6. Medium Voltage Distribution Network Benchmark

The medium voltage (MV) distribution network benchmark is derived from a physical MV network in southern Germany, which supplies a small town and the surrounding rural area. Compared with this original network, the number of nodes for the benchmark network was reduced to enhance user friendliness and flexibility while fully maintaining the realistic character of the network. The benchmark network in this chapter is representative of physical MV networks typical of North America and Europe. It is to be noted that distribution network design approaches and installation common practices vary greatly between North America and Europe; a discussion of these differences is given in Appendix 9.1.

6.1 North American Configuration

Structure: North American MV distribution feeders are three-phase and either of meshed or radial structure, with the latter dominating rural installations. The benchmark allows flexibility to model both meshed and radial structures. Each feeder includes numerous laterals at which MV/LV transformers would be connected. In North America, radial structures are prevalent, and single-phase MV lines are included as subnetworks off the three-phase main lines. The nominal voltage on the three-phase sections is 12.47 kV, and on the single-phase sections the line-to-neutral voltage is 7.2 kV. The system frequency is 60 Hz.

Symmetry: Due to the existence of single-phase laterals, the North American MV network configuration is inherently unbalanced. Although effort to balance the loading is made, a balanced three-phase network should not be assumed, particularly for voltage drop calculations.

Line types: Overhead lines are used with bare conductors made of aluminum with or without steel reinforcement, i.e. AAC and ACSR.

Grounding: The grounding of the MV network largely depends on regional preferences. The majority of North American networks are solidly grounded.

6.1.1 Topology

The topology of the North American version of the MV network benchmark is shown in Figure 6.1. Framed by dashed lines are Feeders 1 and 2. Both feeders operate at 12.47 kV and are fed via separate transformers from the 115 kV subtransmission system. Either feeder alone or both feeders can be used for studies of DER integration. Further variety may be introduced by means of configuration switches S1, S2, and S3. If these switches are open, then both feeders are radial. Closing S2 and S3 in feeder 1 would create a loop or mesh. With the given location of S1, it can either be assumed that both feeders are fed by the same substation or by different substations. Closing S1 interconnects the two feeders through a distribution line. If different substations are assumed, then 115 kV subtransmission lines, such as those given in Section 5.3.4 should be used to connect the HV grid equivalent to each of the transformers.

In addition to three-phase lines, MV networks in North America contain single-phase lines. For these cases the single-phase subnetwork shown in Figure 6.2 was developed. It is inserted into the MV network at the locations indicated in Figure 6.1 and connected to the given phase.

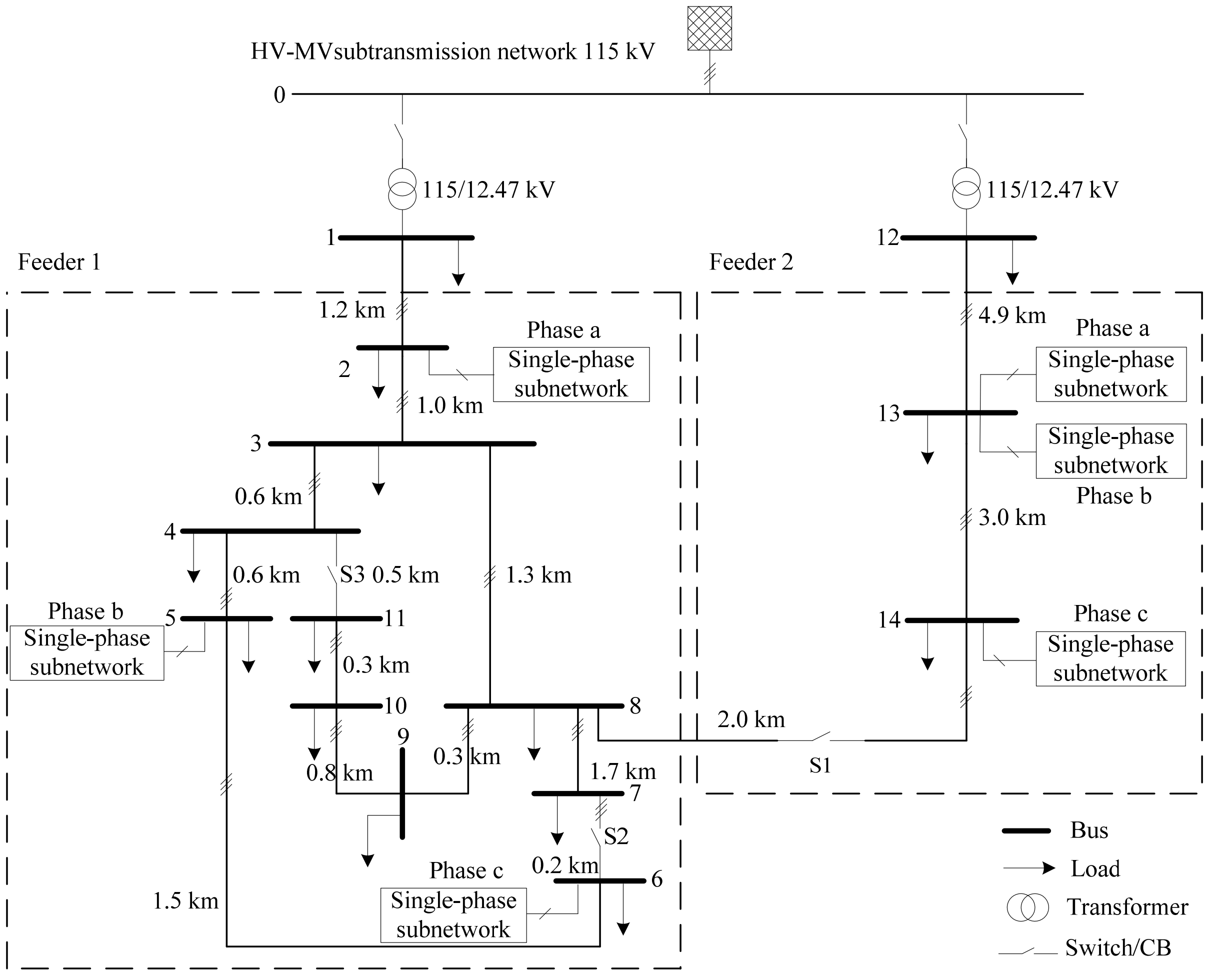

Figure 6.1: Geometry of overhead lines of three-phase sections of North American MV distribution network benchmark

