RES

The first step to using dynamic equivalents for the wind or solar power plants is to prepare their aggregated power flow.

The method is constructed in such a way that during application only the rated power of a given installation is required, as often it is the only information available to other parties. Other methods, such as the one for utility-scale wind and solar power plants developed by the National Renewable Energy Laboratory [9] and adopted by the Western Electricity Coordinating Council (WECC) [8], or North American Electric Reliability Corporation (NERC) rely on detailed information regarding the internal structure of the wind farm or solar power park, which might not be available to the planning department of TSO or DSO.

However, background information required for preparation of the method encompass much more. Detailed data was available for many wind and solar PV power plants and included the topology of the collector system, parameters of the station transformer and lines or cables connecting to the grid (Figure 10). Having available data for many installations enabled calculation of typical parameters for the main components constituting the aggregated equivalent, as depicted in Figure 11 i.e. the station transformer, the collector system and equivalent unit transformer. These parameters were calculated per one MW of the rated power of the park in several power ranges.

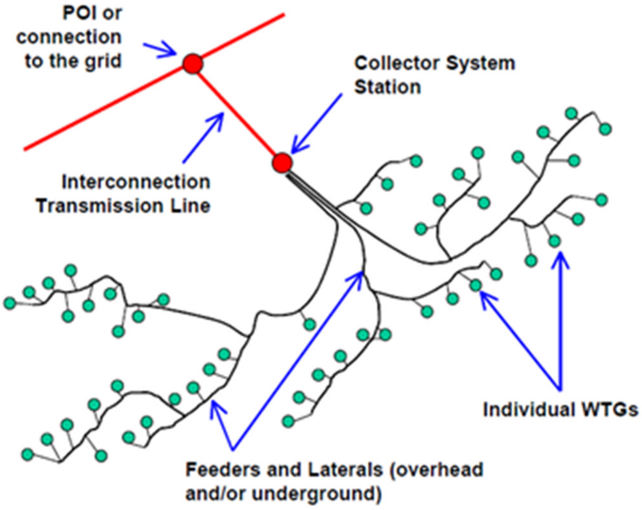


Figure 10: Typical wind power plant topology

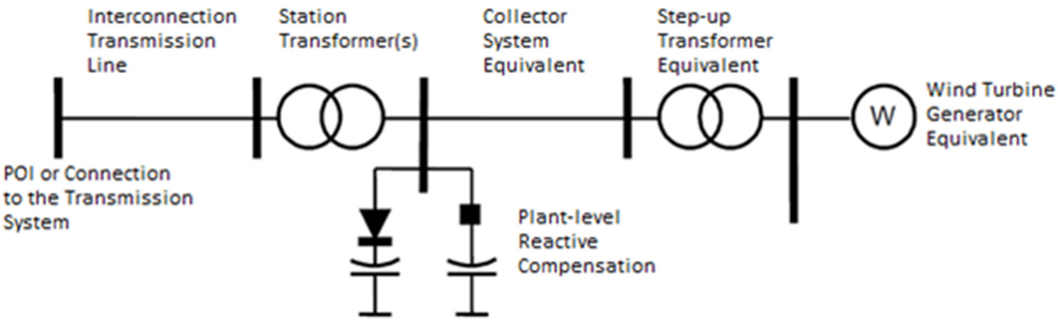


Figure 11. Single-machine equivalent power flow representation for a wind farm

There are two further steps in the procedure in order to simplify the topology of the equivalent presented in Figure 11:

1. Examination of data for different wind farms and PV farms showed that interconnection line and resulting reactive power compensation devices are very specific for each installation, which makes defining typical uniform parameters for these elements impossible. Instead, the overall reactive power capability at PCC should be represented within the wind turbine generator equivalent model and the interconnection transmission line impedance should be represented in the grid equivalent. Accordingly, an equivalent is proposed that consists of an equivalent generator, an equivalent generator step-up transformer and an equivalent collector system (as depicted in Figure 12a).
2. Furthermore, in order to obtain the simplest possible equivalent, further aggregation can be performed to obtain an equivalent that consist only of the generator and impedance representing together the step-up transformer, the collector system and the station transformer (Figure 12b). Detailed information on calculation methodology for each WPP element is presented in the next section.

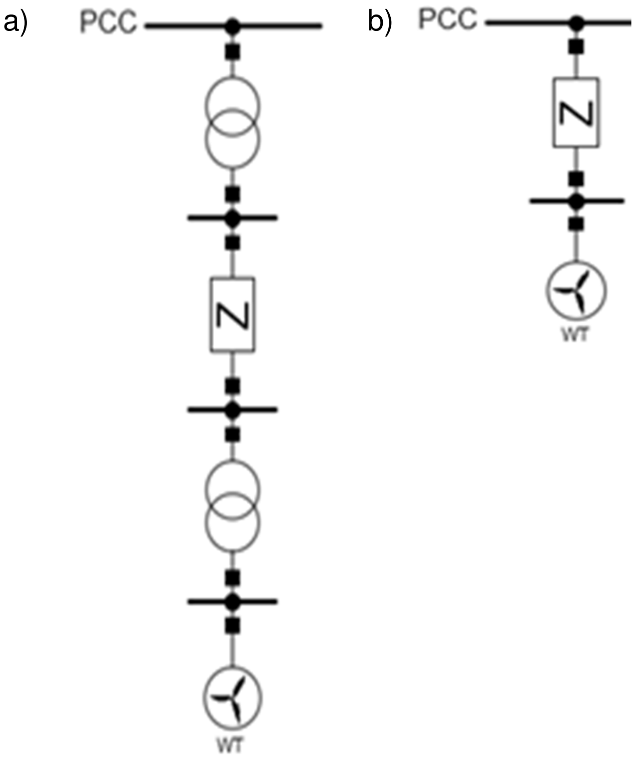


Figure 12: Power flow WPP equivalent: a) extended version, b) simplified version

4.2 Derivation of parameters for power flow equivalent for RES

Parameters for the equivalent station transformer, equivalent collector system and equivalent step up transformer that correspond to Figure 12a were calculated as average values of several tens of such elements represented in detailed topology models of various wind parks. Here ready-to-use values expressed per one MW are presented.

Table 2: ready-to-use values expressed per one MW

Element	Nominal power of the equivalent [MW]	Average R' [Ohm/MW]	Average X' [Ohm/MW]	Average B' [uS/MW]
Station transformer	<50	0.1000	2.000	0.20
	[50-100)	0.0090	0.300	0.15
	[100-150)	0.0030	0.100	0.08
	≥150	0.0010	0.032	0.07
Collector system	<50	0.0150	0.024	66.00
	[50-100)	0.0020	0.003	48.00
	[100-150)	0.0004	0.001	37.00
	≥150	0.0001	0.000	35.00
Step-up transformer	<50	0.0080	0.086	6.00
	[50-100)	0.0007	0.011	6.10
	[100-150)	0.0003	0.003	7.30
	≥150	0.0000	0.001	7.60

These parameters can be used directly, or equivalent model's parameters can be calculated for the exact rated power of the equivalent. In the latter case the following equations can be used:

$$R_{STR} = \left(P_{MAX} - \left(P_{WF} - P_{MIN}\right)\right) \times R'_{STR} \tag{5}$$

$$X_{STR} = \left(P_{MAX} - \left(P_{WF} - P_{MIN}\right)\right) \times X'_{STR} \tag{6}$$

$$B_{STR} = P_{WF} \times B'_{STR} \tag{7}$$

where: P_{MAX} – the maximum nominal power within the range (e.g. 99 MW for the 2nd range)

P_{MIN} – the minimum nominal power within the range (e.g. 50 MW for the 2nd range)

P_{WF} – nominal power for which the equivalent is being created

R'_{STR}, X'_{STR}, B'_{STR} – average resistance, reactance and susceptance values from table above

Figure 13 shows an example of calculation of exact values of the station transformer resistance as a function of rated power of a wind farm based on equation (5) and data in table above. Piece-wise linear characteristics with segments corresponding to power ranges are visible. The rest of the parameters can be calculated in the same way.

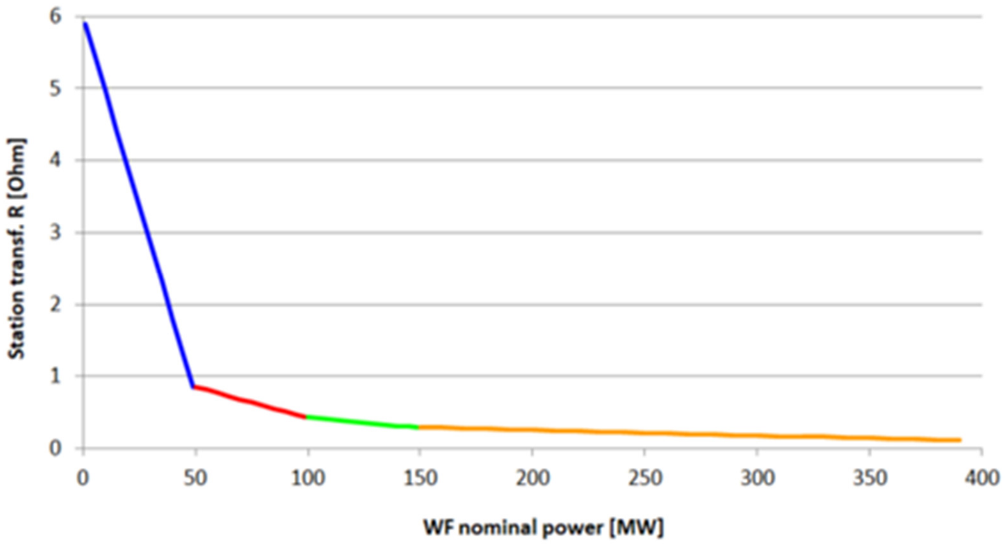


Figure 13: Resistance of equivalent station transformer as a function of the rated power of the wind farm equivalent

4.3 Simplified Version of Power Flow Equivalent

The simplified equivalent can be created based on the extended version of the equivalent. After obtaining the typical impedance and susceptance parameters of station transformer, collector system and step-up transformer, the aggregated impedance for each range can be calculated using network reduction command available in PowerFactory. The selected method is REI equivalent. It is possible to aggregate the entire WPP network into one *common impedance* object, as it is a πmodel that also has built-in transformer equivalent, enabling the connection of the PCC terminal (HV bus) to the LV terminals of wind generator. Figure 14 presents *common impedance* model structure in PowerFactory and table below depicts standard model parameters to be used in this software.

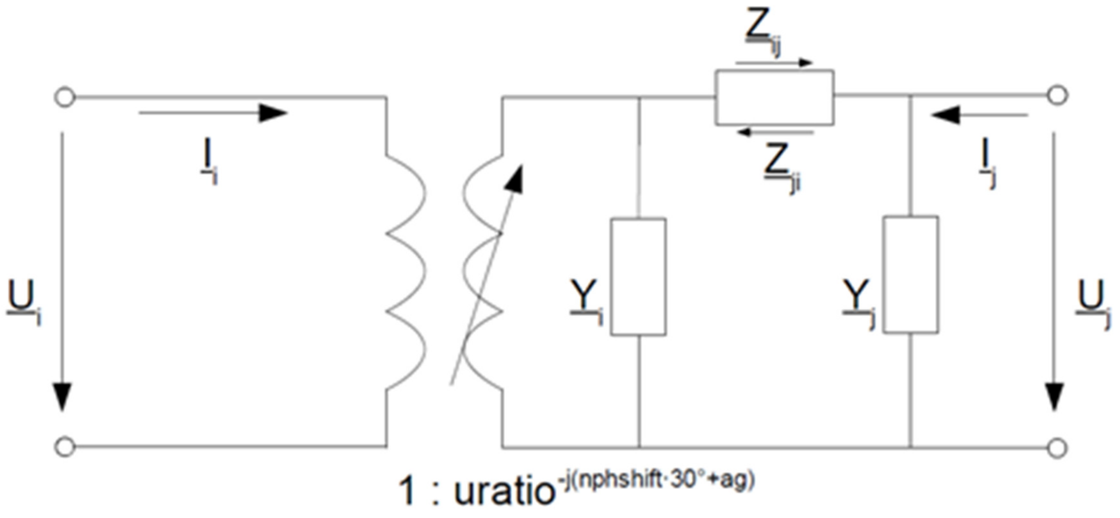


Figure 14: Common impedance model structure in PowerFactory

Table 3: Simplified equivalent parameters per 1 MW (factor a in pu/MW, factor b in pu) to be used in a form of R = aP + b

Nominal power [MW]	**R**		**X**	
	a	b	a	b
<50	-0.00349	0.22160	-0.02927	1.85191
[50-100)	-0.00043	0.06350	-0.00416	0.61927
[100-150)	-0.00011	0.02750	-0.00135	0.33623
≥150	-0.00003	0.01396	-0.00037	0.20113

Nominal power [MW]	**G_i**		**B_i**		**G_j**		**B_j**	
	a	b	a	b	a	b	a	b
<50	1.10E-05	-3.79E-05	1.97E-04	1.03E-04	-1.09E-05	3.84E-05	3.20E-04	-1.01E-04
[50-100)	6.53E-06	-6.20E-08	1.39E-04	-5.23E-07	-6.49E-06	-2.79E-08	2.24E-04	-1.01E-06
[100-150)	5.74E-06	-4.79E-08	9.86E-05	-4.02E-07	-5.72E-06	1.54E-07	1.56E-04	-8.11E-07
≥150	3.94E-06	2.68E-07	7.45E-05	2.32E-06	-3.93E-06	2.29E-07	1.63E-04	6.27E-06

4.4 Models for the dynamic equivalent

Procedure for generating equivalent dynamic models for RES utilises standard dynamic models based on the 2nd generation of dynamic models for RES developed by WECC REMTF (Renewable Energy Modelling Task Force) in cooperation with EPRI, IEC, major WT manufactures and power system simulation software suppliers. These models are available in all popular simulation tools, which inherently ensures that the models can be exchanged between interested stakeholders without the need to use user-defined models. The models are listed in table 3 and their mutual connections for different RES type are shown in figures 15 - 17 [8].

