Representative low voltage feeders and MATLAB/ Simulink models of relevant components – Documentation and user manual.

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Representative Low Voltage feeders:

Figure 1 illustrates the single line diagram of the developed representative low voltage feeders for urban, sub-urban and rural systems. These models have been developed with the aid of the Electricity Authority of Cyprus by analysing several real LV feeders from the power system of Cyprus. Each feeder is presented in detail below and a user manual of how to use and set up their Simulink phasor models is provided in **Appendix A1.**

Urban Feeder: An urban feeder is characterized by a high energy consumption density, relatively short line lengths, a ground mounted distribution transformer with several outgoing laterals and a supply of energy to customers through underground cables. Its load mixture typically consists of residential apartment complexes, commercial/retail stores, and offices. The urban feeder illustrated in Figure 1.a has 3 outgoing laterals servicing in total 12 apartment complexes (10 individual supply points for each apartment complex) and 7 commercial/retail stores. The supply of power is established through 4-wire 3-phase underground cables for both the main feeder lines and the supply lines towards the customers. The overall underground cable length in this feeder is 1.125 km with a highest end-of-feeder distance of 0.265 km. The exact network topology and distribution cable/line parameters for all three feeders are provided in **Appendix B1-B2** respectively.

Sub-Urban Feeder: A representative sub-urban feeder is illustrated in Figure 1.b. The distribution transformer in these systems can either be ground mounted or pole mounted depending on the required feeder capacity. While the load mixture of the considered feeder is pure residential it is common to have sub-urban systems with varying degrees of load mixtures with commercial/retail stores. In total there are 49 residential consumers, of which 9 have a three-phase connection while the remaining 40 are single-phase connected. The total line length is 1.24 km while the highest end-of-feeder distance is approximately 0.5 km.

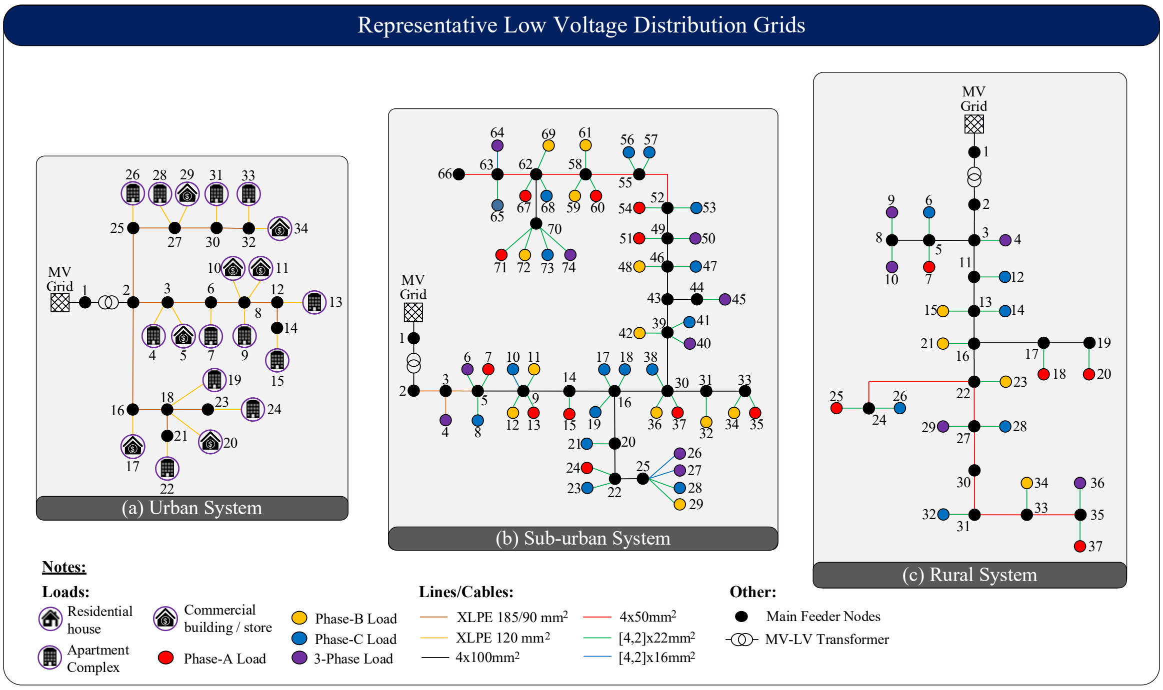

Figure 1: Single line diagram of the three representative low voltage feeders.

Rural Feeder: Due to a low population/energy density a rural system is characterized by larger line lengths when compared to the other types of LV feeders. Typically, the supply of energy from a pole mounted distribution transformer to the consumers is achieved through overhead lines. Because of the larger line lengths, the voltage profile of rural systems is more sensitive to the loading conditions. The load mixture of these feeders is mainly residential. Figure 1.c illustrates a representative rural feeder with 20 consumers of which 5 are three-phase connected. The total length of the distribution lines in this feeder is 1.81 km with an end-of-feeder distance of 0.94 km.

