



HiPerDNO

High Performance Computing Technologies for Smart Distribution Network Operation

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Executive Summary

The purpose of the HiPerDNO project is to develop scalable HPC solutions for smart distribution network operation. The smart operation of the MV network is based on the results of a state estimation function, which must be able to treat large zones of MV networks. This document presents the DSE (Distribution State Estimation) tool developed in Matlab by EDF R&D. This tool allows the user to:

- Load an MV network described in an “m” (Matlab) file format,
- Define the zone of the network on which the state estimation is run (the zonal approach described in D.2.1.2 can be applied),
- Place new sensors and define their errors,
- Run the WLS (Weighted Least Square) DSE algorithm,
- Analyze DSE results in a numerical and a graphical way.

The structure of the developed tool is summarized in Figure 1. This structure facilitates the change of the DSE algorithm to introduce a different one (for example the PSO approach described in D.2.1.1).

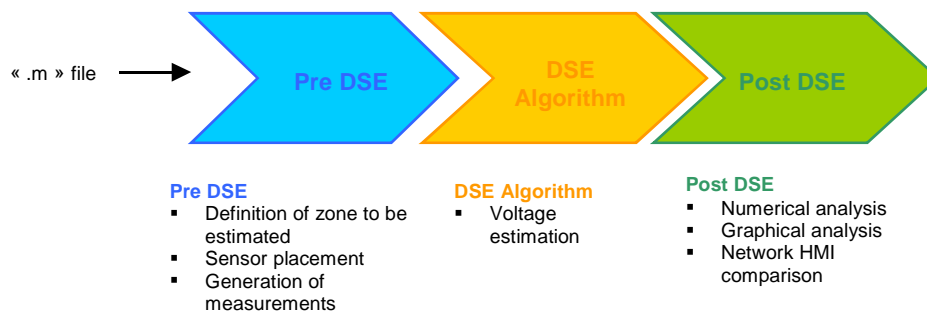


Figure 1: Architecture of DSE tool

The « Pre DSE » block uses the “m” file description of the network to generate the inputs used by the DSE algorithms. In this phase, the real state of the network is defined with a load flow calculation, the zone that is going to be estimated is chosen and the sensors are placed in the network (the measurement noise is also simulated).

Once the DSE inputs are generated by the “Pre DSE”, the “DSE algorithm” is run and estimated voltages are obtained as outputs. The algorithm inside this block can be changed by another as the PSO if the inputs of both algorithms are identical.

Finally, the “Post DSE” block analyzes the estimation results. These analyses can be numerical or graphical and results can also be integrated in the network HMI.

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Abstract	This document presents the DSE software tool developed by EDF R&D. This tool, developed in Matlab, allows the user to simulate the real state of the network, define a study zone, place new sensors and define their errors, run DSE algorithms and analyze estimated variables.			
Keywords	Distribution State Estimation, Scalability, DMS, Zonal approach, software			

Table of Contents

1. INTRODUCTION	6
2. Principles	7
2.1. Network simulator.....	7
2.1.1. Use of load flow results	8
2.2. Selection of the estimated area	8
2.2.1. Treatment of zone limits	9
2.2.2. Electrical representation of the zone	10
2.3. Measurements.....	10
2.3.1. Sensors.....	10
2.3.2. Pseudo-measurements.....	13
2.4. Description of the options for DSE calculation.....	15
2.4.1. Calculation options.....	15
2.4.2. Transferred information to DSE.....	16
2.5. Results analysis.....	16
2.5.1. Estimated variables	16
2.5.2. Errors of the estimations	17
2.5.3. Numerical results.....	18
2.5.4. Graphical results.....	19
2.5.5. DSE results in the network HMI.....	20
3. How to.....	21
3.1. Install DSE tool.....	21
3.2. Choose and treat a network.....	22
3.2.1. Load the network.....	22
3.2.2. Select load curve for load/generator	26
3.2.3. Define a new load curve	27
3.2.4. Define the instant of load flow run for P(t)	27
3.2.5. Change the state of switches.....	28
3.3. Select the estimated area.....	29
3.3.1. Zone between remote controlled switches.....	29
3.3.2. Zone downstream a node.....	30
3.3.3. User's definition zone.....	31
3.3.4. MV feeder with the zonal approach.....	32

HiPerDNO

3.4. Choose date for DSE	34
3.4.1. Load flow at Pmax	34
3.4.2. Load flow at P(t)	35
3.5. Sensors placement in the MV network	36
3.5.1. Define sensors configuration.....	36
3.5.2. Change mean value for pseudo-measurements	42
3.5.3. View sensors' position	43
3.5.4. Reset sensors information.....	43
3.6. Run the DES algorithm.....	44
3.6.1. Create noise measurements.....	44
3.6.2. Start the DSE calculation	44
3.7. Analysis results	45
3.7.1. Numerical analysis.....	45
3.7.2. Graphical analysis: ellipses	46
3.7.3. DSE results in the network HMI.....	46
3.7.4. Voltage profiles.....	47
4. Case study.....	48
4.1. User's definition zone.....	48
4.2. Zonal approach	53
5. Conclusion	58
6. Bibliography.....	59
7. Appendices	60
7.1. Appendix 1. Structure of ".m" files.....	60
7.2. Appendix 2. Inputs of DSE algorithm.....	60
7.2.1. Matrice_Y_perunit.....	61
7.2.2. data_from_donnees	62
7.2.3. Grandeur_VIPQ.....	64
7.2.4. Vecteur_Mesure_Z.....	65

1. INTRODUCTION

The purpose of the HiPerDNO project is to develop a new generation of distribution network management systems using near to real time High Performance Computing (HPC) solutions. This new generation of distribution network management systems uses DSE (Distribution State Estimation) algorithms to estimate the state of the network in near to real time (1-3 minutes) and provide it to new DMS functionalities. To determine the accuracy of developed DSE algorithms, it is necessary to run different case studies with different sensors configurations and for different networks.

To facilitate these case studies a Matlab tool has been developed by EDF R&D. This tool allows the user to:

- Load an MV network described in an “m” (Matlab) file format,
- Define the zone of the network on which the state estimation is run (the zonal approach described in D.2.1.2 can be applied),
- Place new sensors and define their errors,
- Run the WLS (Weighted Least Square) DSE algorithm,
- Analyze DSE results in a numerical and a graphical way.

The structure of the developed tool is summarized in Figure 2. This structure facilitates the change of the DSE algorithm to introduce a different one (for example the PSO approach described in D.2.1.1).

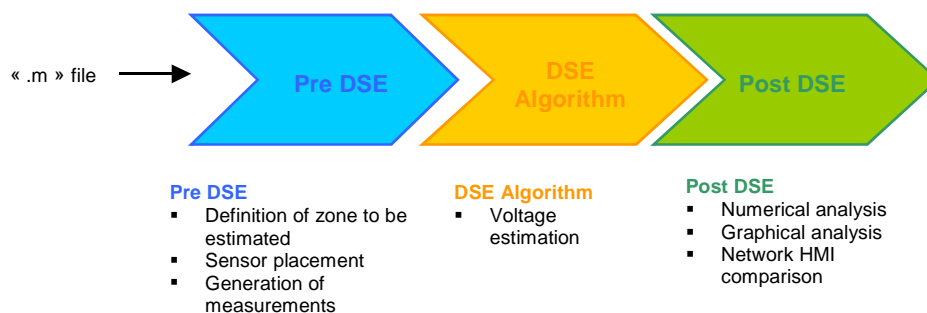


Figure 2: Architecture of MV network DSE tool

The « Pre DSE » block uses the “m” file description of the network to generate the inputs used by the DSE algorithms. In this phase, the real state of the network is defined with a load flow calculation, the zone that is going to be estimated is chosen and the sensors are placed in the network (the measurement noise is also simulated).

Once the DSE inputs are generated by the “Pre DSE”, the “DSE algorithm” is run and estimated voltages are obtained as outputs. The algorithm inside this block can be changed by another as the PSO if the inputs of both algorithms are identical.

Finally, the “Post DSE” block analyzes the estimation results. These analyses can be numerical or graphical and results can also be integrated in the network HMI.

2. PRINCIPLES

This chapter presents the most important principles used in the DSE software tool. These principles allow the user to define the network zone where the DSE is run, to place new sensors and build their corresponding measurement noise, run the algorithm and analyze the results.

2.1. NETWORK SIMULATOR

As no real time information is available, and to be able to test different network configurations, a distribution network simulator has been developed to define the real state of the network. This real state of the network is going to be use by the DSE tool to:

- Create noisy measurements,
- Determine the error of the estimated variables.

This network simulator has been developed in Matlab and is based on an open source load flow program called PSAT [1]. This load flow program is completed with Matlab functions to reproduce different regulations already existing in the field. These regulations are: on-load tap changer for HV/MV transformers, Capacitors banks (connected to MV busbars) and Distributed Generation models (use of load curves, function diagrams, local regulation for reactive power...).

For needs of the DSE tool, three states of the networks are calculated:

1. Pmax: all loads and generators consume/produce their maximum power. This state can be used to generate noisy measurements of real sensors and for load models (if it is defined as the real state of the network).
2. Pmean: all loads and generators are considered to consume/produce their mean power. For the loads, the same ratio (define by user when loading the network) is used. This ratio is defined by:

$k(\%) = \frac{h}{8760} \cdot 100$ where h is considered as the number of hours in which the load can be considered as being at its maximum power.

For generators, it is possible to define a different ratio per generator (the same ratio as for loads is proposed to user by default). This state of the network is only used for load models.

3. P(t) : each load/ generator has an active and reactive power calculated for the instant t with the following expressions:

$$P(t) = P_{\max} * Coef_P_{pu\ load\ courbe}(t) \qquad Q(t) = Q_{\max} * Coef_Q_{pu\ load\ courbe}(t)$$

with $Coef_P_{pu\ load\ courbe}(t)$: the value of the load curve (of the load) for active power at the instant t and
 $Coef_Q_{pu\ load\ courbe}(t)$: the value of the load curve (of the load) for reactive power at the instant t

This state of the network can be used to define the noise of measurements of real sensors and load models (if it is defined as the real state of the network).