Table 4: List of available WECC 2nd generation dynamic models for RES

Model Name	Description	Applicability
WT1G	Induction generator	Type 1 WTG
WT1T	Turbine	Type 1 WTG
WT1P_B	Pitch control	Type 1 WTG
REGC_A	Generator/Converter	Type 3&4 WTG, PV, BESS
REEC_A **REEC_B** **REEC_C**	Electrical P,Q control	Type 3&4 WTG, PV PV (not using MC) BESS
REPC_A **REPC_B**	Plant controller	For controlling one device For controlling multiple devices
WTGT_A	Drive-train	Type 3 &4 WTG
WTGAR_A	Turbine aero-dynamics	Type 3 WTG
WTGPT_A	Pitch control	Type 3 WTG
WTGTRQ_A	Torque controller	Type 3 WTG

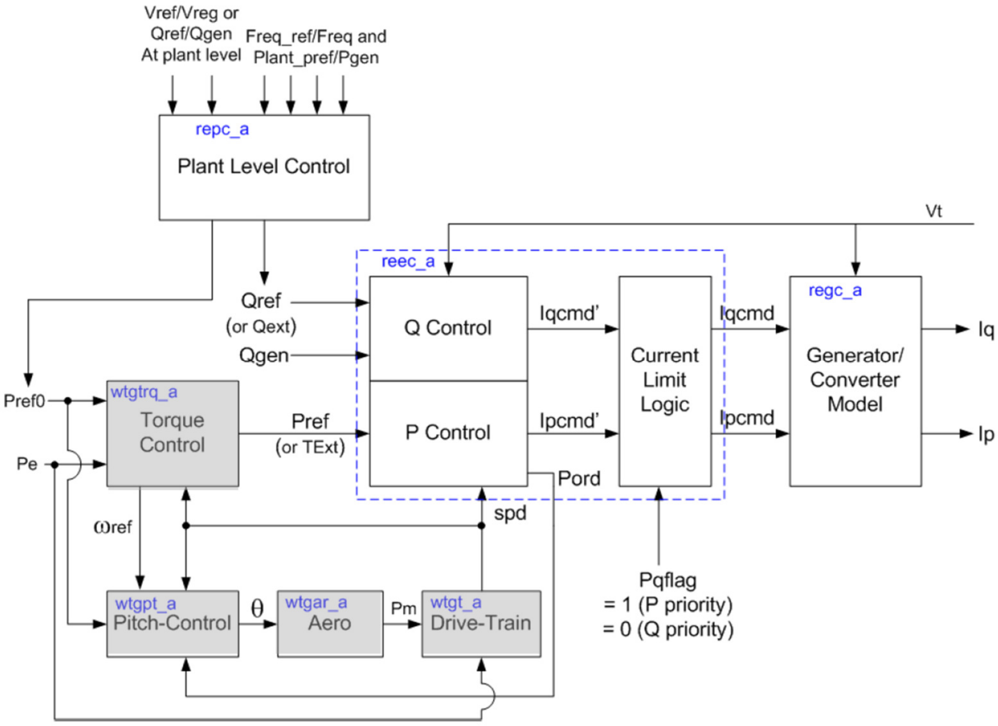


Figure 15: General block diagram for wind machine type 3 (grey fill indicates optional modules)

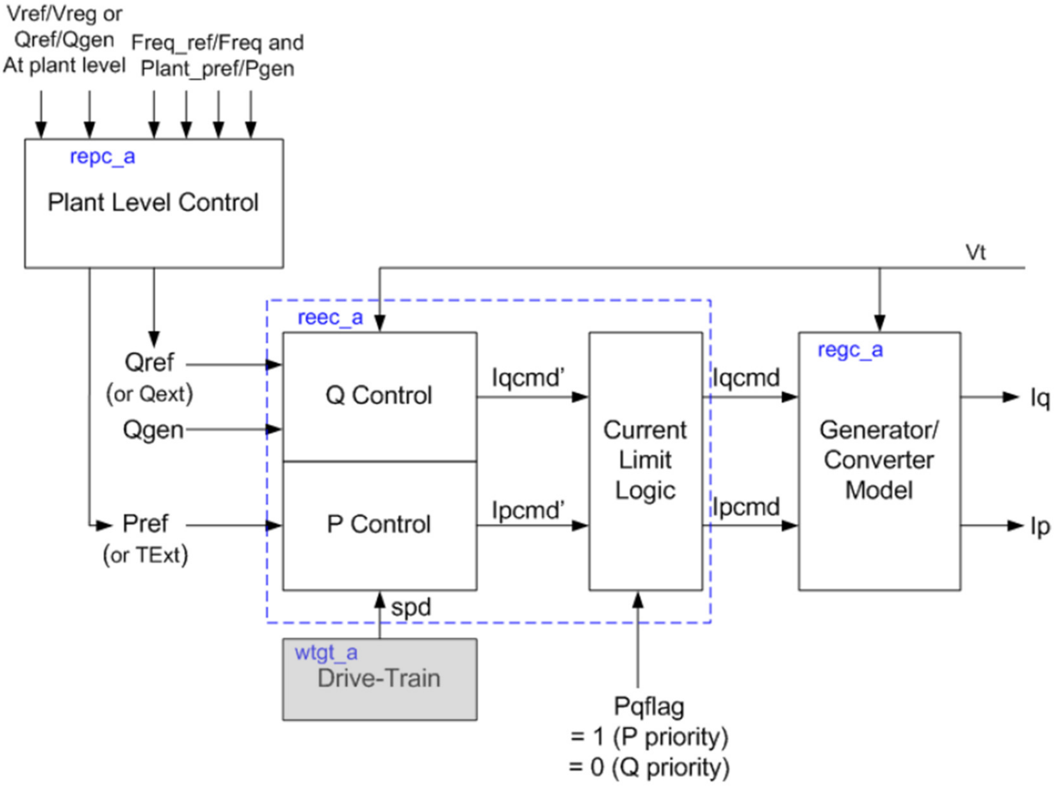


Figure 16: General block diagram for type 4 wind machines (WT with full converter)

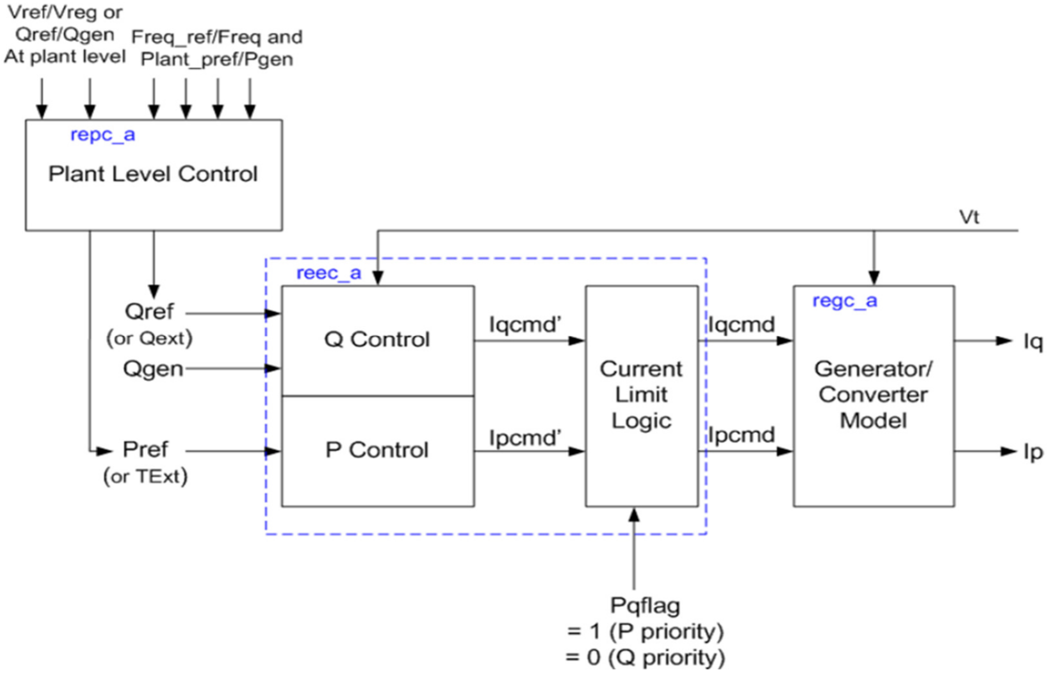


Figure 17: General block diagram for solar PV and energy storage

The general concept of the RES generic dynamic models is that the models focus on the inverter interfacing the RES with the grid. This is due to the properties of inverters that using a DC circuit inside can entirely separate the dynamics of energy source from the grid in the RMS simulation frequency range. Only for DFIG (double-fed induction generator) wind turbines, in which the inverter controls a part of power, aerodynamic and mechanical phenomena are to some extent transferred to the device terminals, thus additional models are available.

Choosing parameters for the models listed above is not a trivial task as it requires knowledge about the properties of the renewable resource being modelled. Usually it is the RES owner who in collaboration with the RES manufacturer of vendor delivers the models to the system operator. For development planning purposes usually, typical parameters are enough. These parameters can be found in user manuals of the simulation software tools and will not be listed here. Models with typical parameters show correct responses to typical disturbances.

Given the above, it is highly recommended that except a few cases these parameters should be kept the same in the equivalent models as they are in the full model. Otherwise its dynamic properties could be changed unintentionally. Therefore, in order to construct the dynamic equivalent, the procedure described in sections 4.1 - 4.3 should be followed by adding the dynamic models with unchanged parameters with the following exceptions:

- Dynamic model parameters that correspond to operational limits in the REEC_A and REPC_A modules, i.e. the reactive power range set by Q_{min} and Q_{max} as well as active power range P_{min} and P_{max} should be calculated as a product of the number of individual units and rated power of a single unit.
- The rest of scaling the dynamic model to the size of the renewable energy power plant is done automatically by taking into account the generator MVA base value from the power flow model. The active and reactive power ranges are expressed in per unit on the MVA base.
- Regarding the active power range, special care must be taken with P_{max} value when the LFSM-U mode is activated, as it should be set to the value determined by the available active power at the assumed wind speed. In the rest of cases, typical values are acceptable.

5 Grid equivalents types and examples

In the past, various methods for determining static and dynamic equivalents have been proposed. As described in [5] equivalenting methods can roughly be divided into two groups. The first group requires no knowledge about the configuration and parameters of the external system. Usually, these methods solely utilise measurements from the study system and its boundary (e.g. those described in, [10]). The second group requires knowledge about the external system and the methods are generally referred to as model reduction methods. The resulting equivalents can be suitable for static and/or dynamic studies.