Distributed Energy Resources

Besides the representative LV feeders, several phasor Simulink models are provided for various Distributed Energy Resources (DERs). These include:

- PV systems with:
  - static/dynamic curtailment capabilities
  - several different reactive power control (RPC) schemes
    - constant power factor
    - $cos\phi(P)$ - watt/power factor control,
    - $cos\phi(P, V)$ – watt-volt/power factor control,
    - $Q(V)$ - volt/var control and
    - constant var, $Q = P_{PV}^{rated} tan\,(cos^{-1}(0.9))$.
- battery storage systems
  - operating in a self-consumption mode
- electric vehicle charging
  - normal/passive mode
  - smart charging mode considering available transformer capacity

A guide on how to use and set up these Simulink models is provided in Appendix A2.

Appendix A – Simulink models

A1. LV feeders

The Simulink models of the three LV feeders follow a similar structure. Here it is shown how to set up the Urban feeder and what are the output data of the model after its execution.

First, by opening Modeling➔Modeling properties➔Callbacks➔InitFcn as shown in Figure 2 the commands for the model initialization can be found. The *network_parameters* mat file contains the network related data such as the line parameters, line lengths, power profiles of each load and the source voltage profile. The parameters *Vnom_MV* and *Vnom_LV* define the nominal voltage of the MV and LV grid respectivly while *Tstep* defines the fixed step size of the solver in seconds. Parameter *MV_LV_transf* specifies if a distribution transformer is connected and is necessary for a correct initialization of the LV grid voltages. A distribution transformer can be neglected (remove physically the transformer block from the model and define *MV_LV_transf=0*) if the source voltage in the *network_parameters* is given directly for the LV side. In the StopFcn a matlab script is run after the execution of the model is finished to give the simulation results in a structured format (more details below).

The power profile of each load is given in the *LC* structure in the *network_parameters* mat file. *LC(i).time* is the time that the power set points in *LC(i).signals.values* corresponds to. For a single phase load *LC(i).signals.values* has two columns representing the active and reactive power of the specific load while for a three-phase load there are 6 columns for *Pa Qa Pb Qb Pc Qc*. For example *LC(2).signals.values(10,1)* corresponds to the active power *Pa* set point of load 2 at the time instance *t=16200* seconds (*LC(2).time(10)= 16200).*

The *Source_Voltage* variable contains the voltage profile of the source. The first column corresponds to the time of the given voltage set points which are given in a rectangular format for each phase. For

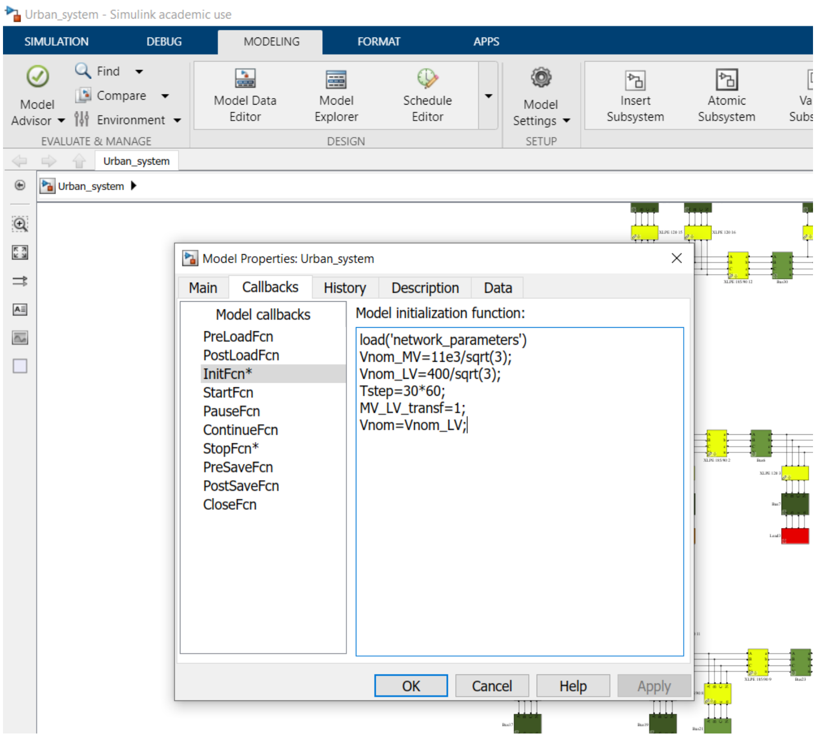

Figure 2: Model initialization

example, column 2 contains the real part of phase-A voltage set points while column 3 its imaginary part. Similarly for phase-B and phase-C and the remaining columns.

The operation of an OLTC distribution transformer can be enabled by double clicking on the SS subsystem as illustrated in Figure 3 which then gives the capability of tunning the relevant parameters for its operation.

After running the model for the desired duration, the simulation results are given in a structured format for a higher readability as illustrated in Figure 4. The *Bus* and *I* structured variables contain the RMS voltage and RMS current phasors of each system node respectively. For example Bus(5).signals.values contains the voltage information of node 5 where the first 4 columns correspond to the RMS voltage magnitudes of Va Vb Vc Vn and the remaining 4 columns to their phase angles. Similarly for I(5).signals.values for the current phasors of node 5. In case that a specific node is single-phased then the columns of the missing phases are filled with zeros. *Bus1gen* contains the power flow, voltage and current at the secondary substation as Pa Qa Pb Qb Pc Qc Va Vb Vc Ia Ib Ic. Finally, the *Load* structured variable contains the information of each load in a similar structure for three-phase loads as Bus1gen while for single-phase loads its structure is as P Q V I. Note that the voltage values in the *Load* variable are given as phase-to-neutral.