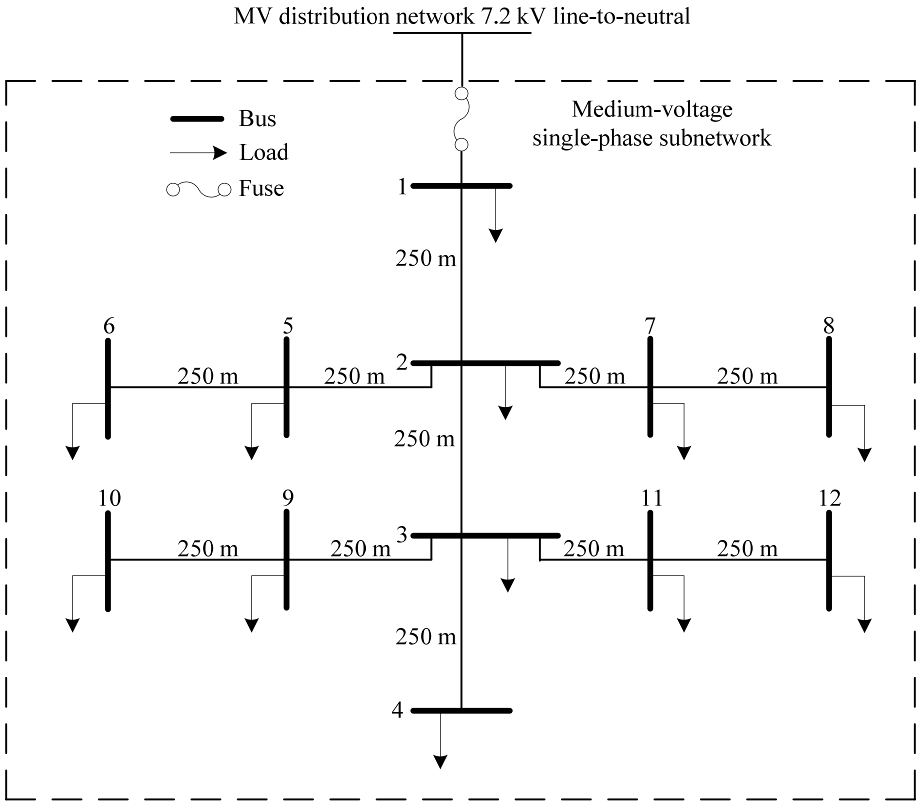

Figure 6.2: Topology of single-phase sections of North American MV distribution network benchmark

6.1.2 Network Data

In the North American version, conductors are mounted on towers as overhead lines. Neutral wires are available in three-phase and single-phase sections as shown. Figure 6.3 and Table 6.1 give the tower geometries for both the three-phase and single-phase lines. The types of conductors used in this benchmark are designated by the Conductor ID. The associated conductor parameters are provided in Table 6.2.

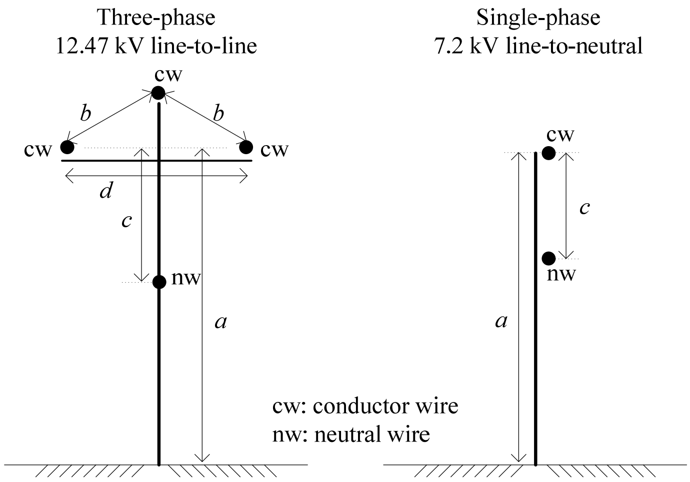

Figure 6.3: Geometry of overhead lines of North American MV distribution network benchmark

Table 6.1: Geometry of overhead lines of North American MV distribution network benchmark

Tower	a	b	c	d
	[m]	[m]	[m]	[m]
Three-phase	13.7	1.64	2.13	3.05
Single-phase	13.7	N/A	2.13	N/A

Table 6.2: Conductor parameters of North American MV distribution network benchmark

Conductor ID	Function	Type	Stranding	Size	d_c	GMR	R'_{dc} at 20 ºC	R'_{ac} at 50 ºC
				[kcmil or AWG]	[cm]	[cm]	[Ω/km]	[Ω/km]
1	conductor wire	AAC "Tulip"	19	336.4	1.69	0.640	0.168	0.190
2	neutral wire	AAC "Phlox"	7	3/0	1.18	0.427	0.338	0.380
3	conductor & neutral	ACSR "Sparrow"	6/1	2	0.80	0.140	0.832	1.010

Note: Conductor type is designated using customary North American notation. R'_{ac} varies with temperature and current flow due to core magnetization in steel cables; for the ACSR in this table, the given values are approximate and account for magnetic effects assuming a current flow of 146 A. Values of d_c, GMR, R'_{dc}, and R'_{ac} obtained from Aluminum Electrical Conductors Manual [5], with GMR for the ACSR obtained from Table 2.3 of [16].

Table 6.3 defines the network topology, line lengths of the three-phase sections of Figure 6.1, and installation type. It also provides the phase and zero sequence resistance, reactance and susceptance values of the lines, as calculated in Appendix 9.3.1. In Table 6.4, the single-phase sections are described similarly.