One of the first developed static network equivalents is the so-called Ward equivalent, which was introduced in [11] and further developed in [12]. In the Ward equivalent, the generators and loads in the external system are converted into constant current injectors, which then allows elimination of all external buses. Aschmoneit and Verstege [13] presented an extension of the equivalent to enable steady-state assessment of generator outages. For that purpose, the effect of the speed governors of the generators in the external system was included in the derivation of the equivalent. In [14], the so-called generalised Ward equivalent was introduced. This extension allowed to account for changes in reactive power injection from the external system, by expressing it solely as a function of the bus voltages at the study system's boundary. A dynamic Ward equivalent for transient stability analysis was discussed in [15]. It allows to eliminate all buses in the external system where voltage-dependent loads are connected.

Another approach uses REI (radial, equivalent and independent) equivalents. The method was first presented in [16] and aimed at replacing a set of nodes by one new equivalent node. In order to perform the reduction, a zero-loss network is setup, which connects all load (resp. generator) buses of the external system with a new fictitious bus. Subsequently, the generators and loads of the external system are merged at the new buses and the external nodes are eliminated. A dynamic REI equivalent suitable for transient stability studies was presented in [17]. The authors propose to determine REI equivalents at the boundary buses of the study system. At the newly created nodes, equivalent generators of coherent generator groups are defined. Then the machine parameters of the equivalent generators are determined through participation factors. For aggregation of coherent generators, several other approaches were developed. In [18], the parameters of an equivalent generator and its controllers are determined through a least-square fit of the transfer function of the coherent generator group. A trajectory sensitivity method is used in [19] to determine the exciter parameters of the aggregated generators. In [20], the authors proposed a structure preserving technique to compute the parameters of the equivalent generator.

Depending on the topology of the required network and the focus voltage level, there are several possibilities when generating grid equivalents.

5.1 Basic static grid equivalents

The basic grid equivalent should represent in a simple model the complex grids by only considering basic characteristics like connection node voltages and reactive and active power values. This can be achieved by scaling up of most representative feeders based on grid clustering. Thus, the resulting grid equivalent should look like a small network model with one or more feeders types depending on the different identified feeder/network classes. Figure 18 and Figure 19 depict the equivalenting method and how a simple equivalent can be represented.

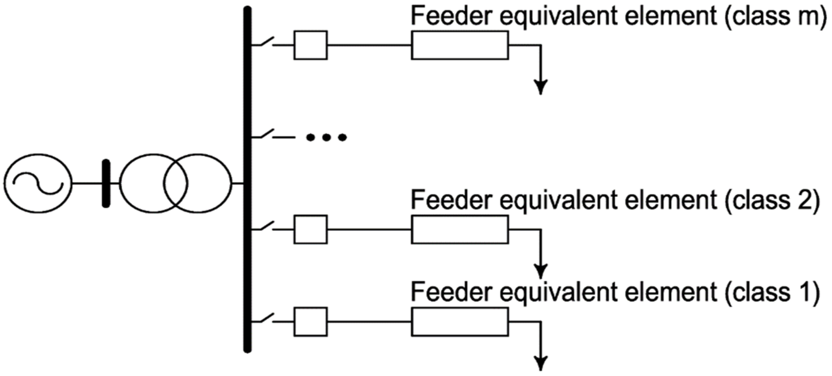


Figure 18 Equivalenting of the population of feeder classes

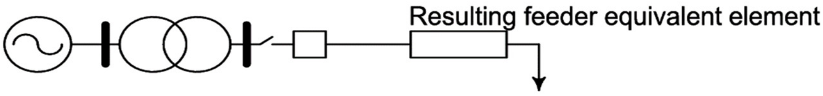


Figure 19: Single equivalent representation

Basic grid equivalents examples used within INTERPLAN Project

The developed concept of grid equivalents was applied to selected LV feeder elements of the DECAS synthetic network (see detailed grid description in Deliverable D4.1, § 3.2.3), which was extended with 22 LV feeders modelled in detail (5 of them for the urban area and 17 for the rural). To guarantee security of energy supply and keep the transformer loading within the permissible limits, a nominal power for the one of MV/LV transformers in urban area has been set to 1 MVA. The accuracy of the equivalenting process can be improved by increasing the observation number, thus, it was decided to escalate the clustering data set from 9000 to approx. 27000 LV feeders.

It should be mentioned, that LV feeders selected for the simplification have preferably a radial structure and demonstrate similar properties to the feeders have been used for clustering in terms of topological parameters (such as for example, number of nodes, length to the critical node, total feeder length, ratio of underground cables and overhead lines), as well as electrical characteristics (rated current of the feeder main line, maximal current of the feeder main line, short circuit resistance at the critical node, etc.). All these feeders have been classified according to the criterion of minimal distance from the given feeder to the one of 8 cluster medoids in multidimensional space of 13 feeder parameters specified for clustering (for more details see Deliverable D4.1 “Method for clustering distributions grid”, Table 2: Parameters chosen for feeder clustering [5]).

Two main feeder types were identified as a result of the classification process: the great majority of considered feeders (17 feeders) were assigned to the cluster #5, and 5 feeders correspond to the cluster #7. The relevant feeder characteristics are summarized in Table 5.

Table 5: The most relevant properties of representative feeders for 8 clusters

Class id	1	2	3	4	5	6	7	8
feeder main line type	AYY 4x150	AYY 4x150	AYY 4x150	XAY2Y-J 4x150	AYY 4x120	Al 4x70	A2Y 4x95	XAY2Y 4x150
rated current of the feeder main line, [kA]	0.27	0.27	0.27	0.275	0.242	0.27	0.185	0.27
max. current of the feeder main line, [kA]	0.1461	0.0262	0.0244	0.0456	0.0809	0.0128	0.1257	0.0455
loading of the feeder main line, [%]	54.1154	9.6867	9.0456	16.5989	33.4489	4.7501	67.9715	16.8633
feeder main line length, [km]	0.072	0.361	0.116	0.062	0.036	0.07	0.265	0.361
total feeder length, [km]	0.558	0.907	0.18	0.709	1.073	0.127	1.486	1.196
total cable length in feeder, [km]	0.558	0.703	0.147	0.709	0.252	0.005	0.1	0.847
total length of ohl in feeder, [km]	0	0.204	0.033	0	0.821	0.122	1.386	0.349
number of cables in feeder	8	10	4	21	27	3	21	17
number of ohl in feeder	0	6	1	0	20	4	21	9
number of nodes in feeder	7	16	5	21	47	7	42	26
short circuit resistance of critical node, [Ohm]	0.0494	0.2253	0.0426	0.1381	0.2262	0.0685	0.3137	0.3331
dv/dP Sensitivity at critical node, [p.u./MW]	0.3185	1.4606	0.2659	0.8657	1.4785	0.4300	2.3924	2.2487
dv/dQ Sensitivity at critical node, [p.u./Mvar]	0.2006	1.0179	0.2248	0.3682	0.711	0.3408	1.0745	1.3500
feeder terminal minimal voltage, [p.u.]	1.0055	1.0012	1.0212	1.0142	0.9854	1.0176	0.9145	0.9769
feeder maximal voltage drop, [%]	2.4704	1.7155	0.338227	1.4757	3.7885	0.3059	9.2946	4.0358
active power losses, [MW]	0.00211	0.00025	0.00005	0.00037	0.00166	0.00002	0.00616	0.00099
active power losses related to infeed, [%]	2.0302	1.3731	0.2818	1.1459	2.9114	0.2593	7.06825	3.107431
average line loading, [%]	18.8487	2.8330	3.3533	7.6532	4.4021	3.6092	8.5786	5.2087
equivalent impedance per feeder, [Ohm]	0.0352	0.1335	0.0296	0.0626	0.0901	0.0552	0.1397	0.1779

Table 5 gives an overview of the main structural and electrical characteristics of representative feeders for 8 clusters. Each representative feeder was obtained as a real feeder having minimal distance to the calculated cluster centre. Each representative feeder should ideally cover the overall feeder properties of the corresponding cluster; therefore, its characteristics can be distributed on the whole feeder set formed the cluster. Knowing the class membership of the given feeder, a descriptive value for the KPIs associated to this particular feeder can be directly obtained from the appropriate representative feeder. This may significantly facilitate network analysis by reducing the complexity of specific calculations or even neglecting them. Another important advantage of using representative feeders is that it allows to get any missing feeder parameter in case of the input data limitation.

As shown in Table 5, both of representative feeders defined as equivalents for the extended DECAS synthetic network have almost the same number of nodes, as well as a cable/ line ratio; moreover, for the representative feeder #7 total number of underground cables is equal to the total number of overhead lines, however, their total length differs markedly. Maximal voltage drop of about 9% and higher active power losses (about 7% related to infeed) are immediately apparent for the representative feeder #7. Average line loading of feeder #7 is double that of feeder #5. Main line of feeder #5 head section is implemented as underground cable AYY 4x120, while feeder #7 main line is overhead line A2Y 4x95, which also demonstrate a 68%-line utilization rate (twice as much as line utilization rate for the main line of feeder #5).

Figure 20 and Figure 21 illustrate the topology of considered representative feeders, modelled via DIgSILENT PowerFactory.