Once the network has been loaded, it is then no longer possible to change load curves or to change the ratios used to define the mean state of the network.

2.1.1. Use of load flow results

In the case of the DSE tool, the results of load flows are used to create noisy measurements and pseudo-measurements. To do so, the following results are saved in order to be used in a later calculation:

- For each node of the network, the following results are saved:
 - Magnitude and phase of the voltage,
 - Active and reactive power produced/ consumed (all loads/ generators connected to the same node are aggregated),
 - Current entering the node (this value is calculated with the admittance matrix and voltage vector [magnitudes and phases]).
- For each line/cable of the network, the following results are saved:
 - Apparent, active and reactive power flowing from node N1 to N2,
 - Apparent, active and reactive power flowing from node N2 to N1,
 - Current flowing through the MV line/cable.

Two options are proposed to the user:

- Direct load flow results: all results directly available from PSAT variables are directly gathered and the other electrical magnitudes are calculated with these results.
- Recalculated load flow results: only voltages magnitudes and phases are directly gathered from PSAT variables and all other results are recalculated using these voltages and the admittance matrix (Y).

2.2. SELECTION OF THE ESTIMATED AREA

To apply DSE, it is necessary to define in which zone the algorithm is applied as the whole network is not estimated at the same time. A zone is defined by:

- MV lines and cables in the zone and their electrical characteristics (Resistance, Reactance, Capacity and Length),
- Nodes in the zone and type of load connected to each node,
- Active and reactive power of each load,
- Slack bus,
- Zone limits.

Four different ways of defining the network zone are proposed to the user. These choices are:

- **Zone between remote controlled switches:** the DSE tool divides the network into different zones between remote controlled switches (these switches are not included) and the user can choose the desired zone. If the analyzed network has no remote controlled switches this option does not work.
- **Zone downstream a given node:** the DSE tool proposes several nodes and the zone is considered as all elements downstream the chosen node.
- **User's defined zone:** the DSE tool asks the user to define zone limits, a node in the zone and the node to be considered as the slack bus of the zone.

- **MV feeder with the zonal approach:** the DSE tool asks the user to choose an MV feeder and this MV feeder is divided into zones between remote controlled switches. In this case, switches are included in the estimated zones. If the analyzed network has no remote controlled switches this option does not work.

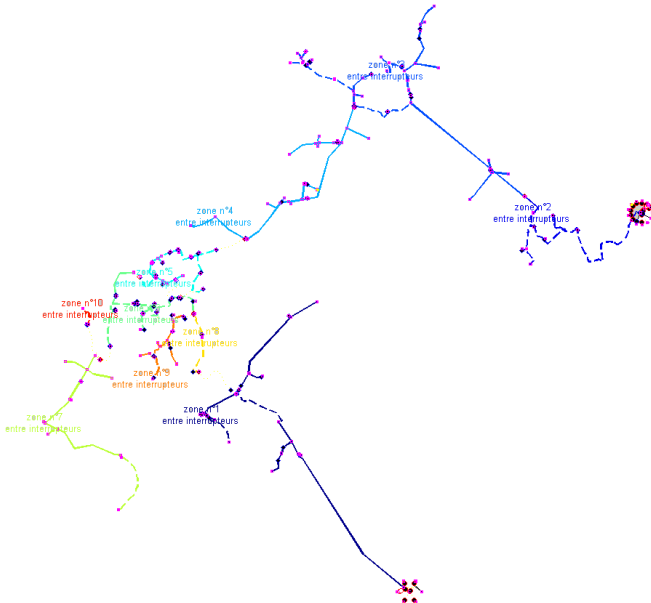


Figure 3: Zone between remote controlled switches

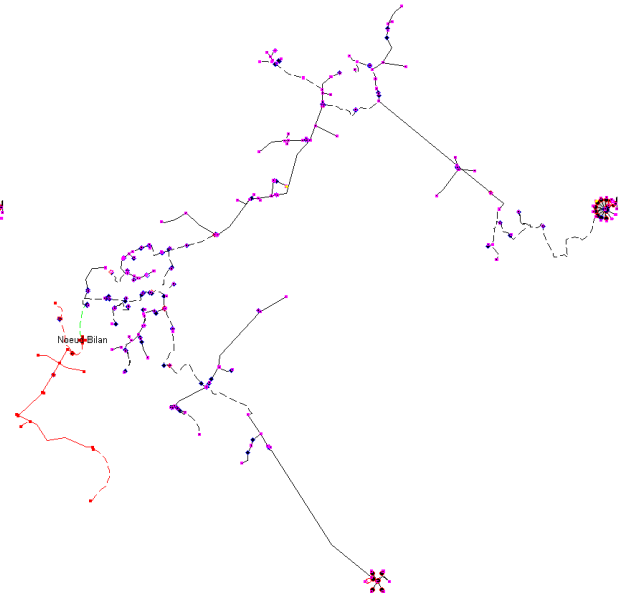


Figure 4: Zone downstream a node

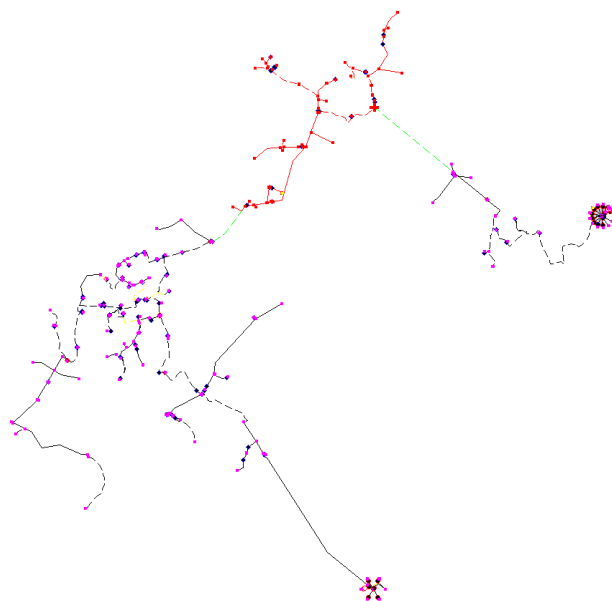


Figure 5: User's defined zone

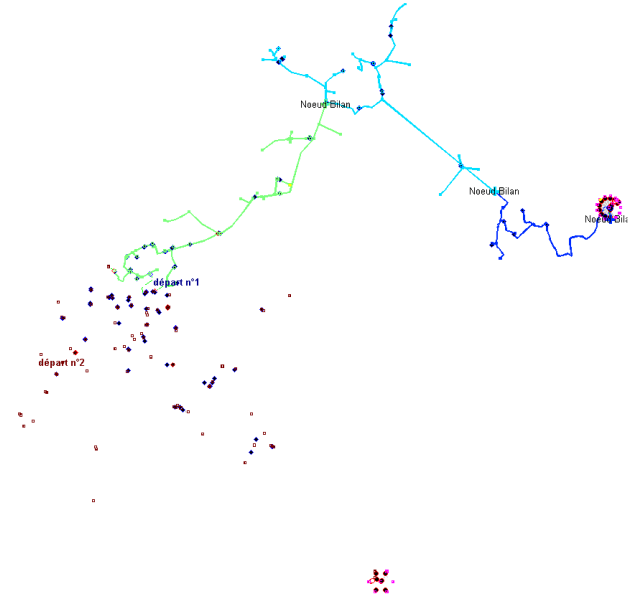


Figure 6: MV feeder with the zonal approach

For all of these options some important concepts as zone limits and the electric representation of the zone are described in the following paragraphs.

2.2.1. Treatment of zone limits

It is important to know how zone limits are treated and what elements are always considered as zone limits and are never included into the zone. These elements are:

- Lines/cables in primary substations,
- Open switches,
- Lines/cables directly connected to a transformer

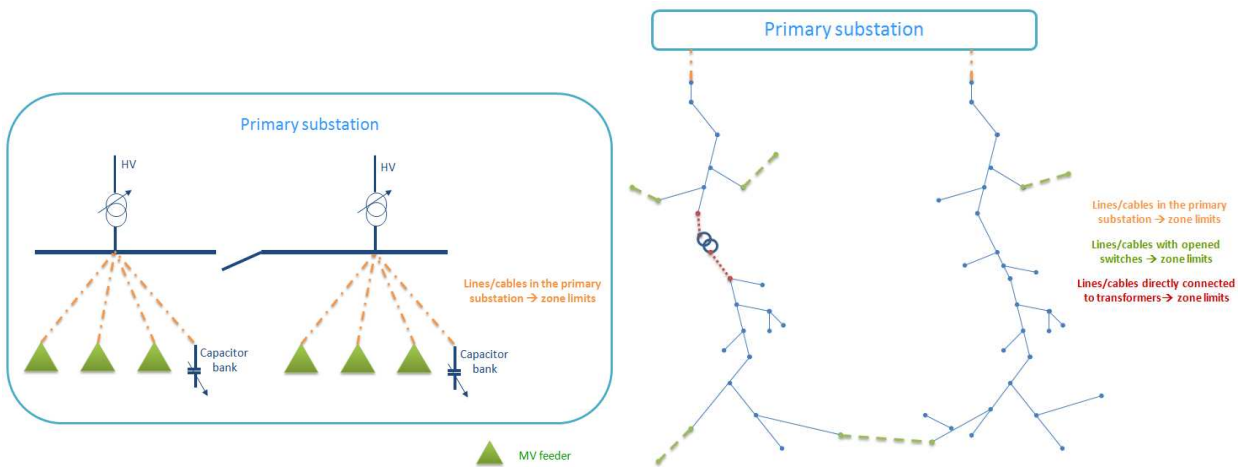


Figure 7: Lines/cables considered as zone limits

Each zone limit is firstly treated as a node with a connected load as if the border line/cable is closed and power flows out of the zone. So it is necessary to define a real sensor or a load model in these nodes in a first treatment. Once noisy measurements are built, and if there is no power flowing out of the zone by this border, this sensor or load model will be removed.