Table 6.3: Connections and line parameters of three-phase sections of North American MV distribution network benchmark

Line segment	Node from	Node to	Conductor ID	R'_{ph}	X'_{ph}	B'_{Ph}	R'_0	X'_0	B'_0	l	Installation
				[Ω/km]	[Ω/km]	[μS/km]	[Ω/km]	[Ω/km]	[μS/km]	[km]	
1	1	2	1,2	0.282	0.703	3.193	0.466	1.243	1.826	1.20	overhead
2	2	3	1,2	0.282	0.703	3.193	0.466	1.243	1.826	1.00	overhead
3	3	4	1,2	0.282	0.703	3.193	0.466	1.243	1.826	0.61	overhead
4	4	5	1,2	0.282	0.703	3.193	0.466	1.243	1.826	0.56	overhead
5	5	6	1,2	0.282	0.703	3.193	0.466	1.243	1.826	1.54	overhead
6	6	7	1,2	0.282	0.703	3.193	0.466	1.243	1.826	0.24	overhead
7	7	8	1,2	0.282	0.703	3.193	0.466	1.243	1.826	1.67	overhead
8	8	9	1,2	0.282	0.703	3.193	0.466	1.243	1.826	0.32	overhead
9	9	10	1,2	0.282	0.703	3.193	0.466	1.243	1.826	0.77	overhead
10	10	11	1,2	0.282	0.703	3.193	0.466	1.243	1.826	0.33	overhead
11	11	4	1,2	0.282	0.703	3.193	0.466	1.243	1.826	0.49	overhead
12	3	8	1,2	0.282	0.703	3.193	0.466	1.243	1.826	1.30	overhead
13	12	13	1,2	0.282	0.703	3.193	0.466	1.243	1.826	4.89	overhead
14	13	14	1,2	0.282	0.703	3.193	0.466	1.243	1.826	2.99	overhead
15	14	8	1,2	0.282	0.703	3.193	0.466	1.243	1.826	2.00	overhead

Table 6.4: Connections and line parameters of single-phase sections of North American MV distribution network benchmark

Line segment	Node from	Node to	Conductor ID	R'_{ph}	X'_{ph}	B'_{ph}	l	Installation
				[Ω/km]	[Ω/km]	[μS/km]	[m]	
1	1	2	3	1.144	0.884	2.374	250	overhead
2	2	3	3	1.144	0.884	2.374	250	overhead
3	3	4	3	1.144	0.884	2.374	250	overhead
4	2	5	3	1.144	0.884	2.374	250	overhead
5	5	6	3	1.144	0.884	2.374	250	overhead
6	2	9	3	1.144	0.884	2.374	250	overhead
7	9	8	3	1.144	0.884	2.374	250	overhead
8	8	7	3	1.144	0.884	2.374	250	overhead
9	9	10	3	1.144	0.884	2.374	250	overhead
10	10	11	3	1.144	0.884	2.374	250	overhead
11	9	12	3	1.144	0.884	2.374	250	overhead

In Table 6.5, the transformer parameters are given. Delta to grounded-wye transformers are most commonly used in North America with phase angle of the delta leading that of the wye. The three MVA rating values indicate the power ratings for the cases of natural cooling, fan cooling with a single fan, and fan cooling with dual fans, respectively. The impedances were calculated based on the lowest MVA rating and referred to the low voltage side, as described in Appendix 9.3.3.

Table 6.5: Transformer parameters of North American MV distribution network benchmark

Node from	Node to	Connection	V_1	V_2	Z_{tr}†	S_{rated}
			[kV]	[kV]	[Ω]	[MVA]
0	1	3-ph Dyn1	115	12.47	0.010 + j1.24	15
0	12	3-ph Dyn1	115	12.47	0.013 + j1.55	12

† refers to V_2 side

To achieve power flows with acceptable voltages at each bus, tap changers are essential. The power flow results given in Appendix 9.2.3 make use of the following suggested specifications for a tap changing transformer:

- Primary: ±5 % in 2.5 % increment no-load taps.
- Secondary: ±10 % in 0.625 % increment load changing taps.

Table 6.6 gives the parameters of the equivalent HV network connected at the high voltage side of the substation transformers.

Table 6.6: HV-MV subtransmission equivalent network parameters of North American MV distribution network benchmark

Nominal system voltage	Short circuit power, S_{SC}	R/X ratio
[kV]	[MVA]	
115	5000	0.1

6.1.3 Load Data

Load Data Table 6.7 gives the values of the coincident peak loads per phase for each node of the three-phase sections. Table 6.8 provides coincident peak load values for the residential single-phase subnetworks separately. Note that the appropriate coincidence factor is applied in Table 6.7. The coincidence factor is a function of the number of customers served. The use of coincidence factors is described in Appendix 9.3.4. Coincidence factors should also be used when the single-phase subnetworks are not modeled in detail but are instead reduced to a single equivalent load.

The load values given for nodes 1 and 12 are much larger than those given for the other nodes. These loads represent additional feeders served by the transformer and are not actually part of the feeder that is modeled in detail. This is made clear by the topology in Figure 6.1. Daily load profiles for residential and commercial or industrial loads are given in Figure 6.4.

Table 6.7: Load parameters of three-phase sections of North American MV distribution network benchmark

Node	Apparent Power, *S* [kVA]						Power Factor, *pf*	
	Phase A		Phase B		Phase C			
	Residential	Commercial or Industrial	Residential	Commercial or Industrial	Residential	Commercial or Industrial	Residential	Commercial or Industrial
1	5010	3070	4910	2570	3860	3520	0.93	0.87
2	100 + Subnetwork	200	50	300	200	300	0.95	0.85
3	---	80	200	80	50	80	0.90	0.80
4	200	---	100	---	100	---	0.90	---
5	200	50	Subnetwork	200	---	50	0.95	0.85
6	50	---	100	---	Subnetwork	---	0.95	---
7	---	100	100	100	---	100	0.95	0.95
8	100	---	150	---	---	200	0.90	0.90
9	100	---	150	---	100	---	0.95	---
10	150	---	100	---	250	---	0.90	---
11	50	150	50	150	---	150	0.95	0.85
12	1060	1260	1060	1260	1060	1260	0.90	0.87
13	Subnetwork	225	Subnetwork	225	---	225	0.95	0.85
14	---	90	---	90	Subnetwork	90	0.90	0.90

Table 6.8: Load parameters of single-phase sections of North American MV distribution network benchmark

Node	Apparent Power, *S* [kVA]	Power Factor, *pf*
1	15	0.90
2	15	0.95
3	15	0.90
4	15	0.90
5	10	0.95
6	50	0.95
7	50	0.95
8	10	0.95

Node	Apparent Power, S [kVA]	Power Factor, pf
9	50	0.95
10	15	0.90
11	10	0.95
12	10	0.95