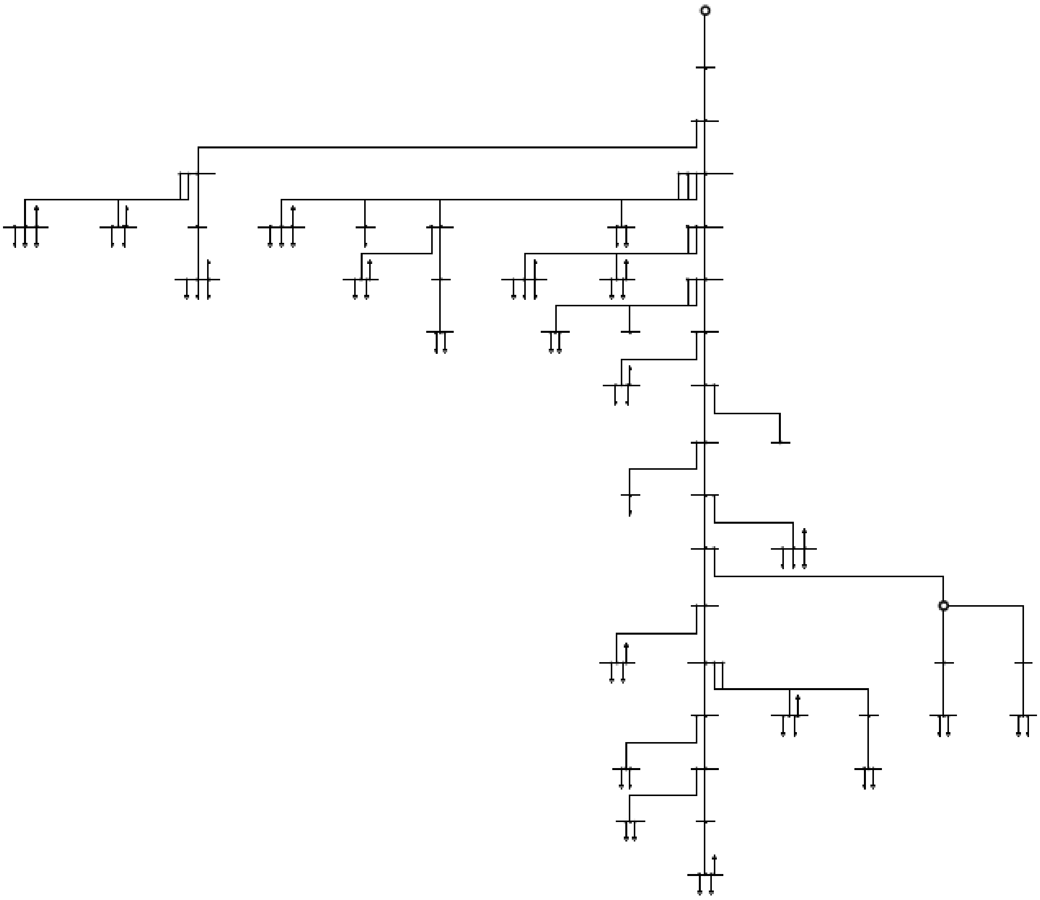


Figure 20: Topological structure of the representative feeder for cluster #5

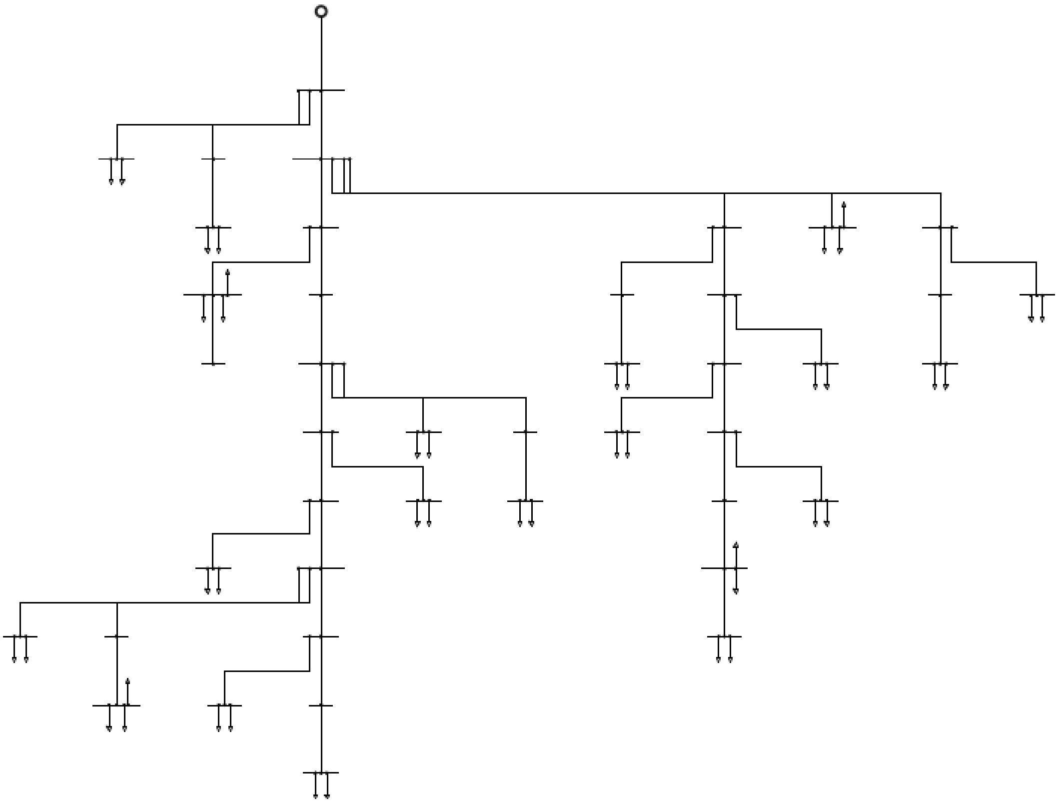


Figure 21 Topological structure of the representative feeder for cluster #7

The equivalenting procedure can be performed in DIgSILENT PowerFactory environment based on replacement of original feeders with their equivalents presented on the figures above. The equivalent load is being assumed to be equal to the total active and reactive power consumed by the load of the original feeder. In such a case the actual load behaviour at each connection point along the simplified feeder isn't exactly known. The only available information is the value of total power flowing into the feeder. In radially operated distribution networks this problem can be solved by applying the feeder load scaling tool, which is realized in DIgSILENT PowerFactory.

This method could be adopted for the simplification of feeders having a more complex structure with the large number of branches comparing to the equivalents shown in Figure 20 and Figure 21. It brings benefits for the analysis of the given syntactic network in terms of the tenfold reducing the total number of feeder nodes from about 400 to 42, as well as for the control of feeder variety through their unification.

5.2 Advanced static grid equivalents

This type of grid equivalents should be a combination of basic grid equivalents considering the topology and different voltage levels. The main idea is to keep as intact as possible the grid transformers parameters of the voltage levels under focus. Figure 22 shows for what parts of the network grid equivalenting should/could be performed.

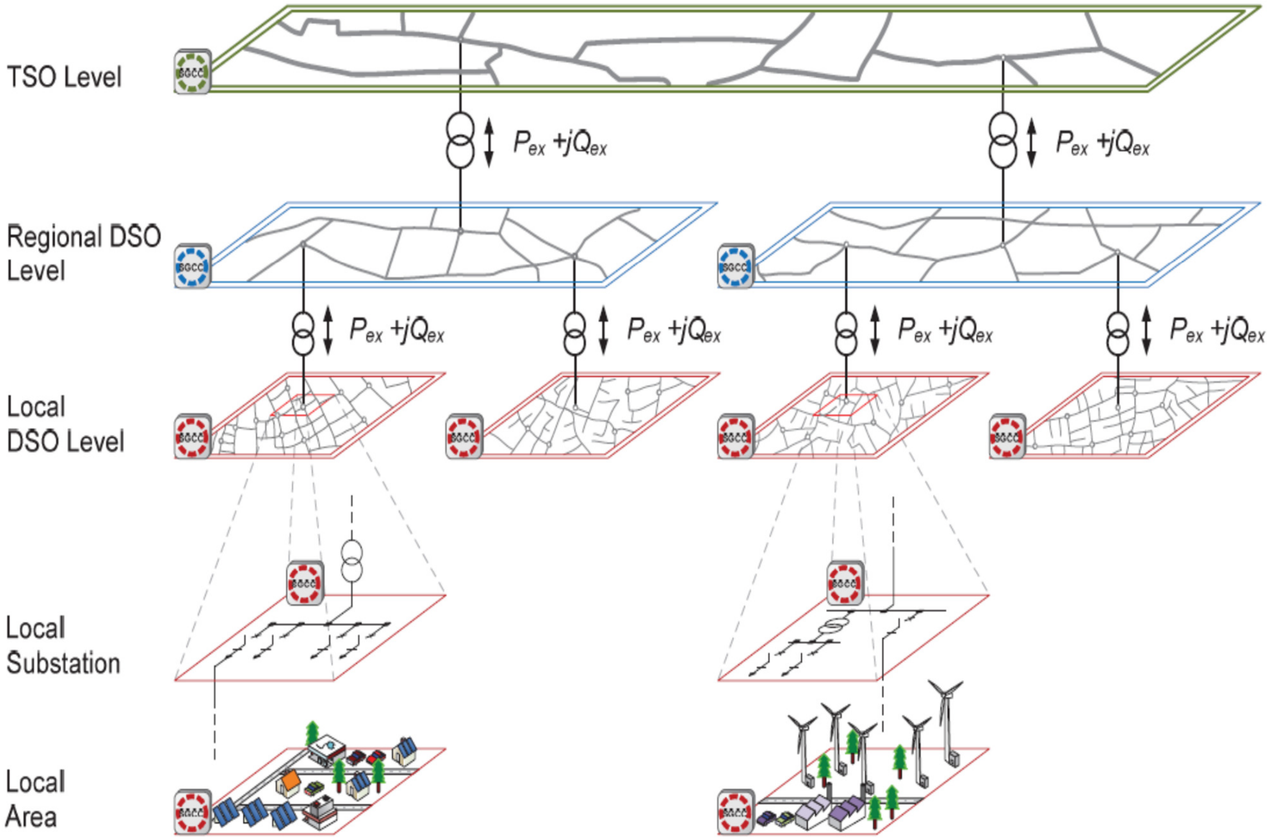
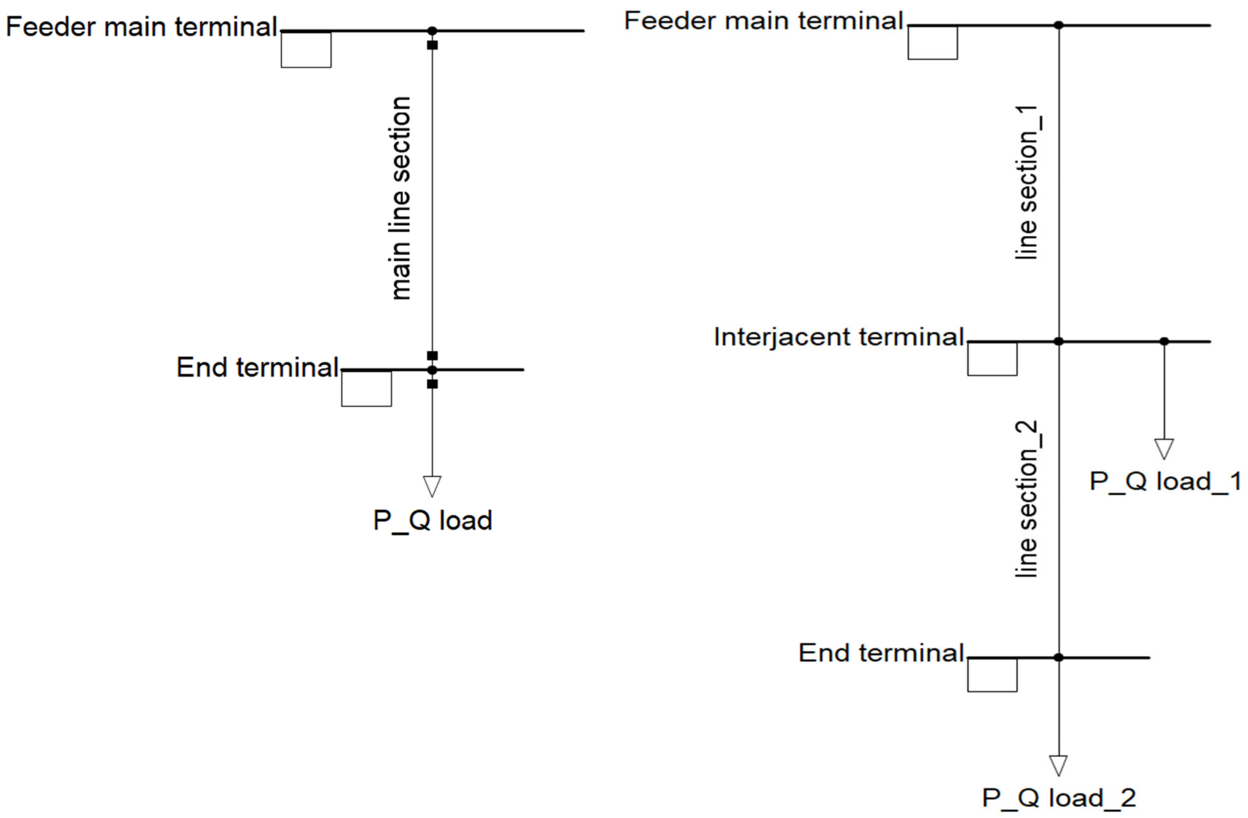


Figure 22: Voltage levels used for the advanced grid equivalents

Advanced static grid equivalents examples used in the INTERPLAN project

In an ideal case, each radial feeder connected to the substation terminal and having a branched structure should be substituted with its equivalent only containing the main line element and the load connected to the end terminal (see left part of Figure 23). The right part of Figure 23 illustrates a specific situation, when feeder main line must be split, and some amount of the load has to be shift from the end terminal to the splitting point (so called “interjacent” terminal) to keep the voltage at the end terminal within the set limits.



Feeder Equivalent of Type A

Feeder Equivalent of Type B

Figure 23: Schematic representation of two main types of feeder equivalents

It is important, that equivalent feeders demonstrate the same behaviour as feeders of the real network, especially in terms of equality of parameters associated with the concrete project KPI. For the use case 7, whose main objectives, among others, are to minimize the energy interrupted during a contingency event, minimize the energy losses in the network and increase the network hosting capacity, the following parameters were put into equivalent:

- equivalent impedance;
- active and reactive power of the total load;
- line loading;
- voltage value at the end terminal (should be ≥ 0,95 p.u.).

According to the methodology presented in Chapter 3 two types of feeder equivalents, representing structurally feeder topologies shown in Figure 23, were created and implemented into the network used for the use case 7 simulations. Number of parallel lines and line length for each feeder section have been optimized beforehand to maintain the acceptable value of line loading and to reach the 5% of accuracy for the feeder equivalent impedance. Feeder line types correspond to the main line type of the representative feeder for the class the given feeder belongs to. The equivalent load is equal to the total active and reactive power flowing into the original feeder. The corresponding parameter data is summarized in Table 6.