Note that the load profiles can be modified by modifying the set points in the *LC* variable and then overwriting the *network_parameters* mat file. If its necessary to modify the internal operation of the load model, then this can be done through the included library. All load models in the feeder are linked with the relevant library model such that any modification is automatically passed to all load models.

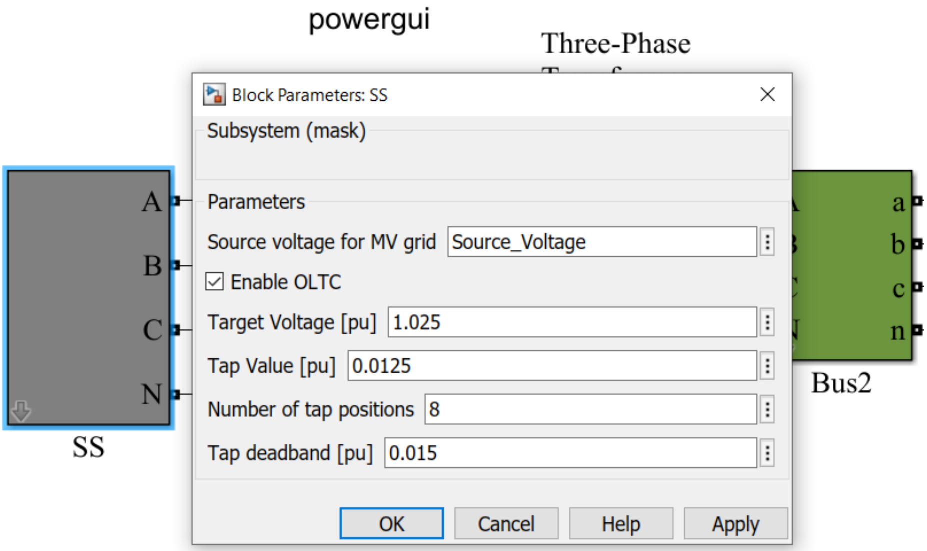

Figure 3: Enabling an OLTC distribution transformer

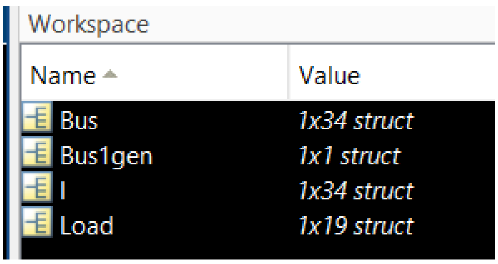

Figure 4: Simulation results

A2. DERs

PV Curtailment, Reactive Power Control and Battery Storage Systems

Besides the representative LV feeders, an example of how to use the models of several DERs is also included in the provided files. Figure 5 shows a system node with a load, a PV system, and a battery storage system. Figure 6 illustrates the additional parameters related with the operation of the PV and battery storage systems.

Setting up the PV systems: The normalized active power generation profile of the PV systems is given by the *PV* variable in the *network_parameters* mat file which is then scaled accordingly with the specified capacity of single phase and three phase PV systems. To enable static/dynamic curtailment and/or RPC for the PV systems the included library must be opened, unlocked and then the relevant models modified accordingly. This is done so that when many PV systems are considered their settings and operation can be easily modified. If different settings/operation is desired for some PV systems, then the link of these models with the library must be broken. By looking under the mask of the 3-ph

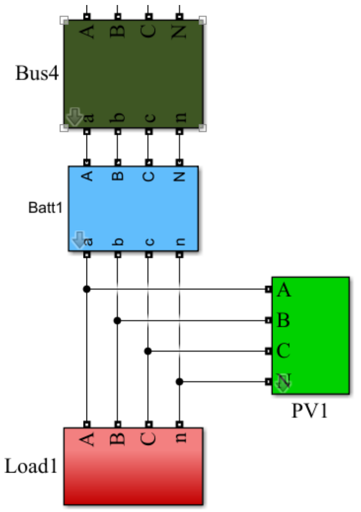

Figure 5: System node with load, a PV system, and a battery storage system

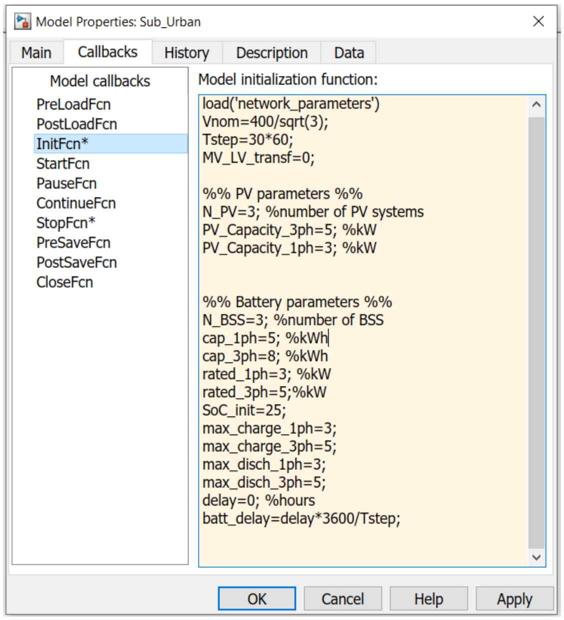

Figure 6: Model initialization with parameters for the PV and battery storage systems.