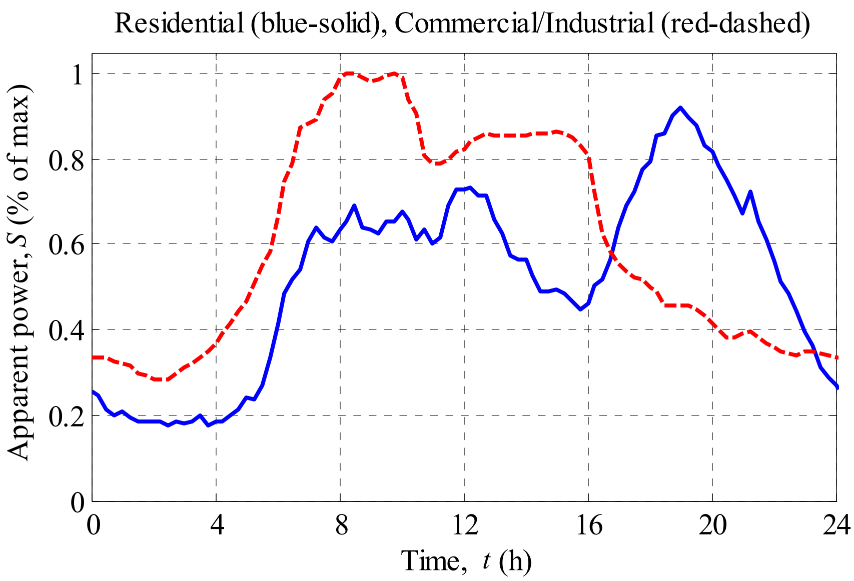

Figure 6.4: Daily load profiles of MV distribution network benchmark

6.2 European Configuration

Structure: European MV distribution feeders are three-phase and either of meshed or radial structure, with the latter dominating rural installations. The benchmark allows flexibility to model both meshed and radial structures. Each feeder includes numerous laterals at which MV/LV transformers would be connected. The nominal voltage is 20 kV. The system frequency is 50 Hz.

Symmetry: Efforts are typically made to balance the various low voltage laterals along the MV lines, but some unbalances are still typically experienced in practice. Unbalance is not explicitly included in the European benchmark, but it can be introduced if desired. Section 6.3 on flexibility provides further information.

Line types: Overhead lines are used with bare conductors made of aluminum with or without steel reinforcement, i.e. A1 or A1/S1A. Underground cables are XLPE with round, stranded aluminum conductors and copper tape shields.

Grounding: The grounding of the MV network largely depends on regional preferences. European networks are typically ungrounded or impedance-grounded.

6.2.1 Topology

The topology of the European version of the MV distribution network benchmark is shown in Figure 6.5. Framed by dashed lines are Feeders 1 and 2. Both feeders operate at 20 kV and are fed via separate transformers from the 110 kV subtransmission network. Either feeder alone or both feeders can be used for studies of DER integration. Further variety can be introduced by means of configuration switches S1, S2, and S3. If these switches are open, then both feeders are radial. Closing S2 and S3 in feeder 1 creates a loop or mesh. With the given location of S1, it can either be assumed that both feeders are fed by the same substation or by different substations and closing S1 interconnects the two feeders through a distribution line. If different substations are assumed, then 110 kV subtransmission lines, such as those given in Section 5.3.4, should be used to connect the HV grid equivalent to each of the transformers.

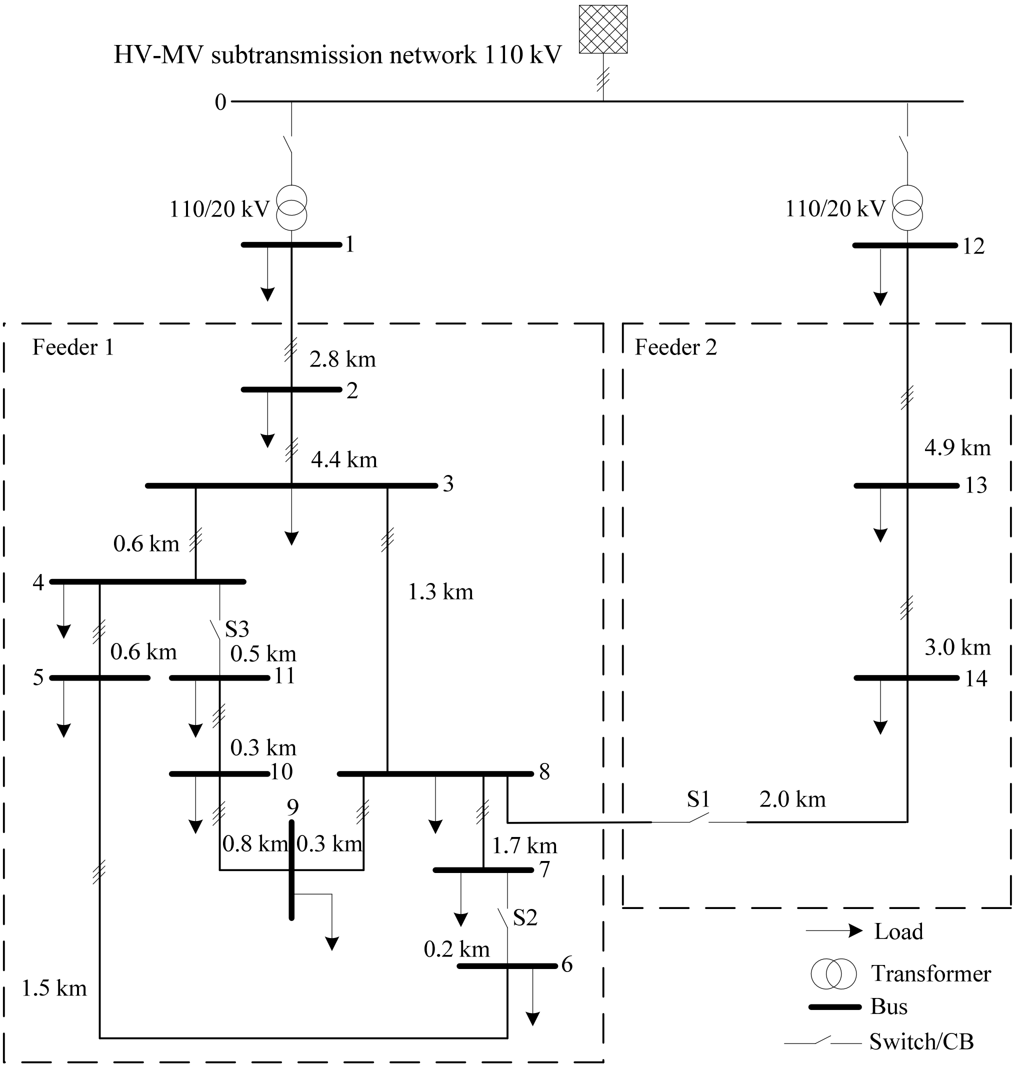

Figure 6.5: Topology of European MV distribution network benchmark

6.2.2 Network Data

In the European version of the benchmark, overhead lines are mounted on towers without neutral wires, and underground cables are tape-shielded and buried in back-filled trenches with a protective plate. Figure 6.6 and Table 6.9 give the geometries for the overhead lines and underground cables, from which line parameters can be derived. The types of conductors used in this benchmark are designated by the Conductor ID. The associated conductor parameters are provided in Table 6.10 for overhead and Table 6.11 for underground.