If one or several loads are directly connected to the border node, an aggregation of all these loads is performed if a load model is allocated at this node (§2.3.1.5 and §2.3.2.4).

2.2.2. Electrical representation of the zone

The electrical characteristics of the zone are defined through the admittance matrix $[Y]$. This matrix is a symmetric matrix: in distribution networks this matrix is quite sparse. The admittances in the diagonal $Y(N1,N1)$ of the matrix are called self-admittances at the nodes and are equal to the sum of all admittances of lines/cables connected at the node. The other admittances $Y(N1,N2)$ are called mutual admittances of the nodes and each one is equal to minus the sum of admittances of lines/cables directly connected between both nodes. Once this matrix is calculated, it is possible to calculate the current injected/ consumed at each node having voltages magnitudes and phases as input.

$$\underline{I}_{injected / consumed} = [Y] \cdot \underline{V}_{node}$$

2.3. MEASUREMENTS

Near to real-time DSE algorithms use the information of real sensors and pseudo-measurements as well as the network topology to determine the real state of the network. In this paragraph the definition of a real sensors and pseudo-measurements in the DSE software tool are described.

2.3.1. Sensors

A sensor is a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument. As there is no real information coming from existing sensors in the

network, the noisy measurements have been created using the considered real values (obtained with the load flow) with an error.

2.3.1.1. Sensors type

The developed DSE tool can manage different sensors types. The available sensors types are different for different elements in the network. Sensors measuring: voltage magnitude, voltage phase, active power injection and reactive power injection can be associated to a node. Sensors measuring current flow, active and reactive power flow can be associated to an MV feeder.

2.3.1.2. Information related to sensors

For each sensor, different information has to be stored:

- Network element: reference to the network element which electrical magnitude is measured. For sensors associated to lines/cables, the end (node) at which the sensor is placed has to be memorized¹.
- Type: electrical magnitude measured by the sensor.
- Accuracy: information regarding the accuracy of the sensor.
- Error model: as sensors' noise is generated by the DSE software tool, it is necessary to know the error distribution of the sensor in order to generate the corresponding noise. At the moment of writing this document, only a Gaussian error has been integrated.

2.3.1.3. Measurement noise: Gaussian model

For the moment the DSE software tool takes only into account Gaussian errors. The measured value is represented as a Gaussian distribution $N(\mu, \sigma)$ with two parameters:

- μ : mean value,
- σ : standard deviation.

For real sensors no bias is considered so the mean value is considered as the real value obtained with the network simulator. To define the standard deviation, the real value and the percent of error of the sensor (accuracy) are used.

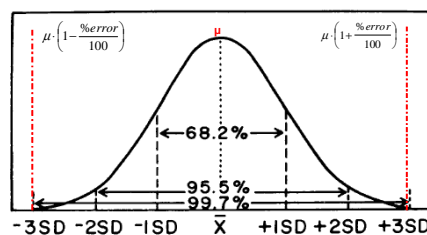


Figure 8: Gaussian model of errors

The standard deviation is calculated considering that the error of the sensor has a probability of 99.7% of being smaller than the percent of error defined for the sensor.

¹ This information is important because the sign of the flow is going to be different depending on the end of the line/cable at which the sensor is placed and losses will not always be integrated in the measured value.

$$\sigma = \frac{\% \text{ error of the sensor} \cdot \text{real value}}{3 \cdot 100}$$

Once the mean value and the standard deviation have been calculated, it is possible to calculate the measured value:

$$\text{measured value} = \left(\text{real value} + \underbrace{\sigma \cdot N(0,1)}_{\text{error}} \right)^2$$

If one of the measurements is equal to zero, several solutions have been developed as this zero value cannot be treated by the DSE algorithm. In our case, and as we considered no transmission errors, only active and reactive power injections and flows in lines/cables can be equal to zero. If the active or reactive powers of one node/line/cable are equal to zero, two options exist:

- Both measurements (active and reactive power) are equal to zero. In this case, both measurements are removed and the node is considered as a virtual node.
- Only one of the measurements (active or reactive power) is equal to zero. In this case, the measurement is kept but the standard deviation associated to this zero measurement is equal to the active or reactive power non-zero measurement standard deviation.

If the current flowing through a line/cable is equal to zero, this measurement is removed.

2.3.1.4. Initial sensors configuration

A default sensors configuration is proposed to the user. If no zonal approach has been requested, this default configuration is:

- PQV sensor at the slack bus of the zone,
- PQ pseudo-measurements for all loads and border nodes.

If a zonal approach has been requested, the default sensor configuration depends on the approach chosen for the calculations (cf deliverable D.2.1.2 for more details):

- Serial approach: a PQV sensor is placed at the beginning of the MV feeder and pseudo-measurements at all loads.
- Parallel approach: a PQV sensor is placed at the beginning of each zone and pseudo-measurements at all loads. PQ sensors at the beginning of the zones are sensors measuring power flowing through the section of the network.

One can add more sensors or change the characteristics of sensors after this initialization.

2.3.1.5. Load sensors on border nodes

As explained on §2.2.1, all loads connected to the same border node are aggregated. This aggregation takes also into account the power flow going out of the zone through the border line/cable. In the case of border node with a PQ sensor, this sensor considers the aggregated load as the real value and the defined percentage of error as the error that has to be applied to the aggregated load.

² N(0,1) is a Gaussian distribution centered on 0 and with a standard deviation of 1. In the tool it is obtained with the “randn” instruction of Matlab.

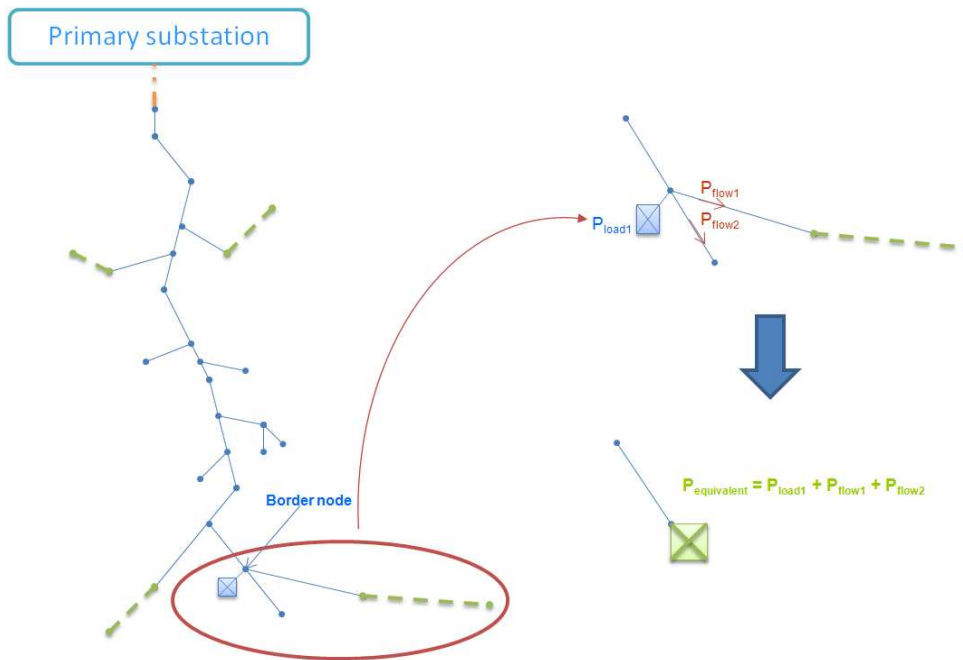


Figure 9: Aggregation of loads on a measured border node

2.3.2. Pseudo-measurements

A pseudo-measurement is a load model used to represent loads that are not equipped with a PQ sensor. These pseudo-measurements are based on statistical models of the load.

2.3.2.1. Information of pseudo-measurements

Some information is required for each pseudo-measurement:

- Load modeled by the pseudo-measurement,
- Mean value used for the statistical model,
- Statistical model used,
- Percentage of error of the pseudo-measurement for a load/ generator.

2.3.2.2. Statistic model of pseudo-measurements

At the moment, each of the pseudo-measurements is a Gaussian distribution centered on a mean value with a standard deviation $N(\mu, \sigma)$:

- μ : mean value,
- σ : standard deviation.

Regarding the mean value, two options are proposed to the user:

- Mean value: the Gaussian distribution is centered on the mean value of the load. This mean value is calculated with ratios defined in the initialization phase (§2.1).
- Real value: in this case, the Gaussian distribution is considered centered on the real value of the load. This real value is the same as the one used for real sensors. The only difference between a real sensor and the pseudo-measurement, in this case, is the accuracy.

The standard deviation of the Gaussian distribution is calculated in the same way as for real sensor:

$$\sigma = \frac{\% \text{ error of the pseudo - measurement} \cdot \text{mean value}}{3 \cdot 100}$$

The final value of the pseudo-measurement is:

$$\text{pseudo - measurement} = (\text{mean value} + \sigma \cdot N(0,1))$$

If new load models are developed in the future, they could be integrated in the DSE tool to offer new possibilities to user. In this case, it would be necessary to adapt the input information to be sure all required information is available.

2.3.2.3. Several pseudo-measurements connected at the same node

As DSE algorithm can only receive one active and reactive power information per node, all loads connected to the same node have to be aggregated. When there is no sensor, each one of the connected loads will be represented by one load model (in our case, Gaussian distributions).