Table 6: Parameters of feeder equivalents (according to Figure 23)

Feeder name	Class id	Type of equivalent	Line type	Line length		Number of parallel lines	Load_1		Load_2		Total load, active power, [MW]	Total load, reactive power, [Mvar]
				Section 1	Section 2		P, [MW]	Q, [Mvar]	P, [MW]	Q, [Mvar]		
Rural LV 1	5	Type A	AYY 4x120	1,073	–	19	0,16190	0,01619	–	–	0,16190	0,01619
Rural LV 10	5	Type B	AYY 4x120	2,683	0,04	7	0,06664	0,0666	0,02856	0,0286	0,0952	0,00952
Rural LV 11	5	Type A	AYY 4x120	2,403	–	13	0,09960	0,00996	–	–	0,0996	0,00996
Rural LV 12	5	Type A	AYY 4x120	1,843	–	10	0,12980	0,01298	–	–	0,1298	0,01298
Rural LV 14	5	Type A	AYY 4x120	2,813	–	14	0,07300	0,00730	–	–	0,073	0,0073
Rural LV 15	7	Type A	A2Y 4x95	2,576	–	12	0,12150	0,01215	–	–	0,1215	0,01215
Rural LV 16	7	Type B	A2Y 4x95	2,136	1,2	12	0,13374	0,01337	0,01486	0,00149	0,1486	0,01486
Rural LV 17	5	Type A	AYY 4x120	3,533	–	13	0,09370	0,00937	–	–	0,0937	0,00937
Rural LV 18	7	Type A	A2Y 4x95	2,236	–	13	0,11150	0,01115	–	–	0,1115	0,01115
Rural LV 20	5	Type A	AYY 4x120	1,973	–	16	0,12700	0,01270	–	–	0,127	0,0127
Rural LV 21	5	Type A	AYY 4x120	2,153	–	18	0,09630	0,00963	–	–	0,0963	0,00963
Rural LV 3	5	Type A	AYY 4x120	2,803	–	8	0,08792	0,00879	–	–	0,08792	0,00879
Rural LV 4	5	Type A	AYY 4x120	4,833	–	12	0,09656	0,00966	–	–	0,09656	0,00966
Rural LV 6	5	Type A	AYY 4x120	1,843	–	11	0,11490	0,01149	–	–	0,1149	0,01149
Rural LV 8	7	Type B	A2Y 4x95	2,546	0,07	13	0,13302	0,01330	0,01478	0,00148	0,1478	0,01478
Rural LV 9	5	Type A	AYY 4x120	4,083	–	14	0,07890	0,00789	–	–	0,0789	0,00789
Urban LV 1	7	Type A	A2Y 4x95	2,476	–	16	0,14710	0,01471	–	–	0,1471	0,01471
Urban LV 3	5	Type A	AYY 4x120	0,713	–	41	0,27230	0,02723	–	–	0,2723	0,02723
Urban LV 5	5	Type A	AYY 4x120	7,363	–	19	0,10095	0,01009	–	–	0,10095	0,01009
Urban LV 7	5	Type A	AYY 4x120	4,753	–	17	0,10176	0,01018	–	–	0,10176	0,01018
Urban LV 9	4	Type A	AYY 4x120	11,873	–	31	0,09000	0,00900	–	–	0,09	0,009

As indicated in Table 6, the great majority of feeder equivalents have a simple structure of type A (see Figure 23), while only three feeder equivalents have been modified to the type B by splitting the main line in two sections and distributing the load. The reason for this is, that the original feeders ‘Rural LV 8’, ‘Rural LV 10’ and ‘Rural LV 16’ demonstrate a significant voltage drop at the end terminal higher than 5%, which is also reflected into their equivalents generated during the first stage of the equivalenting process (see Table 7).

Table 7: Feeder parameters for the original and simplified grid

Feeder name	**Original Grid**				**Simplified Grid** ***(after the first stage of the equivalenting process)***						
	feeder terminal minimal voltage, [p.u.]	equivalent impedance per feeder Z_{eq} , [Ohm]	average line loading, [%]	active power losses, [MW]	feeder terminal minimal voltage, [p.u.]	equivalent impedance per feeder Z_{eq} , [Ohm]	ΔZ_{eq} , [Ohm]	average line loading, [%]	Δ av. loading, [%]	active power losses, [MW]	ΔP_{loss} , [MW]
Rural LV 1	0.9987	0.0150	5.0644	0.0023	1.0042	0.0151	0.3132	5.0862	0.4300	0.0024	4.5679
Rural LV 10	0.9280	0.1091	8.3984	0.0065	0.9493	0.1040	4.6735	8.5874	2.2510	0.0063	3.1429
Rural LV 11	0.9627	0.0519	4.8285	0.0031	0.9823	0.0494	4.8263	4.6749	3.1808	0.0031	2.3312
Rural LV 12	0.9374	0.0516	7.8025	0.0055	0.9700	0.0493	4.5153	8.0213	2.8040	0.0053	2.6141
Rural LV 14	0.9825	0.0565	3.1954	0.0018	0.9899	0.0537	4.9542	3.1573	1.1925	0.0018	2.8196
Rural LV 15	0.9280	0.0718	8.4342	0.0062	0.9564	0.0684	4.7165	8.3007	1.5828	0.0067	8.4293
Rural LV 16	0.8971	0.0933	10.1981	0.0145	0.9186	0.0886	4.9810	10.5699	3.6466	0.0141	2.4204
Rural LV 17	0.9574	0.0764	4.5956	0.0033	0.9691	0.0726	4.8864	4.4582	2.9905	0.0041	22.5603
Rural LV 18	0.9541	0.0575	6.9677	0.0045	0.9722	0.0548	4.6492	6.9175	0.7199	0.0044	1.8091
Rural LV 20	0.9659	0.0347	4.7803	0.0034	0.9913	0.0330	4.9804	4.7997	0.4061	0.0033	3.7889
Rural LV 21	0.9900	0.0336	3.1607	0.0018	0.9994	0.0320	4.7813	3.2086	1.5167	0.0018	2.3176
Rural LV 3	0.9378	0.0985	6.4629	0.0047	0.9681	0.0936	4.9784	6.8043	5.2813	0.0047	0.0117
Rural LV 4	0.9452	0.1133	5.0134	0.0056	0.9522	0.1076	4.9859	5.0656	1.0412	0.0067	19.0075
Rural LV 6	0.9649	0.0469	6.2166	0.0038	0.9820	0.0448	4.5967	6.3756	2.5577	0.0037	4.0072
Rural LV 8	0.9197	0.0675	9.4169	0.0098	0.9484	0.0641	4.9194	9.3991	0.1892	0.0095	3.2444
Rural LV 9	0.9605	0.0819	3.5252	0.0032	0.9766	0.0779	4.8705	3.4589	1.8801	0.0031	3.1124
Urban LV 1	0.9661	0.0518	7.2280	0.0069	0.9782	0.0493	4.7470	7.3694	1.9568	0.0068	1.8408
Urban LV 3	0.9918	0.0045	3.8741	0.0110	1.0203	0.0046	4.3799	3.9019	0.7180	0.0020	81.9937
Urban LV 5	0.9163	0.1090	3.3179	0.0074	0.9591	0.1036	4.9859	3.3207	0.0844	0.0069	6.9865
Urban LV 7	0.9312	0.0786	3.5934	0.0051	0.9787	0.0747	4.8796	3.6662	2.0268	0.0049	4.6439
Urban LV 9	0.9522	0.1077	1.7769	0.0056	0.9685	0.1024	4.9890	1.7969	1.1272	0.0053	4.1880

Table 7 represents the set of feeder parameters associated with KPIs of the use case 7. In the left part of the table feeder characteristics related to the original network are shown. Columns in the right part of the table correspond to characteristics of the simplified network created at the first stage of the equivalenting process. Additionally, data columns containing the information about the percentage difference between corresponding parameter values as well as the values of active power losses were added to validate the results.

It is obvious from Table 7, that after the first stage of the equivalenting process all the values of equivalent impedance are not more than 5 % differ from the original parameter values. For the average line loading this difference lies within the interval of 0,2 ÷ 5,3%. The results regarding the active power losses are also acceptable for most cases, with the exception of feeder 'Urban LV 3', which demonstrates a specific behaviour in terms of power distribution. This could be explained by topological characteristics of the real feeder; moreover, the real feeder 'Urban LV 3' is situated far away from defined cluster centres, and the given data set is therefore not representative enough to describe correctly all the attributes of this feeder.

As it was mentioned above, three feeders 'Rural LV 8', 'Rural LV 10' and 'Rural LV 16' represent a voltage drop higher, than it is required by the use case goals. This problem could be solved during the second stage of the equivalenting process, which provides main line splitting together with the load distribution. The corresponding results are summarized in Table 8.

Table 8: Feeder parameters for the simplified grid after the second stage of the equivalenting process

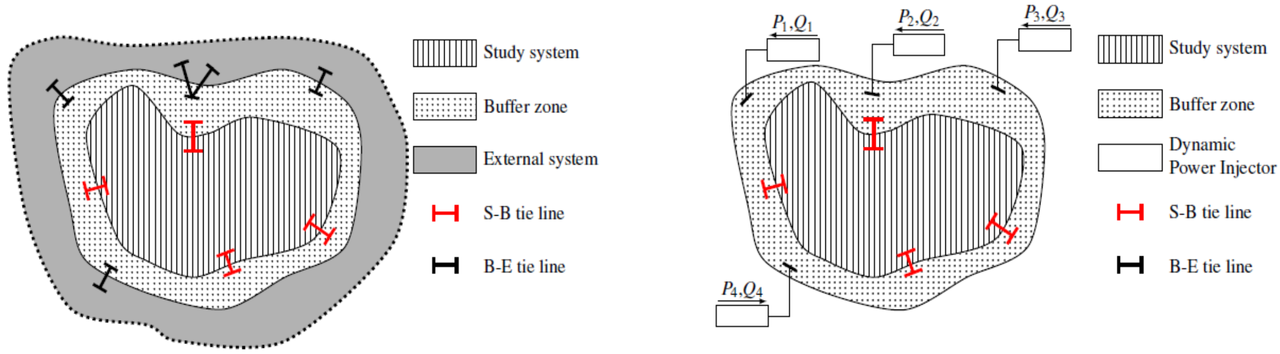
Feeder name	**Simplified Grid** ***(after the second stage of the equivalenting process)***						
	feeder terminal minimal voltage, [p.u.]	equivalent impedance per feeder Z_{eq} , [Ohm]	ΔZ_{eq} , [Ohm]	average line loading, [%]	Δ av. loading [%]	active power losses, [MW]	ΔP_{loss} , [MW]
Rural LV 10	0.9500	0.1026	5.9477	5.5766	33.5989	0.0062	4.6378
Rural LV 16	0.9502	0.0571	38.8167	5.6053	45.0360	0.0085	41.6215
Rural LV 8	0.9501	0.0624	7.4381	5.1598	45.2065	0.0092	6.1728

Table 8 demonstrates that after the second stage of the equivalenting process voltage at the feeder end terminal lies within acceptable limits. For example, for the feeder 'Rural LV 10' shifting the 70% of the total load 40 m closer to the substation terminal was necessary to achieve the permissible voltage level. Applying the proposed method leads to minimizing of power losses, but at the same time increases the difference between the values of power losses for the original feeder and for its equivalent of type B. For feeders 'Rural LV 16' and 'Rural LV 8' only 10% of original total load has been connected to the feeder end terminal (see

Table 6). Feeder equivalent impedance as well as the average line loading will be consequently lower, while the difference between the real parameter values and parameter values of corresponding equivalents will increase. Performing the load distribution can therefore have a positive effect on voltage stability and contribute to the power losses minimization. However, the higher amount of the load will be shift closer to the substation terminal, the higher difference between some other key parameters of the real feeder and its equivalent will be observed. In each individual case it should be decided, what kind of equivalents will satisfy the requirements of the concrete project KPI. As the main goal of the use case 7 consists in securing the continuity of supply to improve system reliability and minimizing energy interruptions, the method of load distribution was applied, and feeder equivalents of type B along with equivalents of type A were implemented into the original network.

5.3 Basic dynamic grid equivalents

In [21], a new method is proposed for representing the inertial and primary frequency control effects of an external system in time-domain simulation. It is assumed that the unreduced system is large and contains the study system. As outlined so far, most techniques for external system equivalenting involve merging the original synchronous machines into a number of equivalent machines. This raises at least two issues: (i) find proper parameters to assign to those fictitious machines (and their associated controllers) and (ii) avoid creating artificial modes of oscillations (not present in the unreduced model) involving those machines. Both these issues are easily addressed with the model proposed in the paper. It consists of dynamic power injectors (DPIs) distributed along the boundary of the study system and emulating the response of the external system to active power imbalance and frequency excursions. Note that the equivalent is not aimed at preserving inter-area electromechanical oscillations, which are assumed to have proper damping. Instead, the equivalent focuses on the global mode (also referred to as common mode by some authors) of rotor oscillation, which is the well-damped oscillatory mode with the lowest frequency present in all machine speed responses. Figure 24 represents and abstract illustration of the reduction of a large power system considering as described above.