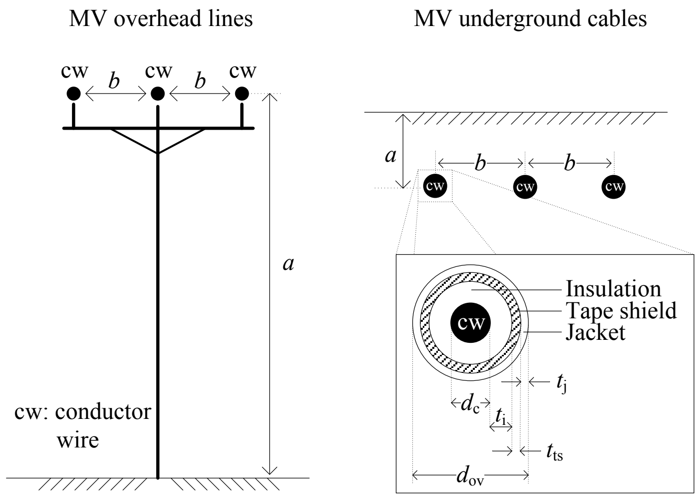

Figure 6.6: Geometry of overhead and underground lines of European MV distribution network benchmark

Table 6.9: Geometry of overhead and underground lines in European MV distribution network benchmark

Installation	a	b
	[m]	[m]
Overhead	9.5	1.0
Underground	0.7	0.3

Table 6.10: Conductor parameters of overhead lines of European MV distribution network benchmark

Conductor ID	Type	Stranding	Cross-sectional Area	d_c	GMR	R'_{dc} at 20 ºC	R'_{ac} at 50 ºC
			[mm^2]	[cm]	[cm]	[Ω/km]	[Ω/km]
1	A1	7	63	1.02	0.370	0.4545	0.5100

Note: Conductor type is designated using IEC notation as specified in IEC61089 [7].
Values of d_c, GMR, R'_{dc}, and R'_{ac} obtained from IEC61597 [8].

Table 6.11: Conductor parameters of underground lines of European MV distribution network benchmark

Conductor ID	Type	Stranding	Cross-sectional Area	d_c	GMR	R'_{dc} at 20 ºC	R'_{ac} at 90 ºC	t_i	t_j	t_{ts}	d_{ov}
			[mm^2]	[cm]	[cm]	[Ω/km]	[Ω/km]	[mm]	[mm]	[mm]	[mm]
2	NA2XS2Y	19	120	1.24	0.480	0.253	0.338	5.5	2.5	0.2	34.2

Note: Conductor type is designated using the German DIN VDE notation for underground cables. Values of d_c, R'_{dc}, R'_{ac}, t_i, t_j, t_{ts}, and d_{ov} obtained from Table 5.6.6b of [12] with stranding and GMR from Tables 3.6 and 3.12 of [16].

Table 6.12 lists the network topology and line lengths of the network of Figure 6.5 and provides the positive and zero sequence resistance, reactance and susceptance values of the lines, as calculated in Appendices 9.3.1 and 9.3.2.

Table 6.12: Connections and line parameters of European MV distribution network benchmark

Line segment	Node from	Node to	Conductor ID	R'_{ph}	X'_{ph}	B'_{ph}	R'_0	X'_0	B'_0	l	Installation
				[Ω/km]	[Ω/km]	[μS/km]	[Ω/km]	[Ω/km]	[μS/km]	[km]	
1	1	2	2	0.501	0.716	47.493	0.817	1.598	47.493	2.82	underground
2	2	3	2	0.501	0.716	47.493	0.817	1.598	47.493	4.42	underground
3	3	4	2	0.501	0.716	47.493	0.817	1.598	47.493	0.61	underground
4	4	5	2	0.501	0.716	47.493	0.817	1.598	47.493	0.56	underground
5	5	6	2	0.501	0.716	47.493	0.817	1.598	47.493	1.54	underground
6	6	7	2	0.501	0.716	47.493	0.817	1.598	47.493	0.24	underground
7	7	8	2	0.501	0.716	47.493	0.817	1.598	47.493	1.67	underground
8	8	9	2	0.501	0.716	47.493	0.817	1.598	47.493	0.32	underground
9	9	10	2	0.501	0.716	47.493	0.817	1.598	47.493	0.77	underground
10	10	11	2	0.501	0.716	47.493	0.817	1.598	47.493	0.33	underground
11	11	4	2	0.501	0.716	47.493	0.817	1.598	47.493	0.49	underground
12	3	8	2	0.501	0.716	47.493	0.817	1.598	47.493	1.30	underground
13	12	13	1	0.510	0.366	3.172	0.658	1.611	1.280	4.89	overhead
14	13	14	1	0.510	0.366	3.172	0.658	1.611	1.280	2.99	overhead
15	14	8	1	0.510	0.366	3.172	0.658	1.611	1.280	2.00	overhead

Table 6.13 gives the transformer parameters. The impedances calculated are referred to the secondary side, as described in Appendix 9.3.3.

Table 6.13: Transformer parameters of European MV distribution network benchmark

Node from	Node to	Connection	V_1	V_2	Z_{tr}†	S_{rated}
			[kV]	[kV]	[Ω]	[MVA]
0	1	3-ph Dyn1	110	20	0.016+j1.92	25
0	12	3-ph Dyn1	110	20	0.016+j1.92	25

† refers to V_2 side

To achieve power flows with acceptable voltages at each bus, tap changers are essential. The power flow results given in Appendix 9.2.4 make use of the following suggested specifications for a tap changing transformer:

- Primary: ±5 % in 2.5 % increment no-load taps.
- Secondary: ±10 % in 0.625 % increment load changing taps.

Table 6.14 gives the parameters of the equivalent HV network connected at the high voltage side of the substation transformers.