To define the model of the aggregated load, a statistical aggregation of load models is performed. In our case, as we consider only Gaussian distributions, this statistical aggregation corresponds to:

$$\text{Aggregated model} = N(\mu_1, \sigma_1) + N(\mu_2, \sigma_2) + \dots + N(\mu_n, \sigma_n) = N((\mu_1 + \mu_2 + \dots + \mu_n), \sqrt{(\sigma_1^2 + \sigma_2^2 + \dots + \sigma_n^2)})$$

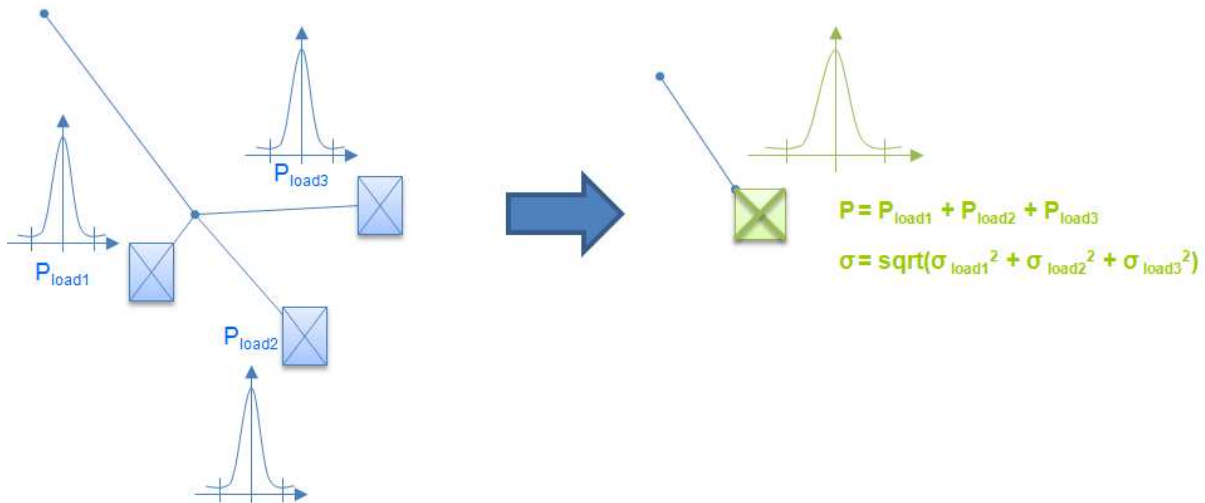


Figure 10: Pseudo-measurement: aggregation of loads connected to the same node

The same approach³ is used if a generator and a load are connected to the same node. However, the accuracy of models can be different as generators are always considered as measured in our tool.

2.3.2.4. Pseudo-measurements on border nodes

If no sensor is placed in a border node, the pseudo-measurement considered at this node will take as mean value of the Gaussian distribution the aggregation of loads and flows directly connected to the node (results of the load flow at the mean state of the network or at the real state depending on the user choice).

³ The only difference is that signs of powers of the load and the generator are different.

2.4. DESCRIPTION OF THE OPTIONS FOR DSE CALCULATION

2.4.1. Calculation options

Some information have to be defined before noisy measurements can be created. These information concern:

- The initialization of the random generator of Matlab. To generate the noise of all measurements, the Matlab random generator has been used. To be able to compare the impact of an isolated sensor in DSE results, it is necessary to be able to define the same noise measurement for a single sensor independently to other sensors noise. To do that two different concepts are used:
 - Initialization of the random matrix: if the user chooses ‘yes’ the same errors are going to be used for the sensors that were already placed.
 - Use of a complete matrix that represents the error of all possible sensors even if they are not placed in the network.

Config 1 :
-Random Initalization
- 7 sensors

Config 2 :
-Random Initalization
- 10 sensors

	1	2	3	4	5	6	7		1	2	3	4	5	6	7
P1	0,94644	0,57698	0,14054	0,02145	0,08772	0,85403	0,41931	P1	0,94644	0,57698	0,14054	0,02145	0,08772	0,85403	0,41931
P2	0,15349	0,26357	0,19582	0,94062	0,87666	0,41188	0,48210	P2	0,15349	0,26357	0,19582	0,94062	0,87666	0,41188	0,48210
P3	0,90456	0,46222	0,08994	0,23079	0,20827	0,32152	0,78557	P3	0,90456	0,46222	0,08994	0,23079	0,20827	0,32152	0,78557
Q1	0,96433	0,89951	0,40996	0,05790	0,20469	0,85492	0,62394	Q1	0,96433	0,89951	0,40996	0,05790	0,20469	0,85492	0,62394
Q2	0,94592	0,80331	0,73984	0,92120	0,21352	0,89490	0,05215	Q2	0,94592	0,80331	0,73984	0,92120	0,21352	0,89490	0,05215
Q3	0,11633	0,98049	0,52719	0,75132	0,54931	0,54832	0,69935	Q3	0,11633	0,98049	0,52719	0,75132	0,54931	0,54832	0,69935
V1	0,15093	0,15483	0,59118	0,72816	0,74544	0,50177	0,66714	V1	0,15093	0,15483	0,59118	0,72816	0,74544	0,50177	0,66714
V2	0,47731	0,41548	0,67837	0,42817	0,58495	0,32135	0,99790	V2	0,47731	0,41548	0,67837	0,42817	0,58495	0,32135	0,99790
V3	0,52186	0,46219	0,50563	0,61487	0,00626	0,19308	0,97499	V3	0,52186	0,46219	0,50563	0,61487	0,00626	0,19308	0,97499
Phi1	0,23741	0,17841	0,14469	0,69814	0,66200	0,18864	0,43414	Phi1	0,23741	0,17841	0,14469	0,69814	0,66200	0,18864	0,43414
Phi2	0,68074	0,26389	0,25766	0,13062	0,78505	0,70265	0,68264	Phi2	0,68074	0,26389	0,25766	0,13062	0,78505	0,70265	0,68264
I1	0,15116	0,82942	0,12553	0,16718	0,26927	0,84762	0,60985	I1	0,15116	0,82942	0,12553	0,16718	0,26927	0,84762	0,60985
I2	0,27450	0,04433	0,29891	0,91757	0,87540	0,60960	0,22325	I2	0,27450	0,04433	0,29891	0,91757	0,87540	0,60960	0,22325
PF1	0,49877	0,67140	0,06101	0,03970	0,06285	0,45732	0,67397	PF1	0,49877	0,67140	0,06101	0,03970	0,06285	0,45732	0,67397
PF2	0,63812	0,78104	0,99755	0,98080	0,13676	0,10238	0,05890	PF2	0,63812	0,78104	0,99755	0,98080	0,13676	0,10238	0,05890
QF1	0,24947	0,06913	0,52720	0,22386	0,05742	0,83553	0,81865	QF1	0,24947	0,06913	0,52720	0,22386	0,05742	0,83553	0,81865
QF2	0,91740	0,87516	0,95825	0,55538	0,86140	0,70497	0,74031	QF2	0,91740	0,87516	0,95825	0,55538	0,86140	0,70497	0,74031

Figure 11: Explanation of the random matrix

In Figure 11, one can see that if the initialization of the random matrix has been chosen, the same errors are applied to the sensors that were already placed (7 sensors) after the placement of 3 new sensors.

Config 1 :
-Random Initalization
- 7 sensors

Config 2 :
-Without Random Initalization
- 7 sensors

	1	2	3	4	5	6	7
P1	0,94644	0,57698	0,14054	0,02145	0,08772	0,85403	0,41931
P2	0,15349	0,26357	0,19582	0,94062	0,87666	0,41188	0,48210
P3	0,90456	0,46222	0,08994	0,23079	0,20827	0,32152	0,78557
Q1	0,96433	0,89951	0,40996	0,05790	0,20469	0,85492	0,62394
Q2	0,94592	0,80331	0,73984	0,92120	0,21352	0,89490	0,05215
Q3	0,11633	0,98049	0,52719	0,75132	0,54931	0,54832	0,69935
V1	0,15093	0,15483	0,59118	0,72816	0,74544	0,50177	0,66714
V2	0,47731	0,41548	0,67837	0,42817	0,58495	0,32135	0,99790
V3	0,52186	0,46219	0,50563	0,61487	0,00626	0,19308	0,97499
Phi1	0,23741	0,17841	0,14469	0,69814	0,66200	0,18864	0,43414
Phi2	0,68074	0,26389	0,25766	0,13062	0,78505	0,70265	0,68264
I1	0,15116	0,82942	0,12553	0,16718	0,26927	0,84762	0,60985
I2	0,27450	0,04433	0,29891	0,91757	0,87540	0,60960	0,22325
PF1	0,49877	0,67140	0,06101	0,03970	0,06285	0,45732	0,67397
PF2	0,63812	0,78104	0,99755	0,98080	0,13676	0,10238	0,05890
QF1	0,24947	0,06913	0,52720	0,22386	0,05742	0,83553	0,81865
QF2	0,91740	0,87516	0,95825	0,55538	0,86140	0,70497	0,74031

	1	2	3	4	5	6	7
P1	0,37588	0,49012	0,44362	0,60657	0,46603	0,01342	0,98543
P2	0,66209	0,64217	0,22022	0,42502	0,20412	0,21711	0,07913
P3	0,69158	0,26072	0,57316	0,26657	0,54017	0,47886	0,58642
Q1	0,69711	0,42016	0,55526	0,86477	0,56082	0,24202	0,45203
Q2	0,07183	0,41779	0,11363	0,66863	0,99285	0,20535	0,93219
Q3	0,56774	0,94130	0,62086	0,39184	0,00826	0,00007	0,68900
V1	0,40698	0,06074	0,72920	0,00773	0,68659	0,95433	0,68624
V2	0,33883	0,96492	0,08673	0,23344	0,04217	0,13465	0,72474
V3	0,44400	0,96664	0,24565	0,67518	0,83230	0,91847	0,66262
Phi1	0,34320	0,00517	0,46397	0,15084	0,22646	0,47137	0,81409
Phi2	0,52484	0,34841	0,33184	0,98113	0,26765	0,97416	0,56521
I1	0,66957	0,76132	0,95344	0,28623	0,63952	0,59469	0,70235
I2	0,66944	0,38425	0,89119	0,88425	0,54173	0,51567	0,91332
PF1	0,32876	0,14042	0,35466	0,81038	0,21673	0,04499	0,94824
PF2	0,36505	0,09805	0,54125	0,15275	0,61169	0,82071	0,40821
QF1	0,30921	0,19575	0,96766	0,47569	0,36734	0,00626	0,91336
QF2	0,86745	0,28671	0,03589	0,82731	0,82164	0,70373	0,36223

Figure 12: Explanation of the initialization of the random matrix

In Figure 12 it is possible to see how the errors used for the same sensor configuration are different as no initialization of the random generator has been done.