PV system in the library and then looking under the mask of the single-phase PV model for phase A (master model) and then opening the *Current calculation* subsystem the operation of all PVs (single-phase and three-phase) can be adjusted, see Figure 7. Here by commenting/uncommenting and connecting the right blocks the PV systems can be set up for static/dynamic curtailment and/or for different RPC schemes. The static curtailment is enabled by connecting it in series with the *Load_Profile* block and the percentage level of the curtailment can be set up by adjusting the upper saturation limit. To switch to dynamic curtailment the relevant block must be placed in series with the *Load_Profile* (the static curtailment must be removed). The settings for the dynamic curtailment can be adjusted by double clicking on the relevant block. In a similar fashion the desired RPC scheme can be selected and then its settings adjusted to the desired values. The operation of the dynamic curtailment and the meaning of each of its set point is illustrated in Figure 8 while Figure 9 shows the operation of the $cos\phi(P)$, $Q(V)$ and $cos\phi(P,V)$ RPC modes. After running the model all PV related data is stored in the *PV_Data* output variable.

Setting up the BSS: The BSS model operates in a self-consumption mode as illustrated in Figure 10. All tuneable parameters are given through the model initialization (Figure 6). The *delay* parameter specifies how many hours after a reverse power flow is detected the charging of the BSS is initiated. After the model execution, all BSS related data (charging/discharging power and SoC of each BSS) are stored in the *BSS_Data* output variable.

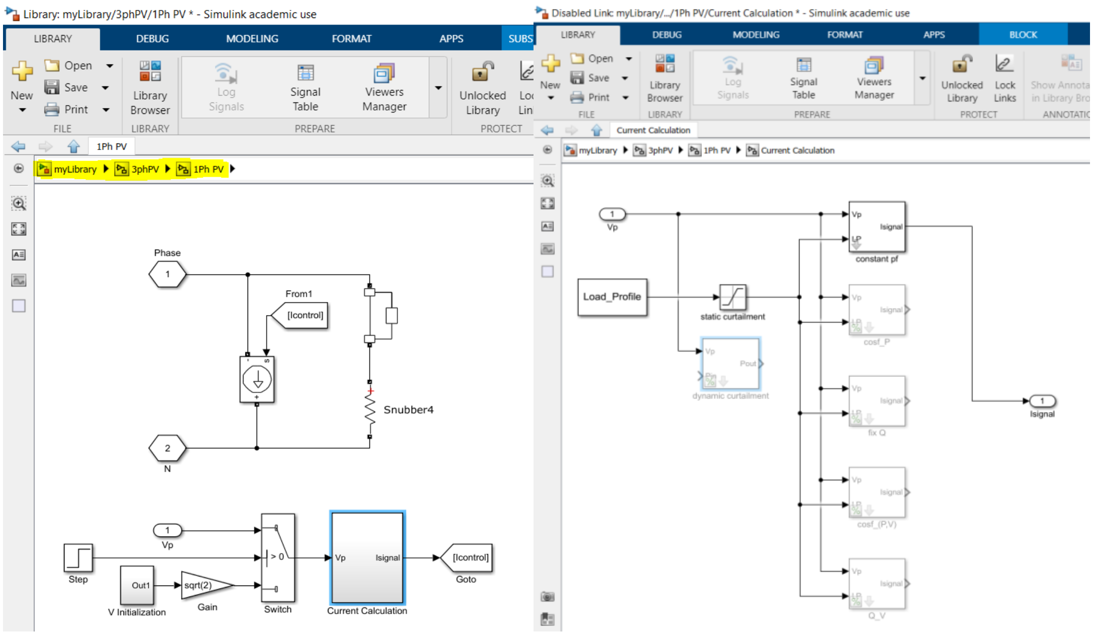

Figure 7: Setting up the PV systems

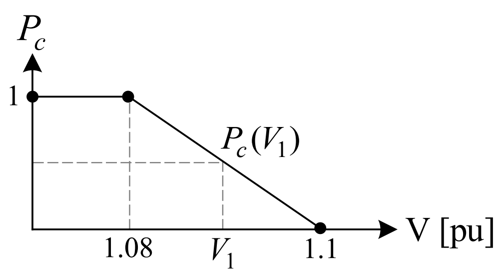

Figure 8: Dynamic PV curtailment based on a voltage droop.

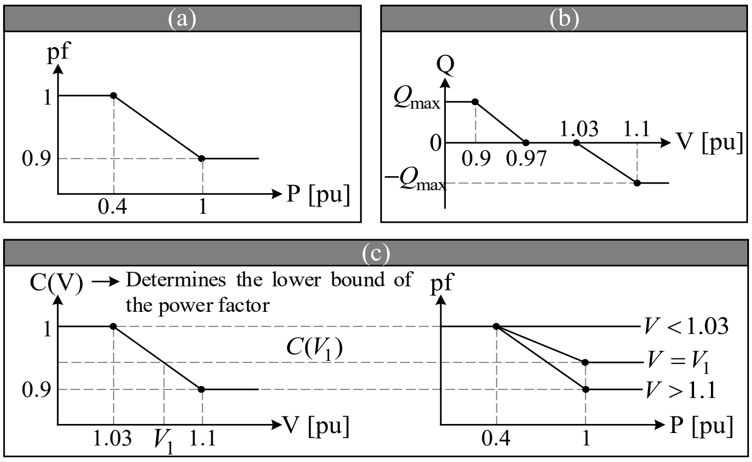

Figure 9: Operation of RPC modes: (a) $cos\phi(P)$, (b) $Q(V)$ and (c) $cos\phi(P,V)$.