Table 6.14: HV-MV subtransmission equivalent network parameters of European MV distribution network benchmark

Nominal system voltage	Short circuit power, S_{SC}	R/X ratio
[kV]	[MVA]	
110	5000	0.1

6.2.3 Load Data

Table 6.15 gives the values of the coincident peak loads for each node of the benchmark. It is assumed that in the European version of the benchmark the loads are symmetric and therefore equal in all three phases. Note that the appropriate coincidence factor is applied in Table 6.15. The coincidence factor is a function of the number of customers served. The use of coincidence factors is described in Appendix 9.3.4.

Note that the load values given for nodes 1 and 12 are much larger than those given for the other nodes. These loads represent additional feeders served by the transformer and are not actually part of the feeder that is modeled in detail. This is made clear by the topology in Figure 6.5. Daily load profiles are given in Figure 6.4.

Table 6.15: Load parameters of European MV distribution network benchmark

Node	Apparent Power, *S* [kVA]		Power Factor, *pf*	
	Residential	Commercial / Industrial	Residential	Commercial / Industrial
1	15300	5100	0.98	0.95
2	---	---	---	---
3	285	265	0.97	0.85
4	445	---	0.97	---
5	750	---	0.97	---
6	565	---	0.97	---
7	---	90	---	0.85
8	605	---	0.97	---
9	---	675	---	0.85
10	490	80	0.97	0.85
11	340	---	0.97	---
12	15300	5280	0.98	0.95
13	---	40	---	0.85
14	215	390	0.97	0.85

6.3 Flexibility

For some studies, it may be of interest to evaluate the impact of a DER under different network conditions. Some guidelines on how to change various benchmark parameters are given in the following subsections. Interesting reference material may also be found in [13].

6.3.1 Voltage

The nominal base voltage of the MV benchmark networks are 12.47 kV for the North American and 20 kV for the European versions. Other voltages are possible, but the conductors, conductor spacing, tower configurations, transformers, etc. may all need to be adjusted appropriately. With this in mind, the base voltages may be modified to study different voltage levels as long as the chosen values are realistic.

6.3.2 Line Lengths

The line lengths as given in Table 6.3, Table 6.4, and Table 6.12 can be modified as long as voltage drops do not become excessive and a reasonable MV distribution network character is retained.

6.3.3 Line Types and Parameters

The MV distribution network benchmark uses overhead lines. It is also possible to use sections of underground cable or even to use an entire underground network. It would then be necessary to modify the line parameters in accordance with information supplied by cable manufacturers. Shunt capacitances are important in cable-based MV networks in order to provide appropriate reactive power compensation. Underground cables are mainly encountered in urban areas with high load densities.

6.3.4 Loads

Load values can be modified as necessary. If unbalanced loads are desired for the European MV distribution network benchmark, a load unbalance of ±10 % would be reasonable. Furthermore, LV subnetworks from Chapter 7 can replace the lumped loads used in this chapter.

6.3.5 Transformers for HV/MV Integration

If the MV distribution network benchmark is to be used to replace a load of the HV transmission network benchmark of Chapter 5, as was described in Section 5.3.4, an alternative to a subtransmission representation is to use a single transformer to step up the voltage to transmission levels. The data for such transformers are given for the North American and European MV distribution network benchmarks in Table 6.16 and Table 6.17, respectively. These transformers could thus substitute for those given above in Section 6.1.2 and Section 6.2.2.

Table 6.16: Suggested transformer parameters in lieu of subtransmission of North American HV-MV network benchmark integration

Node from	Node to	Connection	V_1	V_2	Z_{tr}†	S_{rated}
			[kV]	[kV]	[Ω]	[MVA]
0	1	3-ph Dyn1	230	12.47	0.12 + j1.24	15
0	12	3-ph Dyn1	230	12.47	0.16 + j1.55	12

† refers to V_2 side

Table 6.17: Suggested transformer parameters in lieu of subtransmission of European HV-MV network benchmark integration

Node from	Node to	Connection	V_1	V_2	Z_{tr}†	S_{rated}
			[kV]	[kV]	[Ω]	[MVA]
0	1	3-ph Dyn1	220	20	0.19+j1.91	25
0	12	3-ph Dyn1	220	20	0.19+j1.91	25

† refers to V_2 side

6.4 Case Study: DER in Medium Voltage Systems

The Gas Research Institute of the United States predicts that DER will capture about 30 % of the energy market by 2030. To support such a significant transition, it is important to develop an understanding of the behavior of DER in power electric networks. In the following study, it is shown how the medium voltage distribution network benchmark can be used to study the impact of DER on voltage profile and power flow patterns.

6.4.1 System Specification

The European version of the medium voltage distribution network benchmark described in Section 6.2 was used. The daily profiles of the loads listed in Table 6.15 are modeled as shown in Figure 6.4. The simulations were performed using the commercially available PSS™ NETOMAC program. Generation and storage units were added at various nodes as listed in Table 6.18. The photovoltaic and wind turbine units are implemented as generation units with stochastic outputs and the residential fuel cells and combined heat and power (CHP) units are implemented as deterministic generation. The voltage at the primary transmission HV system is set at 220 kV. Topology of the network in which DER units are integrated is shown in Figure 6.7.