The random matrix has as many columns as estimations are going to be run with the same sensors configuration and the same real state of the network. The number of estimations to be done can be defined by the user.

2.4.2. Transferred information to DSE

The information transferred to the DSE algorithm has been defined so that all necessary information is available for all possible algorithms. These structures are described in Appendix 2.

2.5. RESULTS ANALYSIS

To be able to determine if the results obtained with DSE algorithms are accurate, some developments have been done in the DSE to calculate estimation errors.

2.5.1. Estimated variables

Voltage magnitude and phase at each node of the network have been chosen as primary variables to be directly estimated by the DSE algorithm. The other electrical magnitudes, as currents and power flows, are considered as secondary variables and are recalculated with the estimated primary variables and the admittance matrix of the network. The expressions used to calculate secondary variables are:

- Current injected at nodes: $\underline{I} = [\underline{Y}] \cdot \underline{V}$
- Active and reactive power injected/ consumed at each node: $\underline{S} = \underline{V} \cdot \underline{I}^* \begin{cases} P = \Re(\underline{S}) \\ Q = \Im(\underline{S}) \end{cases}$
- Current flowing through a line/cable: $I_{line(i,j)} = abs(Y_{ii} \cdot V_i - Y_{ij} \cdot V_j)$
- Active and reactive power flowing through a line/cable: $S_{line(i,j)} = V_i \cdot (Y_{ii} \cdot V_i - Y_{ij} \cdot V_j)^*$

2.5.2. Errors of the estimations

The DSE tool calculates relative errors in order to evaluate the accuracy of DSE results. For each state variable, the relative error is calculated with the following expression:

$$\text{relative error} = \frac{\text{real value} - \text{estimated value}}{\text{real value}}$$

The real value is the result of the load flow (§2.1).

2.5.2.1. Errors statistics

To be able to quickly analyze the results obtained with a given sensor configuration, some statistics have been done regarding relative errors. For a fixed accuracy (define by the user), and for each node/line/cable, the percent of estimations in the accepted band is calculated. For each state variable, the mean, maximum and minimum values of percents in different nodes/lines/cables are also available.

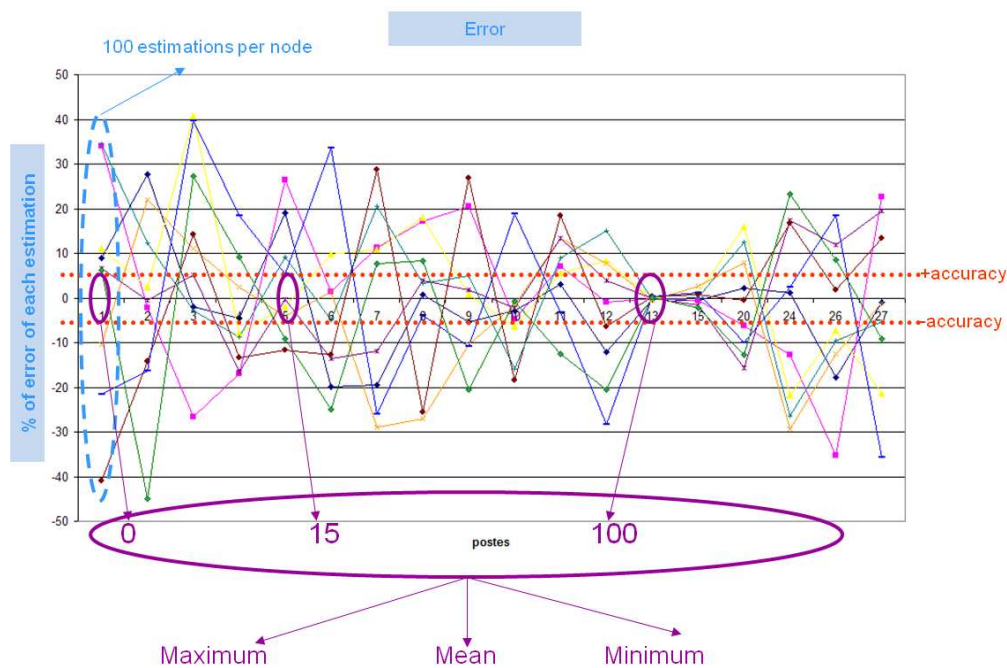


Figure 13: Statistics for errors

Figure 13 shows how the statistics are calculated:

- Relatives errors are calculated per node/line/cable for each estimated variable,
- The percent of the estimations in the accepted band ([-accuracy, +accuracy]) is calculated per node/line,
- The mean, maximum and minimum values of percents in different nodes/lines for each estimated variable are calculated.

In the case of active and reactive power injected/ consumed at each node, the statistics take only into account nodes in which a load/ generator is connected⁴.

To correctly analyze the results, it is important to know the real value of the estimated variable as the relative error can be very large and the absolute error is negligible. This situation can occur:

⁴ The slack bus and border nodes are considered as nodes with a load directly connected.

- For virtual nodes if using the recalculated values as the real state of the network.⁵
- For voltage phase angles if the node is very close to the slack bus.
- For lines/cables which have no load connected at the end.

2.5.3. Numerical results

To summarize the results obtained with the DSE algorithm for a chosen sensor configuration, it is possible to generate an Excel file with all the results. The created Excel file has three worksheets:

- Node results: 'resultats_noeuds'. This worksheet contains the results of all state variables associated to nodes (voltage magnitudes and phase angles, powers injections and current injections). For each of these variables, the name of the node, the real value and the results of each estimation are displayed. The absolute and relative errors are also integrated to this worksheet.
- Line/cable results: 'resultats_segments'. This worksheet summarizes the results of currents and powers flowing through the lines/cables in the zone. The real values and the results of the DSE algorithm are compared.
- Sensors configuration: 'Zone estimée, Capteurs, tirs'. This worksheet summarizes sensors' configuration, load models and the real state of the network (Pmax or P(t)).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Date de réalisation de l'estimation d'état : 22-Nov-2011 14:45:43														
2															
3	Analyse des amplitudes des tensions														
4	Nom du noe	Amplitude d	Amplitude de tension estimée (une colonne correspond à un tir d'estimation)	(kV)											
5	42095E9116 [	19,964	19,984	19,979	19,984										
6	42095P0021	19,946	19,966	19,961	19,966										
7	42099E0003 [	19,932	19,952	19,947	19,952										
8	42099E0016 [	19,908	19,929	19,924	19,929										
9	42099E0017 [	19,909	19,929	19,924	19,929										
10	42099E0001 [	19,923	19,943	19,938	19,943										
11	42099E0002 [	19,923	19,943	19,938	19,943										
12	42099EE010 [	19,93	19,95	19,945	19,95										
13	42099J0911 [	19,923	19,943	19,938	19,943										
14	42099J099C [	19,908	19,929	19,924	19,929										
15	42099P0003	19,94	19,96	19,955	19,961										
16	42099P0006	19,931	19,952	19,947	19,952										
17	42099P0010	19,908	19,928	19,923	19,929										
18	42099P0011	19,934	19,954	19,949	19,955										
19	42099P0012	19,908	19,929	19,924	19,929										
20	42099P0014	19,908	19,929	19,923	19,929										
21	42099P0020	19,931	19,952	19,947	19,952										
22	42099P0024	19,932	19,952	19,947	19,952										
23	42270E0001 [	19,875	19,895	19,89	19,896										
24	42270E0003 [	19,875	19,896	19,89	19,896										
25	42270E0004 [	19,875	19,896	19,891	19,896										
26	42270E0005 [	19,874	19,895	19,889	19,895										
27	42270E0006 [	19,872	19,892	19,887	19,892										
28	42270E0010 [	19,856	19,877	19,871	19,877										
29	42270E0011 [	19,866	19,886	19,881	19,886										
30	42270E0012 [	19,864	19,885	19,88	19,885										
31	42270E0014 [	19,862	19,883	19,878	19,883										
32	42270E0016 [	19,856	19,877	19,871	19,877										
33	42270E0018 [	19,864	19,884	19,879	19,885										
34	42270EE001 [	19,877	19,898	19,893	19,898										
35	42270EE002 [	19,856	19,877	19,871	19,877										
36	42270EE003 [	19,859	19,879	19,874	19,879										
37	42270EE004 [	19,856	19,876	19,871	19,877										
38	42270EE005 [	19,862	19,882	19,877	19,883										

Figure 14: Results file

⁵ The recalculated value is not exactly 0 but very small.