(a) Unreduced system divided into a study system, buffer zone and external system.

(b) Reduced system with external system replaced by DPIs.

Figure 24 Abstract illustration of the reduction of a large power system model [14]

Along the project’s duration, the work on development of dynamic grid equivalent models will continue in order to identify and develop the best method for deriving such models.

Dynamic grid equivalents examples used within INTERPLAN project

Chapter 4 briefly introduced a procedure for creating equivalents of dynamic models of wind or solar power parks, applicable particularly to large and very large power system models (up to tens of thousands of nodes), in which low level of complexity is desired. Such models are often used for operation planning at TSO or pan-European level. The procedure consists of two steps, i.e. creating a power flow equivalent and then selecting the right parameters for the dynamic models. The first step produces a power flow equivalent that is constructed of a minimum number of elements (figure 10b), however preserving the main power flow results of a given object, such as active and reactive power output or power losses. The result of the second step is a standard dynamic model, whose dynamic characteristics is based on typical parameters and therefore might not reflect all features of detailed model but will behave properly in all cases.

This comes particularly useful when the equivalent is supposed to reflect the full model that is based on black-box dynamic models delivered by the manufacturer. Due to high inherent complexity of these models, constructing proper equivalents might involve using several sets of models corresponding to different operational modes or grid conditions. In such case a trade-off can be reached by using standard models - simplicity and usability comes at the cost of acceptable loss of accuracy.

A case where a wind farm modelled in full detail with black-box dynamic models is equivalented is presented below as an example of the equivalenting the procedure described above.

Step 1

The equivalent is prepared for a wind farm consisting of 30 2 MW DFIG wind turbines. The topology of the wind farm is presented in figure 23. Key resultant parameters of the wind farm equivalent are presented in tables Table 9-Table 11.

Table 9: Data for the station transformer of the wind farm

S_{STR} [MVA]	U_{n_HV} [kV]	U_{n_mV} [kV]	R_{STR} [Ω]	X_{STR} [Ω]	B_{STR} [uS]	R'_{STR} [Ω/MW]	X'_{STR} [Ω /MW]	B'_{STR} [uS/MW]
63	115	21	0.666	23.082	9.527	0.011	0.366	0.151

Table 10: Collector system equivalent data of the wind farm; $^{1)}$ Nominal voltage of the collector system, $^{2)}$ Nominal voltage of the wind generator terminal voltage

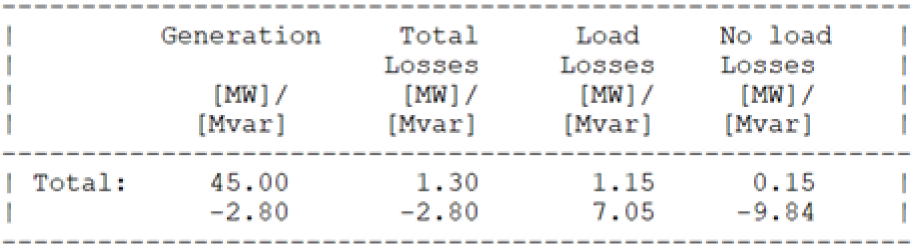
U_{n_MV} [kV]	U_{n_LV} [kV]	R_{CS} [Ω]	X_{CS} [Ω]	B_{CS} [uS]	R'_{CS} [Ω/MW]	X'_{CS} [Ω/MW]	B'_{CS} [uS/MW]
20	0.400	0.096	0.074	2540.0	0.00160	0.00123	42.333

Table 11: Step-up transformer equivalent data of the wind farm

S_{WTR} [MVA]	U_{n_MV} [kV]	U_{n_LV} [kV]	R_{WTR} [Ω]	X_{WTR} [Ω]	B_{WTR} [uS]	R'_{WTR} [Ω /MW]	X'_{WTR} [Ω /MW]	B'_{WTR} [uS/MW]
75	20	0.400	0.043	0.317	0.0	0.00057	0.00423	0.000

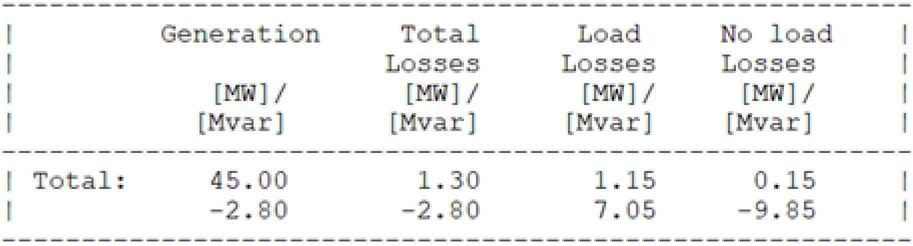
Power flow equivalent presented in figure 24 yields power flow results with very good accuracy - compare Table 12 for full model with Table 13 for the equivalent.

Table 12: Power flow results for the full model



```
----------------------------------------------------------
|          Generation     Total      Load     No load    |
|                         Losses    Losses    Losses     |
|             [MW]/        [MW]/     [MW]/     [MW]/     |
|            [Mvar]       [Mvar]    [Mvar]    [Mvar]     |
----------------------------------------------------------
| Total:      45.00        1.30      1.15      0.15      |
|             -2.80       -2.80      7.05     -9.84      |
----------------------------------------------------------
```

Table 13: Power flow results for the equivalent



```
----------------------------------------------------------
|          Generation     Total      Load     No load    |
|                         Losses    Losses    Losses     |
|             [MW]/        [MW]/     [MW]/     [MW]/     |
|            [Mvar]       [Mvar]    [Mvar]    [Mvar]     |
----------------------------------------------------------
| Total:      45.00        1.30      1.15      0.15      |
|             -2.80       -2.80      7.05     -9.85      |
----------------------------------------------------------
```

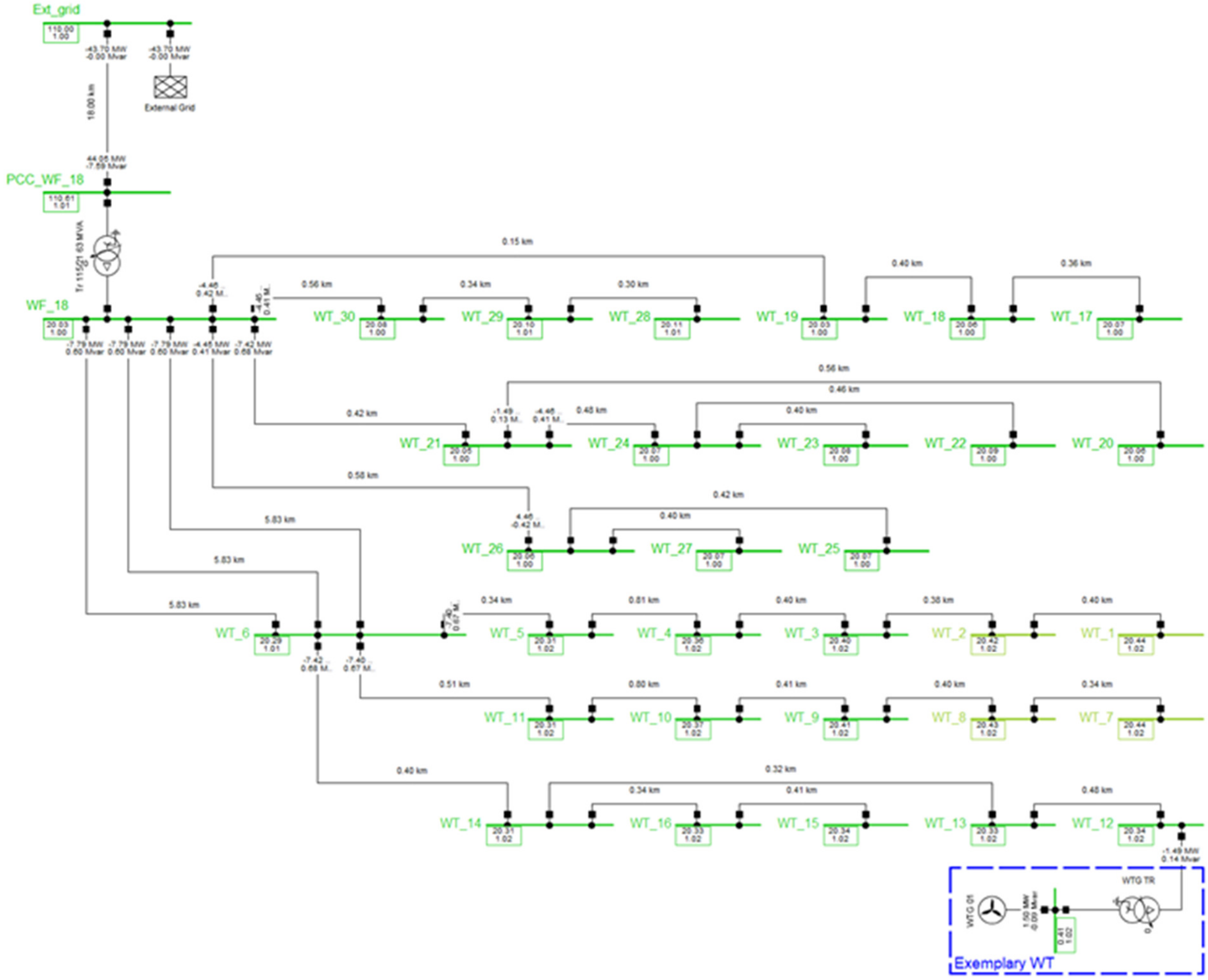


Figure 25 60 MW DFIG wind farm example

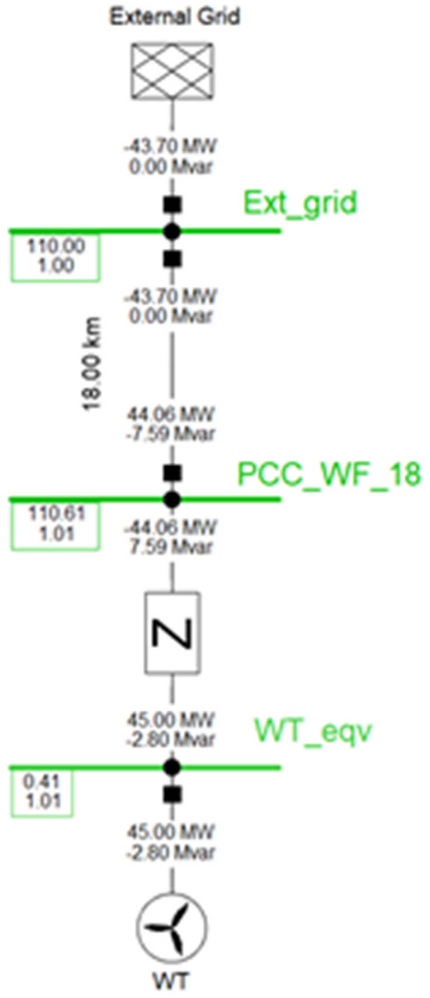


Figure 26 Power flow equivalent

Step 2

In this section simulation results for black-box-based full model and dynamic equivalent utilising generic DFIG model with the proposed typical parameters are compared. The comparison is based on simulation results of a three phase faults cleared after 100 ms (Figure 27).

As evident from the figure, in both cases the behaviour of the black-box models is very complex, especially as far as active power recovery is concerned. The equivalent reflects a reasonable level of discrepancy, nevertheless similar behaviour is preserved. The equivalent does not reflect post-fault oscillations of active power and the first phase of recovery is driven by the ramp function, instead of being instantaneous, but the overall recovery time is preserved. This is an important result which proves that a simplified models obtained with use of standard models and optimised sets po parameters can represent the full detailed models quite accurately.