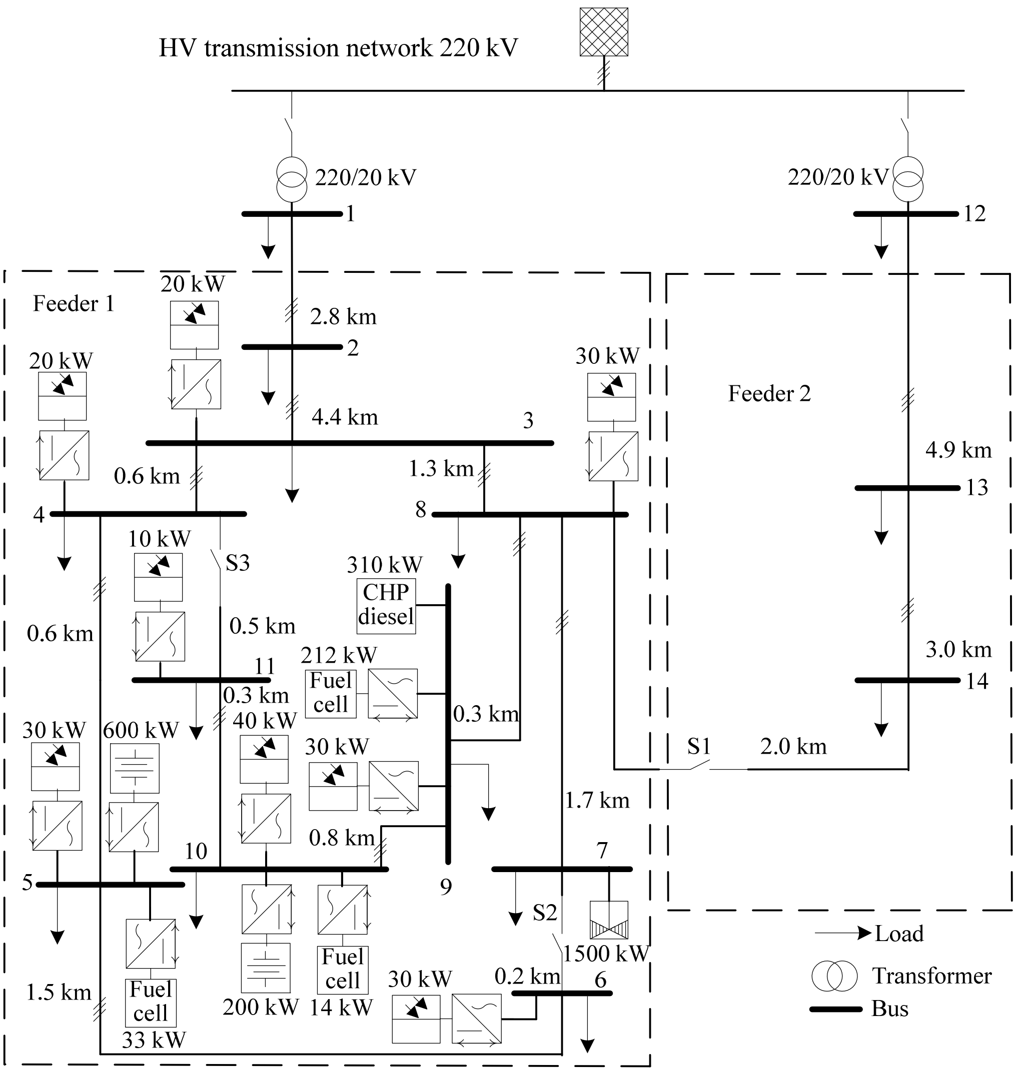

Figure 6.7: MV distribution network benchmark application example: model

Table 6.18: MV distribution network benchmark application example: parameters of DER units

Node	DER type	P_{max} [kW]
3	Photovoltaic	20
4	Photovoltaic	20
5	Photovoltaic	30
5	Battery	600
5	Residential fuel cell	33
6	Photovoltaic	30
7	Wind turbine	1500
8	Photovoltaic	30
9	Photovoltaic	30
9	CHP diesel	310
9	CHP fuel cell	212
10	Photovoltaic	40
10	Battery	200
10	Residential fuel cell	14
11	Photovoltaic	10

6.4.2 Simulation

Figure 6.8 shows the generation profiles of each DER type: wind turbine, photovoltaic array, battery, fuel cell, CHP fuel cell, and CHP diesel, respectively. During the test simulation only one wind turbine with the rated power of 1.5 MW was connected to the network. As the first subplot shows, the wind conditions through the whole simulation day were quite good. The second subplot gives the sum of the power production from photovoltaic arrays connected to the benchmark network. Characteristic for this generation group is its limited availability influenced by available sunlight.

The third subplot of Figure 6.8 gives the sum of the battery system outputs connected to the benchmark network. The state of the batteries was adjusted by a control system that either charges the batteries or injects power into the grid. The operation of the battery system can be controlled in many ways depending on the desired objective. For example, it can be used for peak shaving during peak loads or to avoid the need for DER output limitation in case of bottlenecks on the tie line. Those may occur during periods of low demand and high generation.

The fourth subplot of Figure 6.8 presents the sum of the outputs for the residential fuel cell units. The electrical power generated by each unit is actually higher than that plotted because some power is used to cover the demand of local loads and is therefore not injected into the grid. At the points where the power curve is negative, the electrical demand of the local load exceeds the local generation.

The simulation results for the fuel cell CHP and diesel CHP are presented in the last two subplots of Figure 6.8, respectively. Both units are used as local generation in industrial facilities. The operation of the diesel CHP is more flexible than the operation of the fuel cell CHP, as it can be switched on and off faster. Thus, diesel CHP can be quickly dispatched if there is peak load in the network.