2.5.4. Graphical results

It is possible to analyze the errors using ellipses representation. For each node of the network, four ellipses are represented:

Ellipse 1	Ellipse 2
Voltage magnitude relative error vs. Voltage phase angle relative error	Voltage magnitude absolute error vs. Voltage phase angle absolute error
Ellipse 3	Ellipse 4
Active power relative error vs. reactive power relative error	Active power absolute error vs. reactive power absolute error

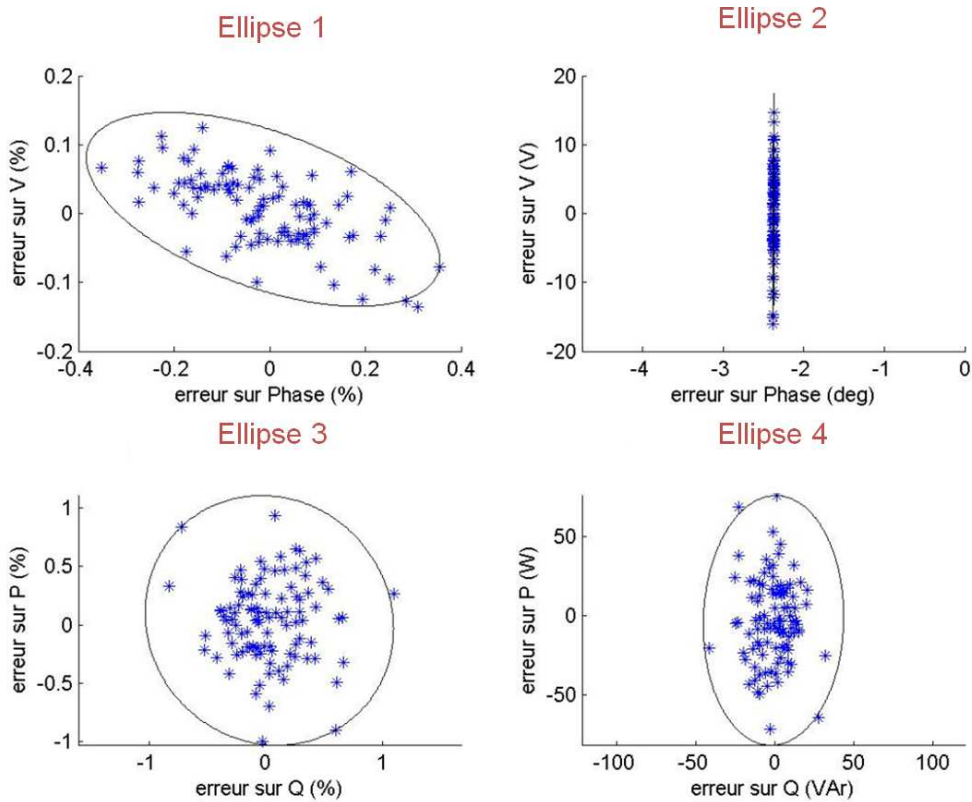


Figure 15: Ellipses for one node and several sensors configuration

Figure 15 shows the ellipses, for one sensor configuration, the results of one node. It is possible to get in the same figure ellipses obtained with different sensor configurations so results can be compared.

2.5.5. DSE results in the network HMI

To perform a quick analysis of the results of DSE algorithm, the results can be integrated on the network HMI. This integration can be done at two levels:

- Global HMI: results obtained in the zone that has been estimated are integrated on the global network HMI.

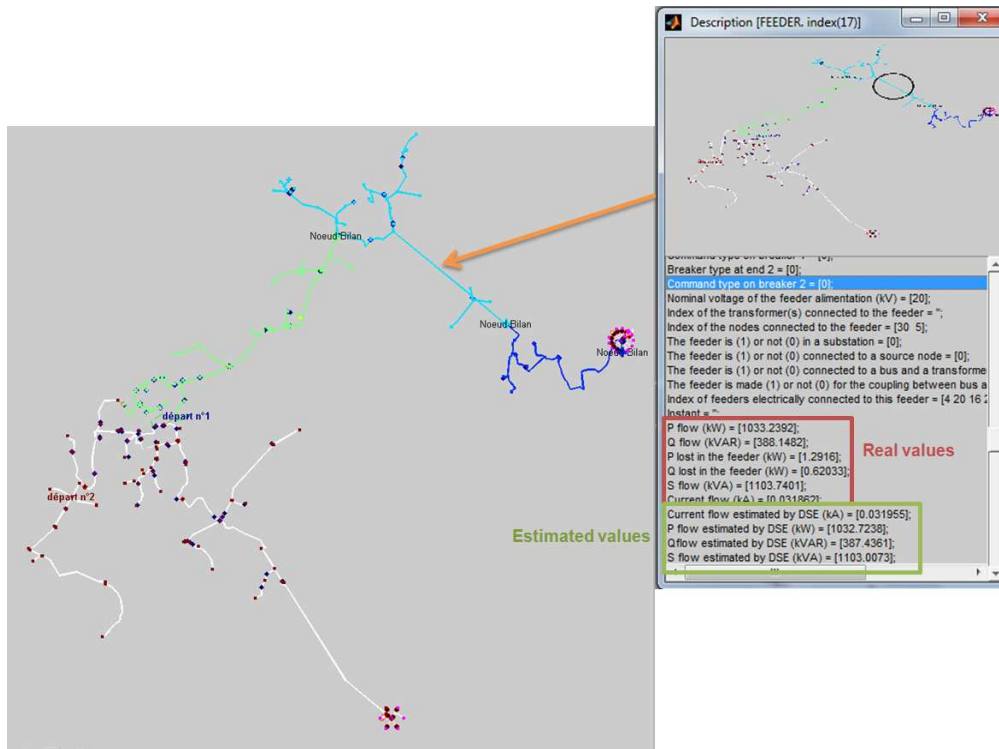


Figure 16: Estimated values in HMI

- Voltage profiles: It is possible to compare the real voltage profile with the estimated one. This figure contains also the measurement value of voltage sensors taken into account by the DSE algorithm.

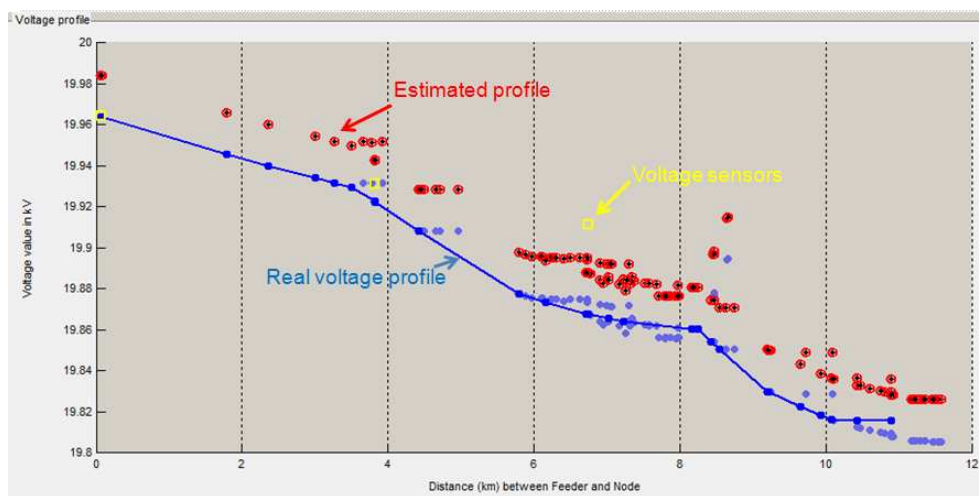


Figure 17: Real and estimated voltage profile

3. HOW TO...

This chapter explains all the options that are available in the DSE tool and how to use them.

3.1. INSTALL DSE TOOL

DSE tool is available as an executable file “DSE_tool.exe”. To install this program on your computer all you have to do is to double click on the file and the installation program will be launched.

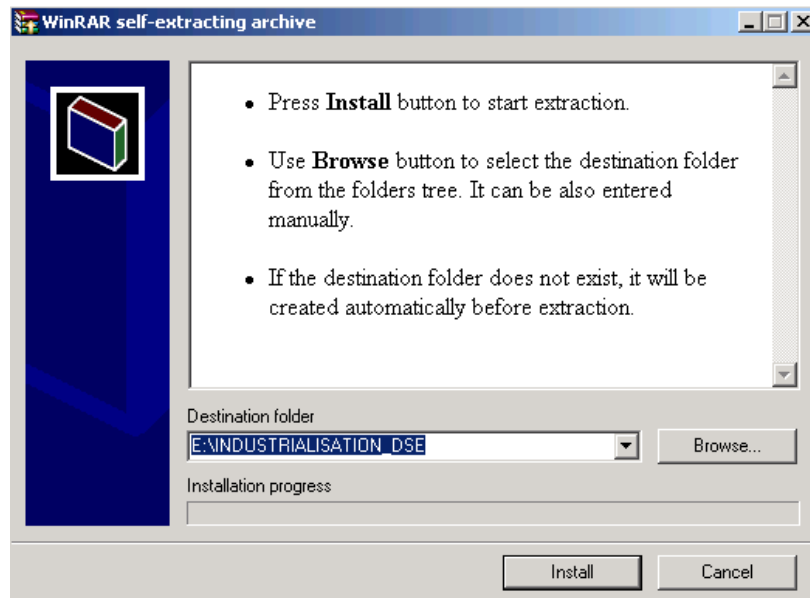


Figure 18: Installing DSE tool

To change the folder in which the DSE tool is going to be created all you have to do is to select the folder you want using **<Browse>** button. It is highly recommended to choose a folder without blanks on its name. Once the installation has finished, the new folder should contain the following folders:

- #Resultats_DSE_mode_etude
- DSE
- POST_DSE
- PRE_DSE
- Reseaux_de_tests

To run the DSE tool, one has to launch Matlab and tape “dse” at the command window and choose the language of the menu (FR for French and UK for English). This will open the menu represented in Figure 19.

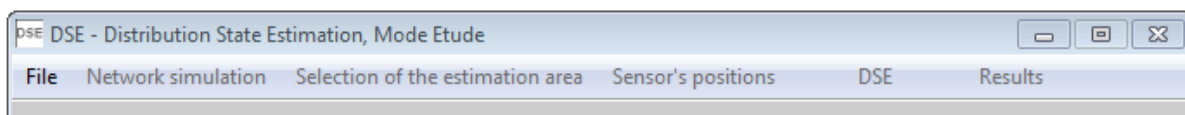


Figure 19: DSE menu

3.2. CHOOSE AND TREAT A NETWORK

3.2.1. Load the network

Once the menu has been launched, it is possible to choose the network one wants to study by clicking into <File> button and selecting “Load” and “M file”.