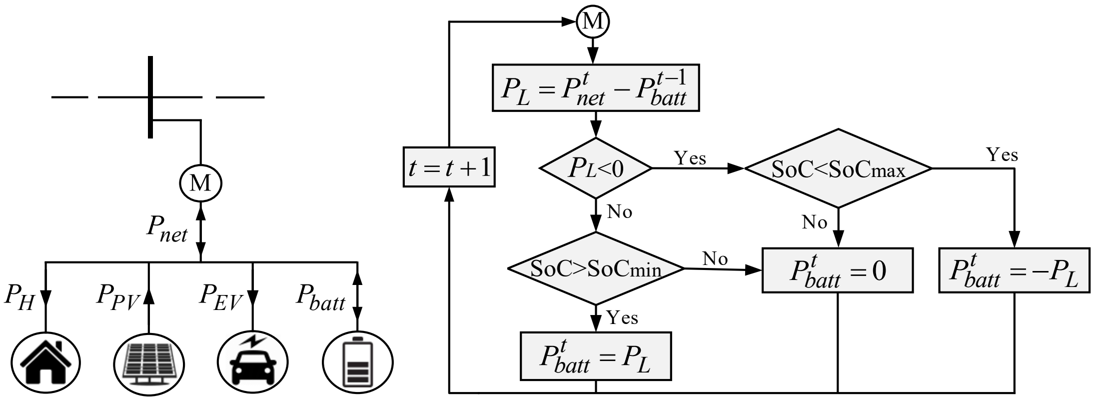

Figure 10: Operation of BSS in a self-consumption mode.

EV Charging

The urban system is utilized for illustrating how to set up and utilize the provided models for simulating a normal and smart charging mode for the considered EVs. Figure 11 shows the additional parameters that are relevant for this operation. *Tr_capacity* refers to the maximum loading limit on the transformer and is used in the smart charging mode, and *smart_charge* is used to enable/disable the smart charging mode. The EVs are placed in blocks, in this example there are in total 60 EVs divided in 2 blocks with 30 EVs in each block. The number of EVs in each block is defined by the *EV_num_**i*** parameter and how many EVs are connected in each phase within the block by the *Phase_**i*** parameter (i=block number). Note that when adding new E*V_Block*s their parameters must be initialized as shown in Figure 11 for the two existing blocks. Then the block properties of the new *EV_Block*s must be modified so that the correct parameters are assigned to the block, as shown in Figure 12.

Normal charging mode: In the normal charging mode (*smart_charge=0*) the EVs are essentially a passive load that follows a pre-determined load profile. These charging profiles are given in the *EV.mat* file and are generated through the *EVs_Profile.m* script. In this script there are several tuneable parameters for generating passive charging load profiles such as battery capacity, driving range, expected driving distances, etc. For more information about the generation of these charging load profiles see [1].

[1] A. Kotsonias, L. Hadjidemetriou, E. Kyriakides and Y. Ioannou, "Operation of a low voltage distribution grid in Cyprus and the impact of photovoltaics and electric vehicles," in *Proc. IEEE PES ISGT - Europe*, Bucharest, Romania, 2019, pp. 1-5

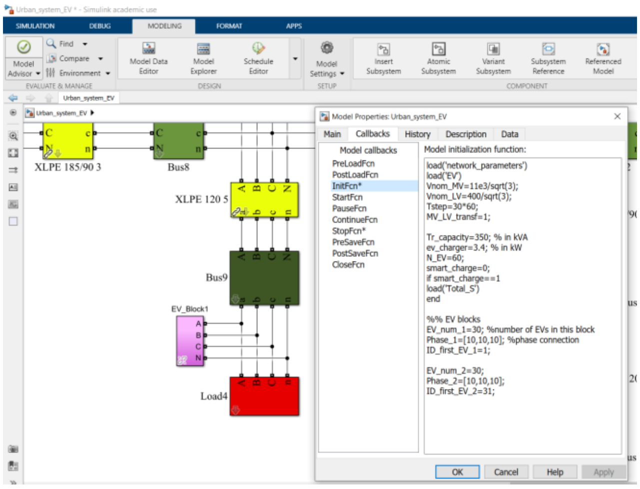

Figure 11: Model initialization for EV charging.

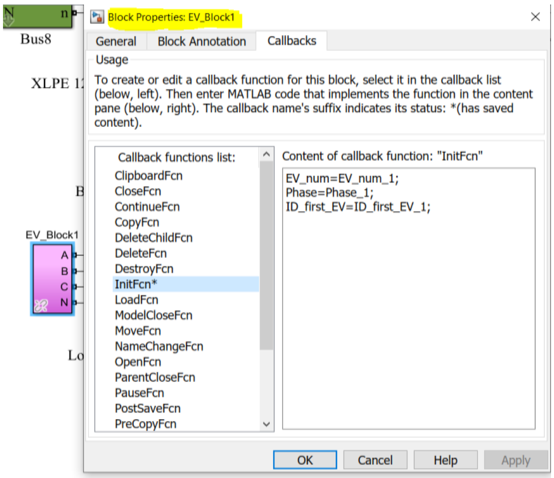

Figure 12: EV Block parameters.