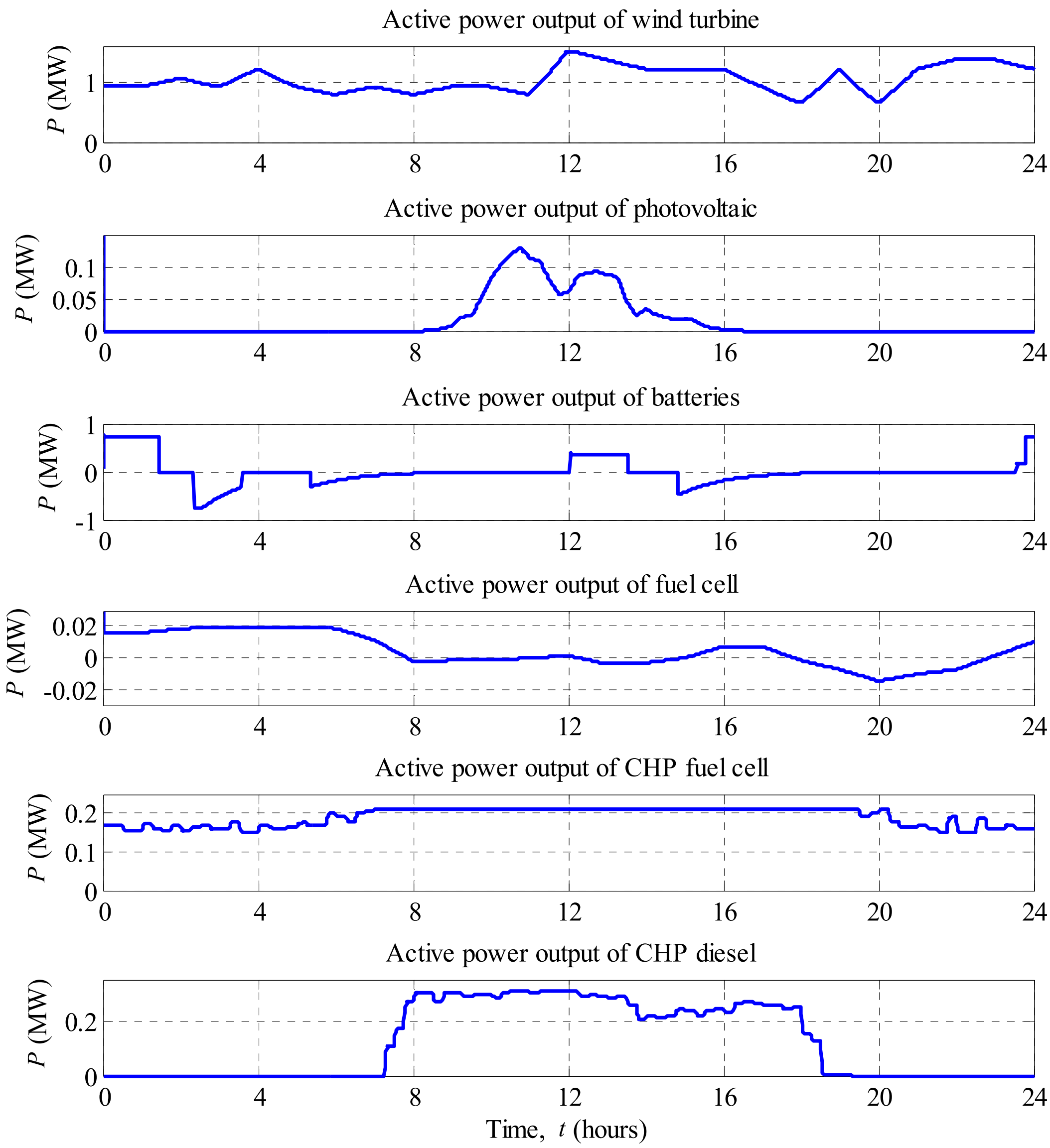

Figure 6.8: MV distribution network benchmark application example: power flow of diverse resources

The results in Figure 6.9 illustrate how the stressed system of the benchmark network can be improved by connecting DER units. The solid curve shows the result for the scenario without DER units connected to the network and the dashed curve shows the result for the scenario with DER as per Table 6.18. The top subplot of the figure shows power flow in the line connecting nodes 2 and 3; the second and third subplots show the voltage profile at nodes 3 and 11, respectively. Due to integration of DER units into the network, the voltage profile has been improved, but still at some points the voltage exceeds the acceptable limits. In the first part of the simulation time it can be seen that the power flow direction in the feeder is reversed and the voltage for this moment is too high. This situation occurs because the energy demand in the network is low at this moment and the generated energy from DER units is high. This situation is very interesting for investigations because the operation of the protection system can be well tested and new protection systems can be evaluated. Secondly, for such a situation with light loading and high DER generation, the application of a decentralized energy management system (DEMS) and limitation of the DER output power may be needed.

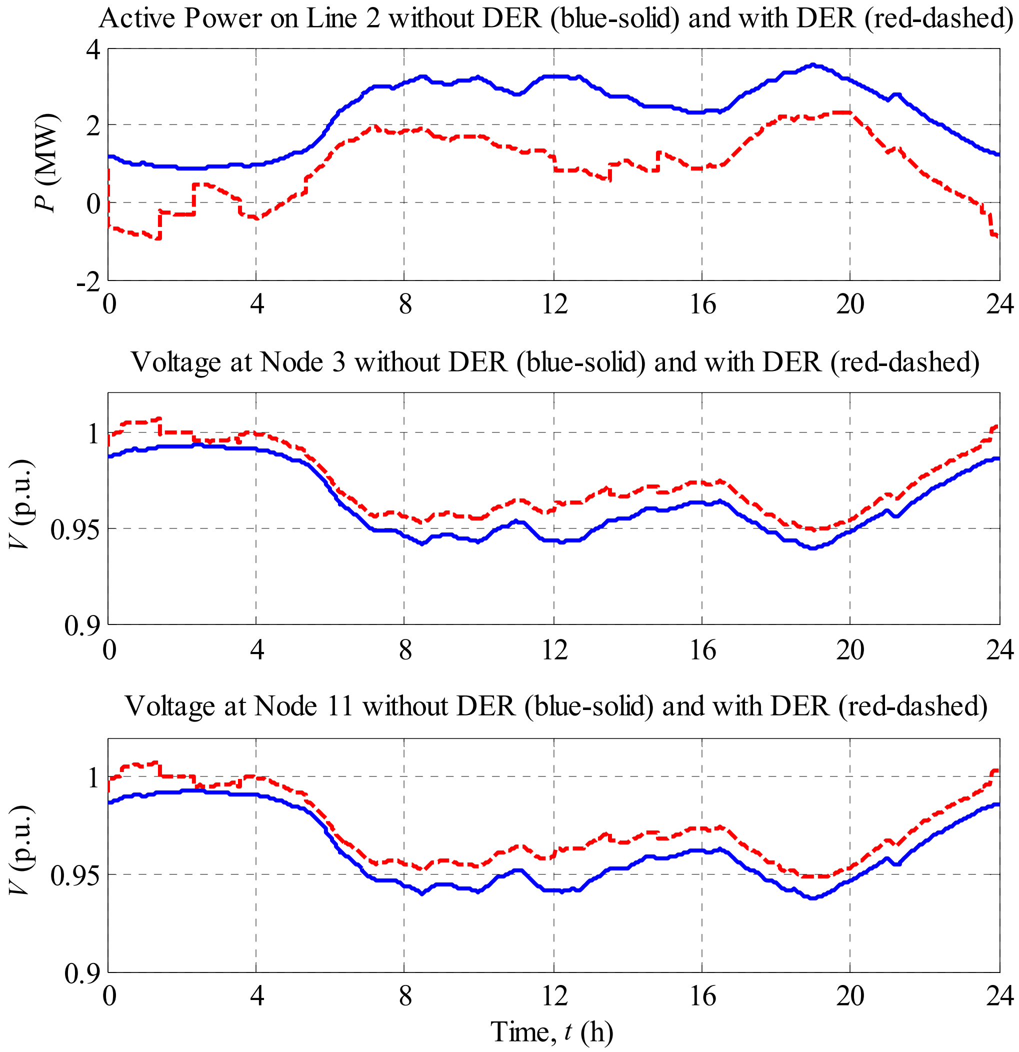

Figure 6.9: MV distribution network benchmark application example: modification of voltage profiles due to DER units