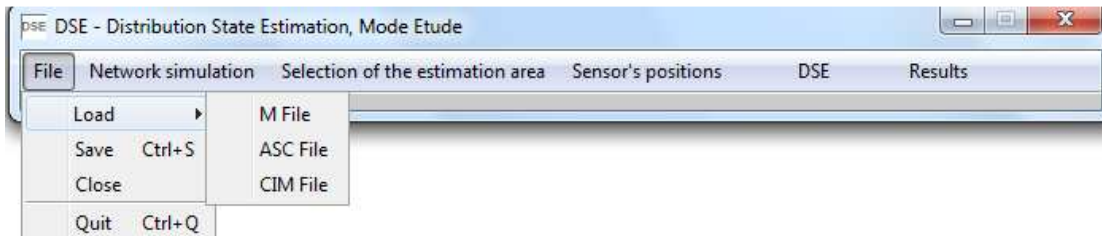


Figure 20: Loading « m » file

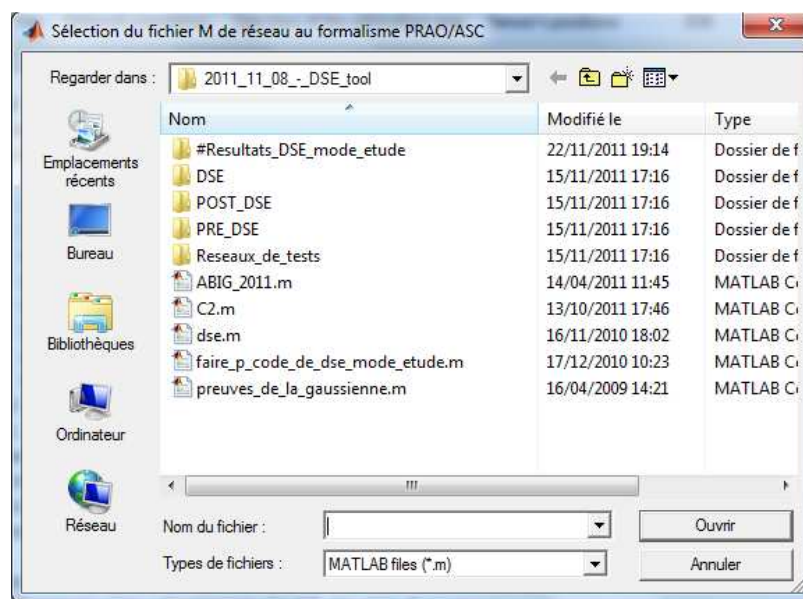


Figure 21: Selecting « m » file

Once the “m” file has been chosen, the network simulator is going to be started and several actions are done:

- Adaptation of “m file” format into PSAT format to run the load flow,
- Confirmation of Slack bus characteristics,
- Confirmation of generators characteristics (PQ or PV),
- Definition of the ratio defining Pmean for all loads,
- Definition of the ratio defining Pmean for each generator,
- Confirmation of parameters chosen for the on-load tap changer regulation,
- Confirmation of parameters chosen for the reactive energy compensation (capacitor banks)
- Charging load curves,
- Random allocation of load curves to each consumer connected to the network. No load curve is associated to generators by default.
- Initialization of the state of the network in three states: Pmax, Pmean and P(t). By default the date used for calculating P(t) is 01/01 at 10:00.

Once all these calculations are finished, the user can modify the state of the network or start calculations. The following sections describe how default options can be changed on the initialization of the network.

3.2.1.1. Generators type: PQ or PV node

It is possible to define whether a generator has a PQ node or a PV node behavior. To do this, one should answer 'o' to the question in Figure 22. This question appears after choosing the network and it is not possible to come back after the initialization of the network.

```
+> Définition de la nature des AUTOPRODUCTEURS
Pas de fichier de préférence
Autoproducteur 1 : au noeud 193_P1, de nature PQ
Autoproducteur 2 : au noeud 201_P1, de nature PQ
Voulez-vous changer ces valeurs ? (O,N) :
```

Figure 22: Changing parameters of generators

After answering 'o' to the question, a new window will be opened to choose the behavior for each one of the generators connected to the network (Figure 23). Each generator is identified by the number of the node to which it is connected.

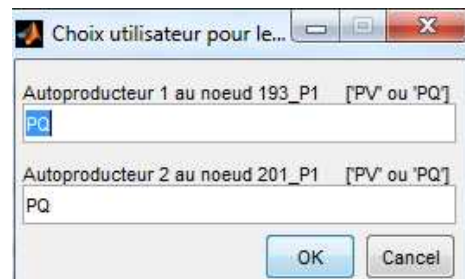


Figure 23: Choosing the behavior of generators

If something different from "PQ" or "PV" is introduced as an answer, the default option ("PQ") will be used.

3.2.1.2. Change load's ratio for the mean state of the network

The state of the network with the mean load is defined by a ratio applied to all loads (§2.1). This ratio represents the number of equivalent hours that loads are supposed to be at their maximal load (maximal load*equivalent hours = total energy really consumed). The ratio used for each load is defined by:

$$k(\%) = \frac{h}{8760} \cdot 100$$

with h : number of equivalent hours

This number of equivalent hours is defined during the initialization of the network and it is not possible to change it during the study. To change the ratio, the number of equivalent hours has to be defined in Figure 24. The default value is 3000.

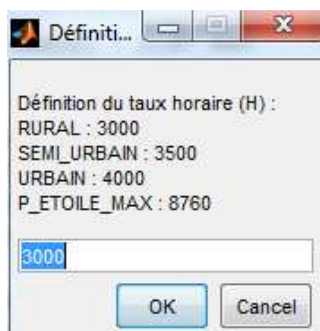


Figure 24: Changing the ratio used to calculate Pmean of loads

3.2.1.3. Change generators ratio for the mean state of the network

To define the state of the network at the mean level of the load, it is also important to define the contribution of generators to this state. To do so, and for each of them, the ratio defining their mean value can be defined. By default, all generators are considered as having the same ratio as loads but this can be changed in the initialization phase.

To change the value considered by default, it is necessary to indicate the number of the DG which ratio is going to be changed in Figure 25. For each one of the chosen generators, a new window as in Figure 26 will be opened. In this case, the ratio is directly introduced (there is no reference to equivalent hours). The information about the contribution of generators to the mean state of the network cannot be changed after the initialization.

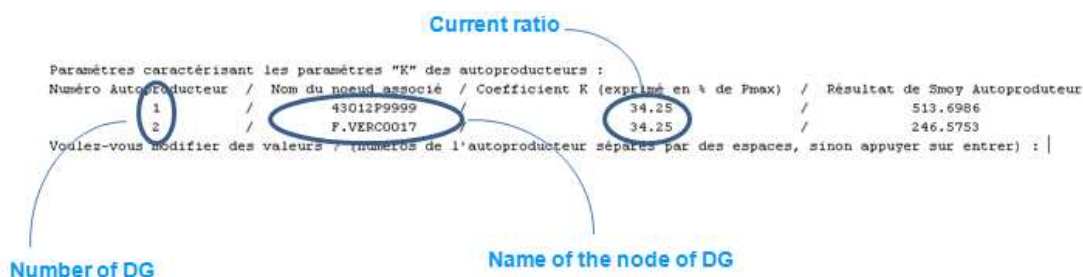


Figure 25: Changing the ratio used to calculate Pmean for generators



Figure 26: Defining the ratio used to calculate Pmean for generators

3.2.1.4. Change on load transformer regulation

The network simulator used to define the real state of the network models the behavior of the on-load tap changer of the HV/MV transformer. The characteristics of this regulation can be changed in the initialization phase indicating the number of the transformers whose characteristics are going to be changed to the question in Figure 27.

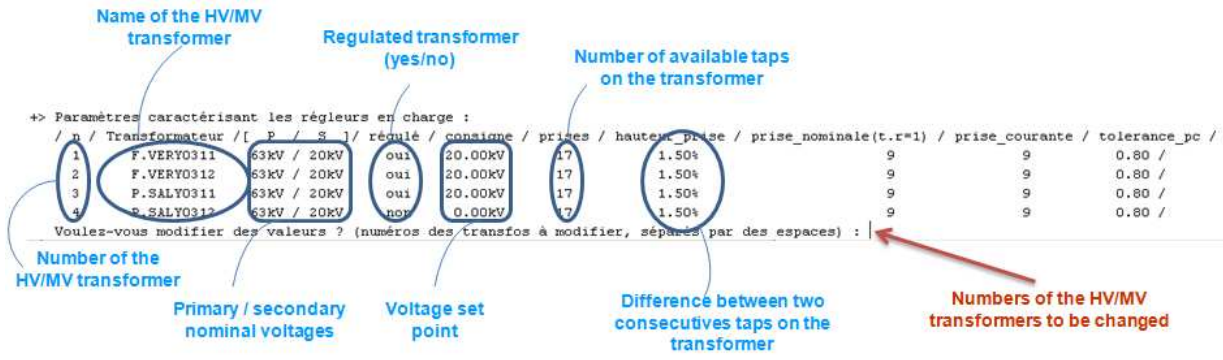


Figure 27: Changing parameters of on-load tap changer regulation

For each one of the selected transformers, a window similar to the one in Figure 28 appears. In this window, it is possible to select the new characteristics that are going to be applied to the on-load tap changer of the HV/MV transformer.