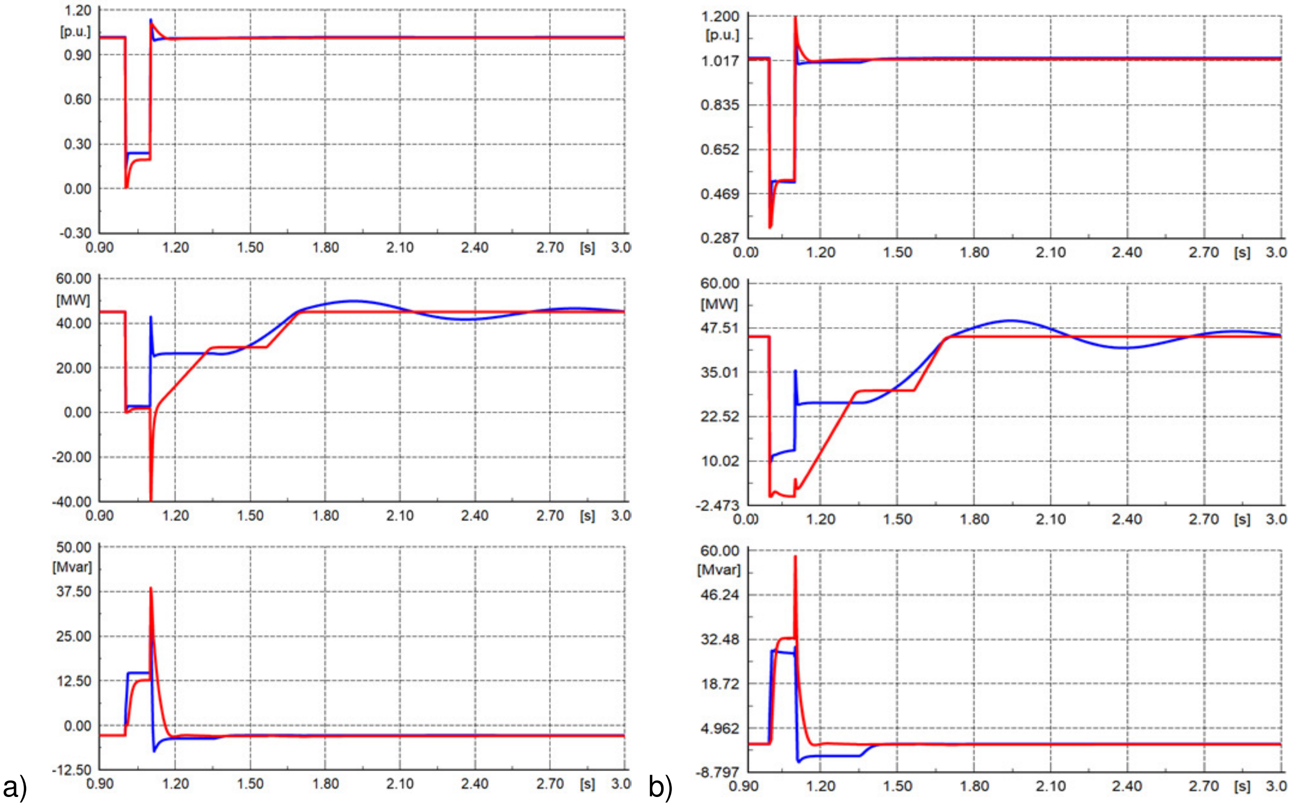


Figure 27 Comparison of responses of the full model (blue) with an equivalent (red) for a three phase short circuit with zero impedance (a) and with non-zero impedance (b) at PCC; top plot: wind farm voltage [pu], middle plot: active power [MW], bottom plot: reactive power [MVAR]

6 Analysis of Grid Equivalents vs. Current State of the Art

6.1 Analysis of the PowerFactory Network reduction tool

This chapter explains how to use the PowerFactory Network Reduction tool. A typical application of Network Reduction is when a network that is part of or adjacent to a much larger network must be analysed, but cannot be studied independently of the larger network. In such cases, one option is to model both networks in detail for calculation purposes. However, there might be situations when it is not desirable to do studies with the complete model. For example, when the calculation times would increase significantly or when the data of the neighbouring network is confidential and cannot be published.

In these cases, it is common practice to provide a simplified representation of the neighbouring network that contains only the interface nodes (connection points). These can then be connected by equivalent impedances and voltage sources, so that the short circuit and load-flow response within the kept (non reduced) system is the same as when the detailed model is used.

PowerFactory offers two methods for producing an equivalent representation of the reduced part of the network and calculating its parameters, valid for both load flow and short-circuit calculations, including asymmetrical faults such as single-phase faults. The first method is based on a Ward Equivalent representation and the second method is based on an REI (Radial-Equivalent-Independent) representation, which enables generators and/or loads to be retained and makes it possible to create power injections according to fuel type.

6.2 How to run the Network Reduction tool

This sub-section describes the procedure you must follow to run the Network Reduction using the default options. Proceed as follows:

1. Activate the base Study Case for the project you wish to reduce.
2. Define a boundary or boundaries that split the grid into the part to be reduced (interior region), and the part to be kept (exterior region).
3. Open the boundary object(s) and use the Check Split button in the ElmBoundary dialog to check that the boundary correctly splits the network into two regions.
4. Select the Change Toolbox button from the main toolbar.
5. Press the Network Reduction icon from the Additional Functions bar. This opens the dialog for Network Reduction Command (ComRed).
6. Select the boundary/boundaries you previously defined using the button.
7. Optional: If you wish to modify the settings of the command, do so in this dialog. However, the default options are recommended, unless you have a specific reason for changing them.
8. Press the Execute button to start the reduction procedure.

Expected Output of the Network Reduction
This sub-section describes the expected output of the network reduction tool after successfully executing it. The output varies depending on whether the reduced project was created in V13.2 or earlier and contains system stages, or if it was created in V14.0 or higher. In addition, the additional objects that the Network Reduction tool creates are explained in the software user manual.

Calculation of Parameters Only
The equivalent parameters are calculated and reported to the output window. If this option is selected then the Network Reduction command does not modify the network model.

Create a new Variation for Reduced Network (Default)

The equivalent parameters are calculated and a Variation will be automatically created to store the reduced network model. If the project already includes System Stage(s) (from PowerFactory version 13.2 or earlier versions) then System Stage(s) will be created instead of a Variation.

Reduce Network without Creating a New Variation

The Network Reduction command will directly modify the main network model if this option is selected. Therefore, this option will destroy data by deleting the 'interior' region of the selected boundary, and replacing it with its reduced model, so this option should be used with care. To avoid losing the original grid data, backup the project.

Clean up empty substations

If this option is selected the empty substations from the reduced systems will be removed by the network reduction. Also the network elements will be created in the grid and not in the former substations by the network reduction.

Mutual Impedance

As part of the Network Reduction process equivalent branches (represented using Common Impedance elements) will be created between the boundary nodes, to maintain the power-flow relationship between them. If such branches have a calculated impedance larger than this parameter, they will be ignored (not added to the network model).
By default, the number of these branches created will be N*(N-1)/2, where N is the number of boundary nodes. A boundary node is defined for each boundary cubicle. Therefore, the number of created branches can be very high. Normally many of these equivalent branches have a very large impedance value, so their associated power flows are negligible, and the branch can be ignored.
The default value for this parameter is 1000 p.u (based on 100MVA).

Minimization of equivalent branches (REI reduction)

This setting is only available in the REI reduction method and minimises the number of common impedances (ElmZpu) created in the reduction. In each separated area of the "to be reduced system", the equivalent network elements created in a REI reduction are interconnected by common impedances to all boundary nodes. Every pair of boundary nodes of each separated area will be connected by a common impedance. For large systems with many boundary nodes this leads to a high number of equivalent branches created during a network reduction.
The setting "Minimise equivalent branches" on the "Advanced Options" page separates the "to be reduced system" into smaller subsystems by retaining some nodes. These subsystems will then be reduced separately. This leads to a significant decrease in the number of equivalent branches, but the number of equivalent loads and generators will increase.
The minimization algorithm is configured with different sets of parameters and the user has 4 different selection possibilities

- Off: The minimization is disabled. Output of the PowerFactory 2018 and older versions.
- Fast minimization: A time optimized minimization with large step sizes and a limited number of
- separated areas.
- Standard minimization: Recommended settings for the minimization.
- Optimal minimization: Time intensive minimization with small step sizes.

6.3 Network Reduction Example

This section presents a Network Reduction example using a small transmission network feeding a distribution system from "Bus 5" and "Bus 6" as shown in Figure 28. The distribution system is represented by “Load A” and “Load B” and the corresponding two transformers. As a user, you would like to study the distribution system in detail but are not concerned with the detailed power flow within the transmission system. Therefore, the Network Reduction tool can be used to create an equivalent model for the transmission system.

The interior region (the area that shall be reduced) is shown shaded in grey, whereas the non-shaded area is the exterior region that shall be kept. The procedure for completing the Network Reduction according to these parameters is as follows (you can repeat this example yourself using the Nine-bus System within the PowerFactory Examples):

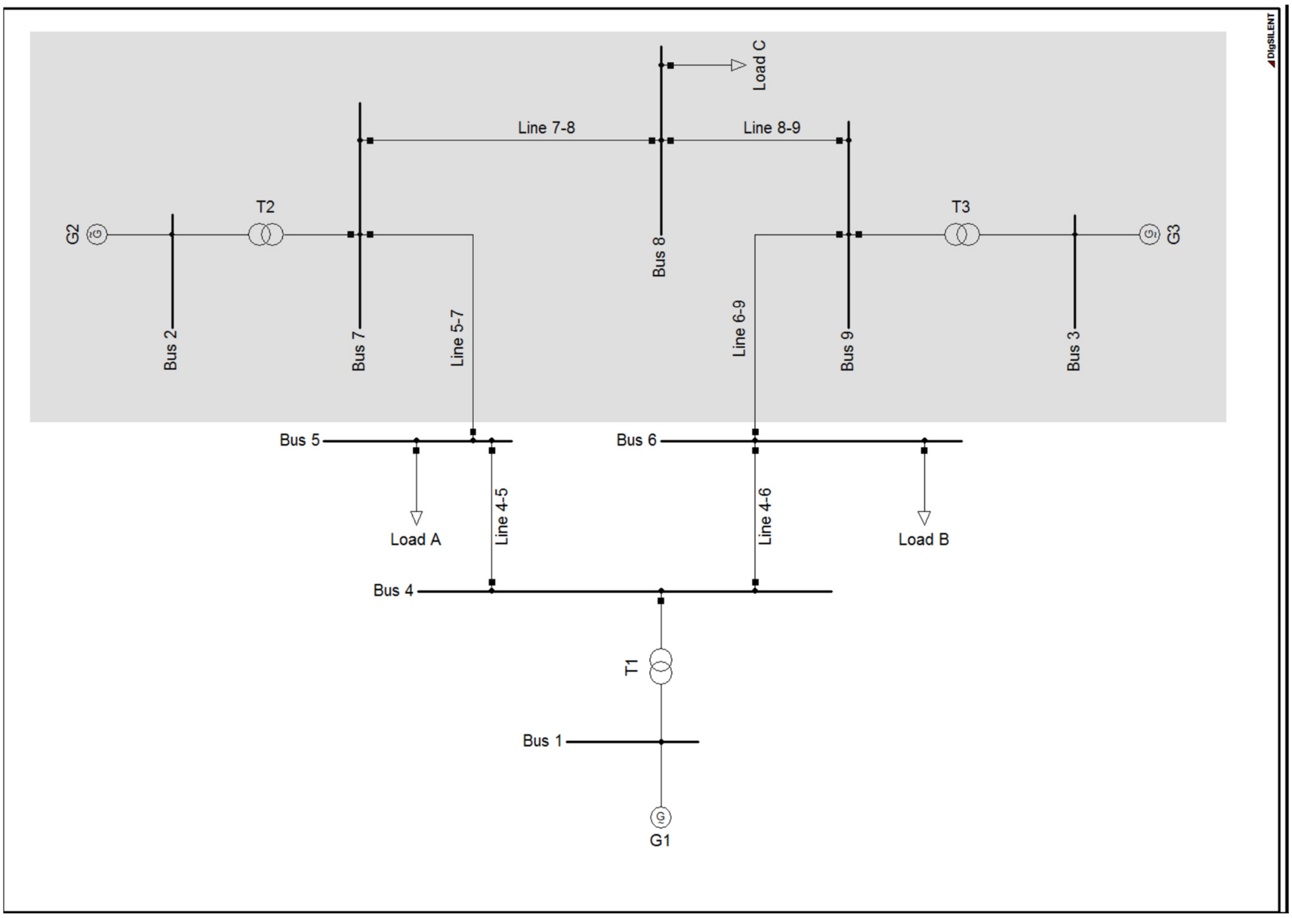


Figure 28: Example System with Original Network

A load flow calculation or a short-circuit calculation in the reduced network (Figure 29) gives the same results for the distribution network as for the original (non-reduced) network.