Smart charging mode: For the smart charging mode to operate, first the model must be run without any EVs so that the total conventional loading on the transformer can be computed. The EVs within the model are easily removed by simply defining *N_EVs=0* in the model initialization window. When the simulation with zero EVs finishes, the total conventional loading can be calculated by using the *compute_S* Matlab function. Then the output variable of this function (*Total_S*) must be saved so that it can be loaded in the next simulation where the smart charging will be enabled. To enable and run the smart charging mode, first the *N_EVs* is changed back to the correct value, *smart_charge* is put equal to 1 and the *EV_Control* block (below the SS) is uncommented. Having the total conventional load and the passive charging profiles from the EVs, the smart mode determines how many EVs can charge in each time step without the total loading on transformer exceeding the defined limit. In case that there is not enough capacity to satisfy all charging demands then priority is given to the EVs with the lowest SoC. Once the simulation finishes, the charging demand signal, SoC and charging profile of each EV are stored in the *EV_Data* output variable.

Appendix B – LV Feeder Data

B1. Network topology of representative LV feeders

Table I: Network topology of urban system

From Bus	To Bus	Line Length [km]	Line Type	Phases
1	2	0	Transformer	ABC
2	3	0.06	XLPE_185	ABC
3	4	0.025	XLPE_120	ABC
3	5	0.025	XLPE_120	ABC
3	6	0.06	XLPE_185	ABC
6	7	0.025	XLPE_120	ABC
6	8	0.06	XLPE_185	ABC
8	9	0.025	XLPE_120	ABC
8	10	0.025	XLPE_120	ABC
8	11	0.025	XLPE_120	ABC
8	12	0.06	XLPE_185	ABC
12	13	0.025	XLPE_120	ABC
12	14	0.06	XLPE_185	ABC
14	15	0.025	XLPE_120	ABC
2	16	0.07	XLPE_185	ABC
16	17	0.025	XLPE_120	ABC
16	18	0.035	XLPE_185	ABC
18	19	0.025	XLPE_120	ABC
18	20	0.025	XLPE_120	ABC
18	21	0.035	XLPE_185	ABC
21	22	0.025	XLPE_120	ABC
18	23	0.035	XLPE_185	ABC
23	24	0.025	XLPE_120	ABC
2	25	0.07	XLPE_185	ABC
25	26	0.025	XLPE_120	ABC
25	27	0.035	XLPE_185	ABC
27	28	0.025	XLPE_120	ABC
27	29	0.025	XLPE_120	ABC
27	30	0.035	XLPE_185	ABC
30	31	0.025	XLPE_120	ABC
30	32	0.035	XLPE_185	ABC
32	33	0.025	XLPE_120	ABC
32	34	0.025	XLPE_120	ABC

Table II: Network topology of sub-urban system

From Bus	To Bus	Line Length [km]	Line Type	Phases
1	2	0	Transformer	ABC
2	3	0.0630	XLPE_185/90	ABC
3	4	0.0072	XLPE_185/90	ABC
3	5	0.0792	XLPE_185/90	ABC
5	6	0.0089	4x22	ABC
5	7	0.0089	2x22	A
5	8	0.0081	2x22	C
5	9	0.0367	4x100	ABC
9	10	0.0029	2x16	C
9	11	0.0093	2x22	B
9	12	0.0132	2x22	B
9	13	0.0340	2x22	A
9	14	0.0256	4x100	ABC
14	15	0.0046	2x22	A
14	16	0.0240	4x100	ABC
16	17	0.0069	2x22	C
16	18	0.0128	2x22	C
16	19	0.0079	2x22	C
16	20	0.0337	4x100	ABC
20	21	0.0050	2x22	C
20	22	0.0206	4x100	ABC
22	23	0.0080	2x22	C
22	24	0.0031	2x22	A
22	25	0.0231	4x100	ABC
25	26	0.0126	4x16	ABC
25	27	0.0101	4x16	ABC
25	28	0.0161	2x22	C
25	29	0.0075	2x22	B
16	30	0.0344	4x100	ABC
30	31	0.0389	4x100	ABC
31	32	0.0063	2x22	B
31	33	0.0212	4x100	ABC
33	34	0.0263	2x22	B
33	35	0.0065	2x22	A
30	36	0.0008	2x16	C
30	37	0.0079	2x22	A
30	38	0.0158	2x22	C
30	39	0.0250	4x100	ABC
39	40	0.0064	4x22	ABC
39	41	0.0132	2x22	C
39	42	0.0165	2x22	B
39	43	0.0241	4x100	ABC
43	44	0.0376	4x100	ABC
44	45	0.0068	4x22	ABC
43	46	0.0199	4x100	ABC
46	47	0.0071	2x22	C
46	48	0.0046	2x22	B
46	49	0.0274	4x100	ABC
49	50	0.0071	4x22	ABC
49	51	0.0065	2x22	A
49	52	0.0213	4x100	ABC
52	53	0.0069	2x22	C
52	54	0.0065	2x22	A
52	55	0.0318	4x50	ABC
55	56	0.0168	2x22	C
55	57	0.0081	2x22	C
55	58	0.0416	4x50	ABC
58	59	0.0040	2x22	B
58	60	0.0086	2x22	A
58	61	0.0364	2x22	B
58	62	0.0239	4x50	ABC
62	63	0.0186	4x50	ABC
63	64	0.0020	4x16	ABC
63	65	0.0090	2x22	C
63	66	0.0147	4x50	ABC
62	67	0.0081	2x22	A
62	68	0.0144	2x22	C
62	69	0.0468	2x22	B
62	70	0.0329	4x100	ABC
70	71	0.0072	2x22	A
70	72	0.0117	2x22	B
70	73	0.0054	2x22	C
70	74	0.0072	4x22	ABC