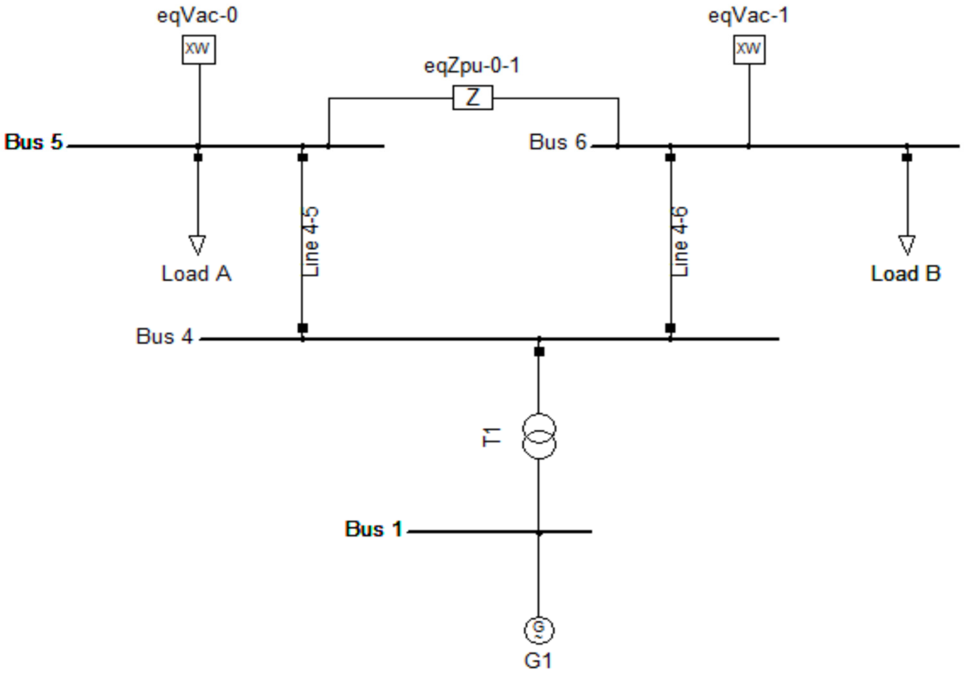


Figure 29: Example System with Reduced Network

6.4 Limitations of the PowerFactory Network reduction tool

This section presents some tips for using the Network Reduction tool and some solutions to common problems encountered by users.

6.4.1 Network Reduction doesn’t Reduce Isolated Areas

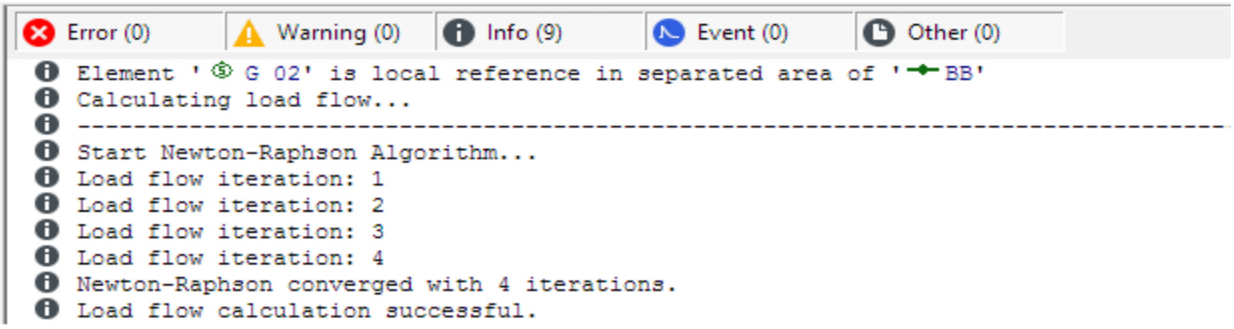
By default, the boundary definition search stops when encountering an open breaker. This means that isolated areas can sometimes be excluded from the interior region and therefore are not reduced by the Network Reduction tool. The solution to this problem is to disable the boundary flag Topological search: Stop at open breakers. This option is enabled by default in all boundary definitions. It is recommended to disable it before attempting a Network Reduction.

A related problem occurs with the project setting (Edit → Project→ Project Settings→ Advanced Calculation Parameters) Automatic Out of Service Detection. It is recommended that this option is disabled before attempting a Network Reduction. However, it is disabled by default, so if you have not made changes to the default project settings you should not need to make any changes to this setting.

6.4.2 The Reference Machine is not Reduced

The Network Reduction tool will not reduce a reference machine defined within the interior region. It also leaves all network components that are topologically one bus removed from the reference machine (and of non-zero impedance). For example, if the reference machine is a typical synchronous machine connected to the HV system through a step-up transformer, then the reduction tool will leave the synchronous machine, the LV bus, the step up transformer and the HV bus within the reduced network.

It is recommended that the reference machine is found within the exterior region before attempting a Network Reduction. The reference machine can be identified by checking the output window following a successful load-flow calculation as illustrated in Figure 30.



```
Element ' G 02' is local reference in separated area of ' BB'
Calculating load flow...
----------------------------------------------------------------------------------
Start Newton-Raphson Algorithm...
Load flow iteration: 1
Load flow iteration: 2
Load flow iteration: 3
Load flow iteration: 4
Newton-Raphson converged with 4 iterations.
Load flow calculation successful.
```

Figure 30: Output window showing the load-flow command output and the indication of the reference machine

6.5 Analysis of Grid Equivalents

After presenting in section 2.2 the requirements of the grid equivalents and after their implementation, the following section presents the conclusions of using different grid equivalents during the use case implementation.

Use Case 1: Coordinated voltage/reactive power control

The goal of this UC is application of reactive power control of DER at the TSO and DSO levels in order to ensure voltage stability in a coordinated way. It presents a control scheme to improve TSO-DSO coordination in managing the grid for voltage stability at all voltage levels by applying a coordinated TSO-DSO optimization methodology.

Usage of a DSO grid equivalent is optional for this use case. The current implementation adopts a simple grid equivalent in one of its steps, in such that the DSO is represented by equivalent generators at the TSO-DSO connection points. The simple grid equivalent used in the current implementation is sufficient and simplifies the calculation.

Use Case 2: Grid Congestion Management

The UC aims to solve/mitigate the eventually congestion problem detected in the power grid .The congestion issues are solved by optimizing the active power variation of flexible resources. In detail, the optimization function evaluates the total minimum active power variation to apply at each busbar for solving the congestion.

No grid equivalenting is used in this UC. Due to it’s need to preserve the lines information, and considering we assumed that all the assets in the grid are controllable, it is not possible provide a grid equivalent. As such the use of a grid equivalent was not feasible since for this Use Case a full and detailed model is required.

Use Case 3: Provision of tertiary control reserve based on coordinated TSO-DSO optimal power flow calculations

The use case aims to ensure the frequency stability through tertiary control. The use case controller will engage the available flexibility of resources connected at both transmission and distribution level in order to participate in balancing and frequency tertiary control of the power systems in an optimal way and through TSO-DSO cooperation.

Usage of grid equivalents is optional for this use case. In case of using grid equivalents, in each stage of 3 stages of the use case, the equivalent model of either transmission or distribution network is used. The simulation is always semi-dynamic.

The simple grid equivalent used in the current implementation is sufficient and simplifies the calculation.

Use Case 4: Fast Frequency Restoration Control

The UC aims to solve eventually instability frequency problems using local fast ramping resources (e.g., RES, storage units, flexible loads).

Usage of equivalents is optional. Dynamic equivalents were used. Equivalenting was used to create equivalents of wind farms. Both static and dynamic parameters were represented in the equivalent.

Usage of equivalents simplified calculations and reduced time required for running UC without discounts in the quality of results.

Use Case 5: Power balancing at DSO level

Optimization of power balancing at DSO level by optimizing the local available flexible and controllable resources.

Usage of a TSO grid equivalent is optional for this use case. The current implementation adopts a simple grid equivalents, in such that the TSO is represented by equivalent generators at the TSO-DSO connection points.

The simple grid equivalent used in the current implementation is sufficient and simplifies the calculation.

Use Case 6: Inertia management

UC aims to ensure secure RoCoF after disturbances in the grid through management of natural and synthetic inertia available at a given timeframe.

Usage of equivalents is optional. Dynamic equivalents were used.

Equivalenting was used to create equivalents of wind farms. Both static and dynamic parameters were represented in the equivalent.

Usage of equivalents simplified calculations and reduced time required for running UC without discounts in the quality of results.

Use case 7: Optimal Energy Interruption Management

The UC aims to minimize the cost associated with generator re-dispatch and load interruption for satisfying operational constraints in the post-contingency operational state of the grid.

Grid equivalenting is needed for this UC for some low-voltage feeders (distribution system).

Grid equivalenting is used for this UC for some low-voltage feeders for the cases in which contingency in MV or neighbouring LV feeder is considered.

The simulation calculation effort is reduced. There was no big deviation between results obtained from full grid model and grid equivalents.

7 Conclusions

In order to define the grid equivalents, a mapping of the requirements for grid equivalents for the developed INTERPLAN use cases and showcases was done by the project partners. Based on the identified requirements, an approach to generate simplified grid equivalents representing the original networks according to the required granularity by the individual use cases was established and presented in this deliverable.

Depending on the topology of the required network and the focus voltage level, several types of grid equivalents were identified and representative examples were presented:

- Basic Grid Equivalents – simple representation of the grid focusing mainly on preserving Voltage, Active and Reactive power characteristics
- Advanced Grid Equivalents – More complex representation considering also different voltage levels and equivalenting different grid areas
- Dynamic Grid Equivalents – Simple or Advanced Grid Equivalents suitable for transient stability studies

Based on the developed INTERPLAN approach to generate simplified grid equivalents, the project provides grid-equivalents covering all voltage levels to be incorporated in the operation planning and semi-dynamic simulations environment. In a further step, the developed grid equivalents were validated during the project runtime. Hence, a validated set of grid equivalents are provided accessible by public on the website (https://interplan-project.eu/resources/) and presented to the scientific community during international conferences and publications. Using appropriate grid equivalents for the distribution grid, the complexity of such investigations can be reduced significantly and can help DSOs to identify the optimal standard parametrization of small-scale DER.

Considering the validation of the grid equivalents during the project runtime, the following conclusions can be outlined:

- Usage of a DSO grid equivalent is optional for UC1: Coordinated voltage/reactive power control. The current implementation adopts a simple grid equivalent in one of its steps, in such that the DSO is represented by equivalent generators at the TSO-DSO connection points. The simple grid equivalent used in the current implementation is sufficient and simplifies the calculation.
- No grid equivalenting is used in UC2: Grid Congestion Management . Due to it’s need to preserve the lines information, and considering we assumed that all the assets in the grid are controllable, it is not possible provide a grid equivalent. As such the use of a grid equivalent was not feasible since for this Use Case a full and detailed model is required.
- Usage of grid equivalents is optional for UC3: Provision of tertiary control reserve based on coordinated TSO-DSO optimal power flow calculations . In case of using grid equivalents, in each stage of 3 stages of the use case, the equivalent model of either transmission or distribution network is used. The simulation is always semi-dynamic.
- Usage of equivalents is optional also for UC4: Fast Frequency Restoration Control and UC6: Inertia management. Dynamic equivalents were used. Equivalenting was used to create equivalents of wind farms. Both static and dynamic parameters were represented in the

equivalent. Usage of equivalents simplified calculations and reduced time required for running UC without discounts in the quality of results.

- Grid equivalenting is needed for UC7: Optimal Energy Interruption Management for some low-voltage feeders (distribution system) for the cases in which contingency in MV or neighbouring LV feeder is considered. The simulation calculation effort is reduced. There was no big deviation between results obtained from full grid model and grid equivalents.

The consortium provided for the integrated operation planning tool the following features and advantages in respect to grid clustering and equivalenting: It includes a library of grid equivalents responding to the needs of showcasing the project results and covering all voltage levels and their active components and provide easy to use grid clustering techniques that are adaptive and responsive to the dynamic growth of the evolving grid thus refreshing and valid as new technologies emerge and adapted in the grid.

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10 **Annex**

10.1 List of Figures

10.2 List of Tables