Table III: Network topology of rural system

From Bus	To Bus	Line Length [km]	Line Type	Phases
1	2	0	Transformer	ABC
2	3	0.07325	4X100	ABC
3	4	0.015	4X22	ABC
3	5	0.05775	4X100	ABC
5	6	0.015	2X22	C
5	7	0.015	2X22	A
5	8	0.05775	4X100	ABC
8	9	0.015	4X22	ABC
8	10	0.015	4X22	ABC
3	11	0.106625	4X100	ABC
11	12	0.015	2X22	C
11	13	0.1033125	4X100	ABC
13	14	0.015	2X22	C
13	15	0.015	2X22	B
13	16	0.0833125	4X100	ABC
16	17	0.05775	4X100	ABC
17	18	0.015	2X22	A
17	19	0.05775	4X100	ABC
19	20	0.015	2X22	A
16	21	0.015	2X22	B
16	22	0.16325	4X100	ABC
22	23	0.015	2X22	B
22	24	0.1775	4X50	ABC
24	25	0.015	2X22	A
24	26	0.015	2X22	C
22	27	0.1825	4X50	ABC
27	28	0.015	2X22	C
27	29	0.015	2X22	ABC
27	30	0.145375	4X50	ABC
30	31	0.075375	4X50	ABC
31	32	0.015	2X22	C
31	33	0.08775	4X50	ABC
33	34	0.015	2X22	B
33	35	0.07775	4X50	ABC
35	36	0.015	2X22	ABC
36	37	0.015	2X22	A

B2. Distribution lines/cables parameters

Underground Cables:

The general geometry that is used for the computation of the impedance matrix of the underground cables is presented in Figure 13. The series and mutual impedances of the conductors are calculated with equations (1)-(2) while the phase-ground capacitance with equation (3) [2]. The computed RLC parameter matrices of the cables that are considered in the representative LV feeders are given in Tables IV-V.

$$z_{ii} = r_i + 0.0493 + j0.1446 \log\left(\frac{930.92}{GMR_i}\right) \Omega/km \quad (1)$$

$$z_{ij} = 0.0493 + j0.1446 \log\left(\frac{930.92}{GMD}\right) \Omega/km \quad (2)$$

$$C_{ig} = 0.0241 \frac{\varepsilon_r}{\log(D_{xi}/d_{xi})} \mu F/km \quad (3)$$

where:

GMD is the Geometric Mean Distance between the conductors,
D_{xi} is the external diameter between the phase and outer sheath,
d_{xi} is the internal diameter between the phase and outer sheath,
ε_r is the relative permittivity of the insulator.

The circuit used for modeling the cable operation is illustrated in Figure 14.

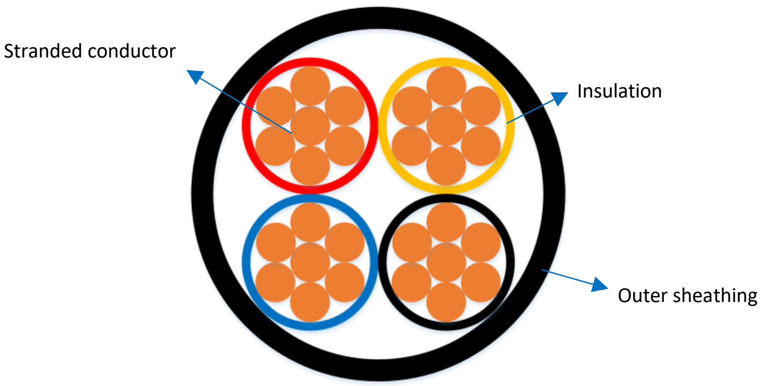

Figure 13: Geometry of underground cables.

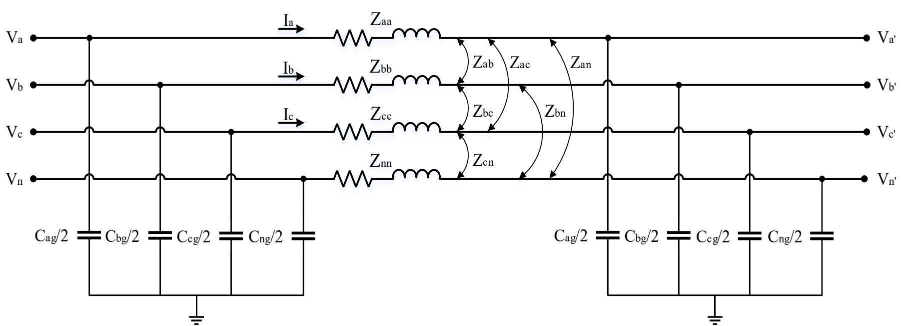

Figure 14: Model for underground cables.

[2] W. H. Kersting, *Distribution System Modeling and Analysis,* CRC Press, Boca Raton, FL, 2007.

Table IV: Impedance Matrix of XLPE 185/90 mm^2 cable

R (Ω/km)				L (mH/km)				C (μF/km)
0.1926	0.0493	0.0493	0.0493	2.36	2.12	2.12	2.12	0.77
0.0493	0.1926	0.0493	0.0493	2.12	2.36	2.12	2.12	0.77
0.0493	0.0493	0.1926	0.0493	2.12	2.12	2.36	2.12	0.77
0.0493	0.0493	0.0493	0.3438	2.12	2.12	2.12	2.44	0.78

Table V: Impedance Matrix of XLPE 120/90 mm^2 cable

R (Ω/km)				L (mH/km)				C (μF/km)
0.2702	0.0493	0.0493	0.0493	2.41	2.16	2.16	2.16	0.82
0.0493	0.2702	0.0493	0.0493	2.16	2.41	2.16	2.16	0.82
0.0493	0.0493	0.2702	0.0493	2.16	2.16	2.41	2.16	0.82
0.0493	0.0493	0.0493	0.3438	2.16	2.16	2.16	2.44	0.78

Distribution OH Lines:

Due to the highly unbalance operation of the low voltage feeders, the single-phase equivalent model is not suitable and thus, the full model of each component must be used to evaluate the operation of each phase according to loading conditions and considering the neutral effect as well. Therefore, both series and mutual impedances of the conductors of a distribution line must be calculated. For an overhead line in a low voltage feeder, the capacitance to ground is neglected as its effect is insignificant due to the short distances, low voltage level as well as due to the long physical distance (height) from the ground. In Figure 15 a typical 4-wire distribution line is illustrated with the series (Z_{ii}) and mutual (Z_{ij}) impedances between the conductors visible. These impedances are calculated with the use of the Carson's equations (4)-(5) as they offer the most accurate representation [3],

$$z_{ii} = r_i + 0.0493 + j0.0628\left(ln\frac{0.3048}{GMR_i} + 8.0251\right)\Omega/km \tag{4}$$

$$z_{ij} = 0.0493 + j0.0628\left(ln\frac{0.3048}{D_{ij}} + 8.0251\right)\Omega/km \tag{5}$$

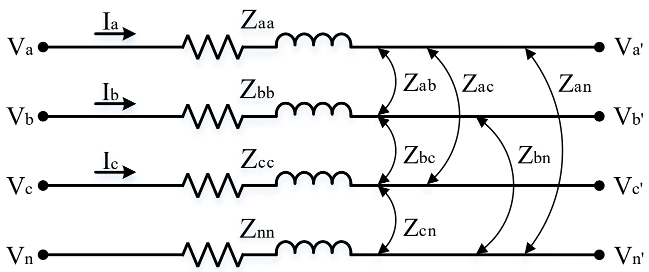

Figure 15: A four-wire distribution line.

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[3] W. H. Kersting and R. K. Green, "The application of Carson's equation to the steady-state analysis of distribution feeders," in *IEEE Power Systems Conference and Exposition,* Phoenix, AZ, USA, 2011, pp. 1-6.

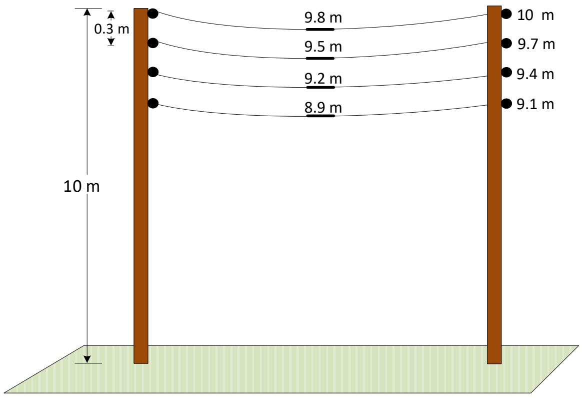

Figure 16: Geometry of over-head distribution lines.

where:
z_{ii} is the self-impedance of conductor i (Ω/km),
z_{ij} is the mutual impedance between conductor i and j (Ω/km),
r_i is the ac resistance of conductor i (Ω),
GMR_i is the Geometric Mean Radius of conductor i (m),
D_{ij} is the distance between conductor i and j (m).

From the above equations it can be concluded that the series impedance of a conductor depends only on its characteristics (ac resistance and GMR) while the mutual impedance between conductors depends only on the geometry of the distribution line. The geometry for the overhead distribution lines that is used in the calculations is illustrated in Figure 16. In Table VI the full impedance matrix of the 4x100 mm^2 line is shown where the diagonal elements of this matrix correspond to the series impedances (Zaa, Zbb, Zcc and Znn) while the off-diagonal elements correspond to the mutual impedances between the conductors of each phase. If all overhead lines have the same geometry, the off-diagonal elements of their impedance matrix are identical and only the diagonal elements differ. In Table VII, the diagonal elements of the remaining conductors are presented.

Table VI: Impedance Matrix of 4x100 mm^2 OH Aluminum Line

R (Ω/km)				L (mH/km)			
0.3157	0.0482	0.0482	0.0483	2.50	1.61	1.47	1.39
0.0482	0.3157	0.0483	0.0483	1.61	2.50	1.61	1.47
0.0482	0.0483	0.3157	0.0483	1.47	1.61	2.50	1.61
0.0483	0.0483	0.0483	0.3157	1.39	1.47	1.61	2.50

Table VII: Series impedance of remaining conductors

Overhead line	R (Ω/km)	L (mH/km)
50 mm^2	0.5901	2.51
22 mm^2	1.2752	2.59
16 mm^2	1.9582	2.63