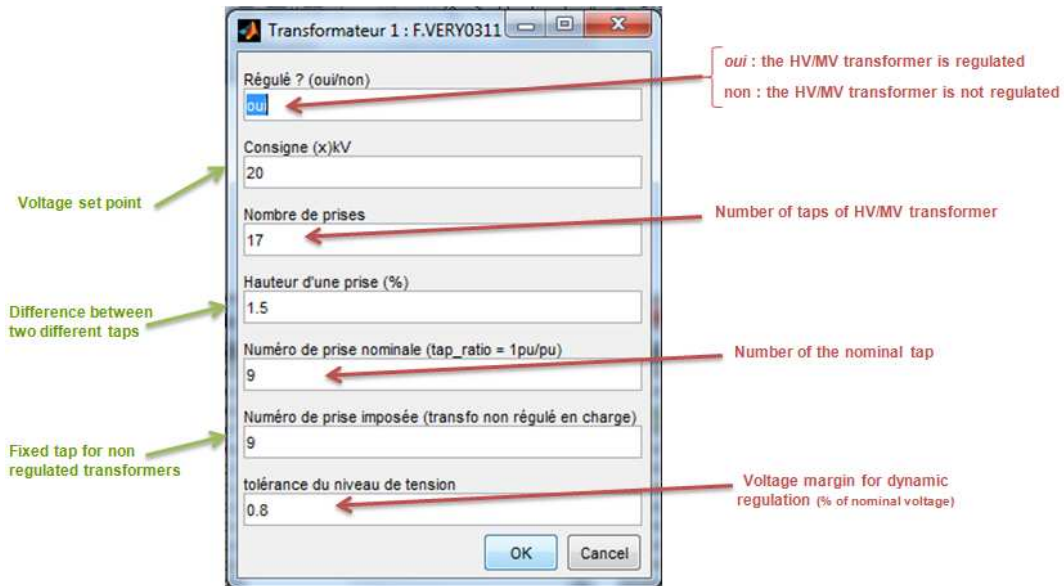


Figure 28: Changing parameters of on-load tap changer regulation

3.2.1.5. Capacitor banks regulation

The parameters of the capacitor banks regulation are defined during the initialization phase. To change the characteristics of this regulation, one has to indicate the number of capacitor banks whose characteristics are going to be modified as an answer of question in Figure 29.

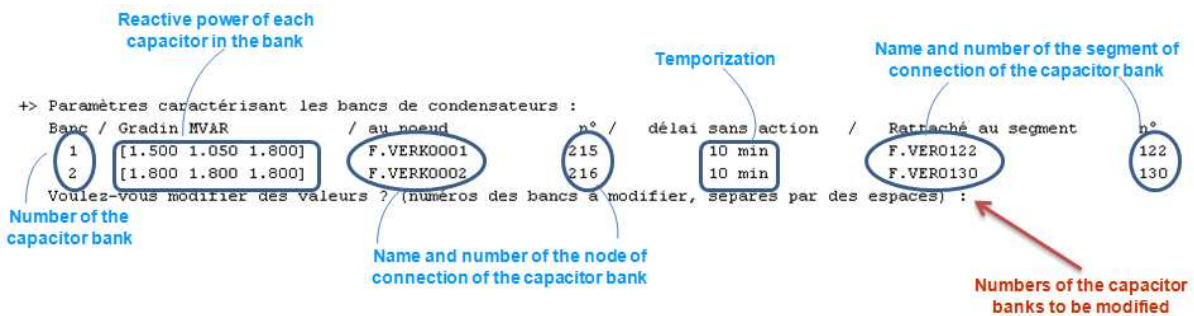


Figure 29: Changing parameters of reactive power regulation (capacitors banks)

For each one of the selected capacitor banks, window in Figure 30 is going to be opened. In this case, only the temporization of the regulation can be changed. Changing this parameter will not change the results of the study as this information is only used when the network simulator is used in a dynamic way.



Figure 30: Changing parameters of reactive power regulation (capacitors banks)

3.2.2. Select load curve for load/generator

Once the initialization phase has finished, it is possible to change the load profile definition that has been created randomly. It is important to note that, a load profile has been allocated to each one of the loads connected to the network. However, no load profile has been allocated to generators existing in the network.

To change the load profiles, one has to click in the **<Network simulation>** and select **'Load profile definition'** as shown in Figure 31. After that, the HMI of the network will be opened. In this HMI each color represents a different load profile.

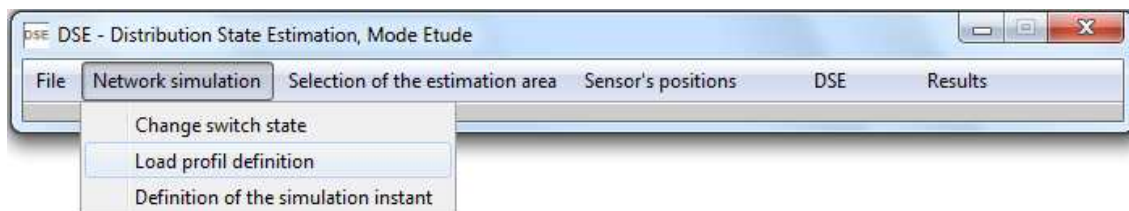


Figure 31: Changing load/ generator profile

To change the existing profile, one has to click left and a new menu will appear (Figure 32). In this menu, one has to select **'Changer le modele de charge'** if it is a load or **'Changer le modele de production'** if it is a generator. A new menu will appear with profiles available for the selected load.

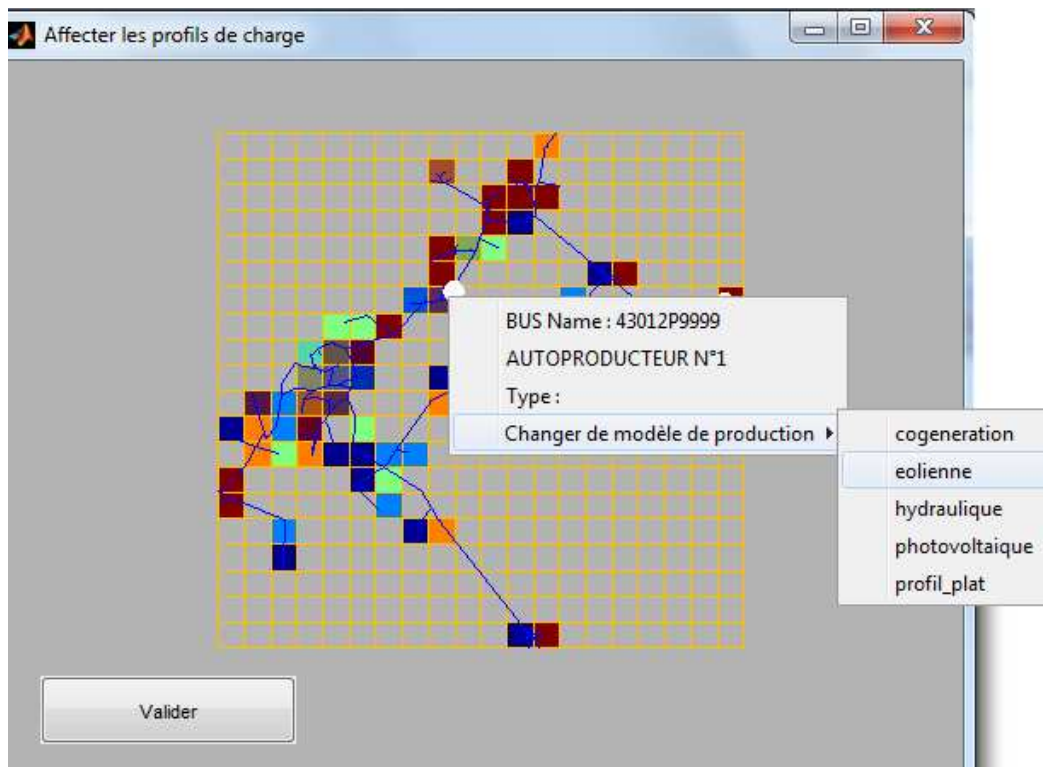


Figure 32: Changing the load curve of a generator

3.2.3. Define a new load curve

It is possible to define a new load curve and allocate it to loads/ generators in the network. However, this operation has to be done before the initialization phase.

To define a new load curve, one has to:

- Generate a .csv file as the ones already available in
 - \PRE_DSE\Simulateur_de_reseau\@courbe_de_charge\AUTOPRODUCTEUR
 - \PRE_DSE\Simulateur_de_reseau\@courbe_de_charge\CONSOMMATEUR

Each “csv” file represents a different load profile (the name of the load profile is the name of the file). It is possible to have a different load profile for active and reactive power. To do so, two columns can be created: the first one represents the active power profile and the second one the reactive power profile. To calculate the load profile that is going to be used to calculate loads, all values in the column are divided by the maximum value of the column.

- Place the file into the generator ('AUTOPRODUCTEUR') or the load ('CONSOMMATEUR') folder, depending on the type of node that is going to be treated.

3.2.4. Define the instant of load flow run for P(t)

It is possible to change the date used for the load flow at P(t). To change this date, one has to click in <Network simulation> and choose 'Definition of the simulation instant' as indicated in Figure 33. In this case a new figure appears as the one in Figure 34. In this figure, the user can define a new date in the format [DD/MM HH:MM] and after clicking on the <OK> button the calculation will be run.

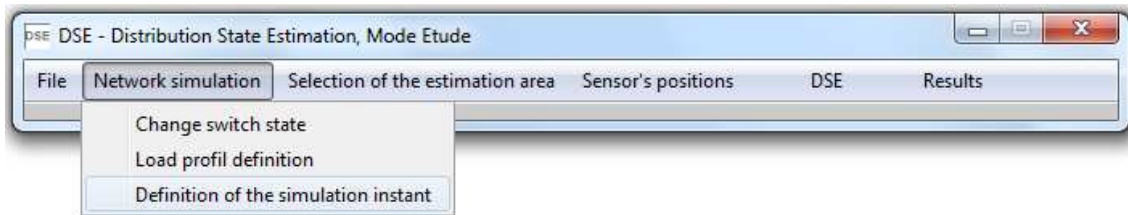


Figure 33: Changing the instant used for P(t)

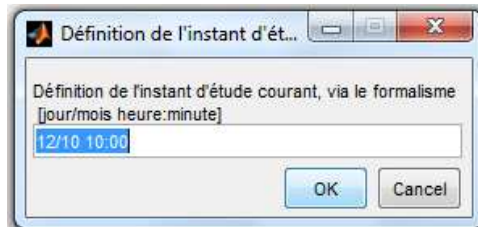


Figure 34: Defining a new instant for P(t)

3.2.5. Change the state of switches

It is possible to change network topology by changing the state of the switches. To change this state, the user has to click in the <Network simulation> button and then select 'Change switch state' as in Figure 35.



Figure 35: Changing the state of switches

A new figure will appear (as Figure 36) after selecting the 'Change switch state' option. In this new figure it is possible to change the state of the switch by clicking on the name of the line with the chosen switch.

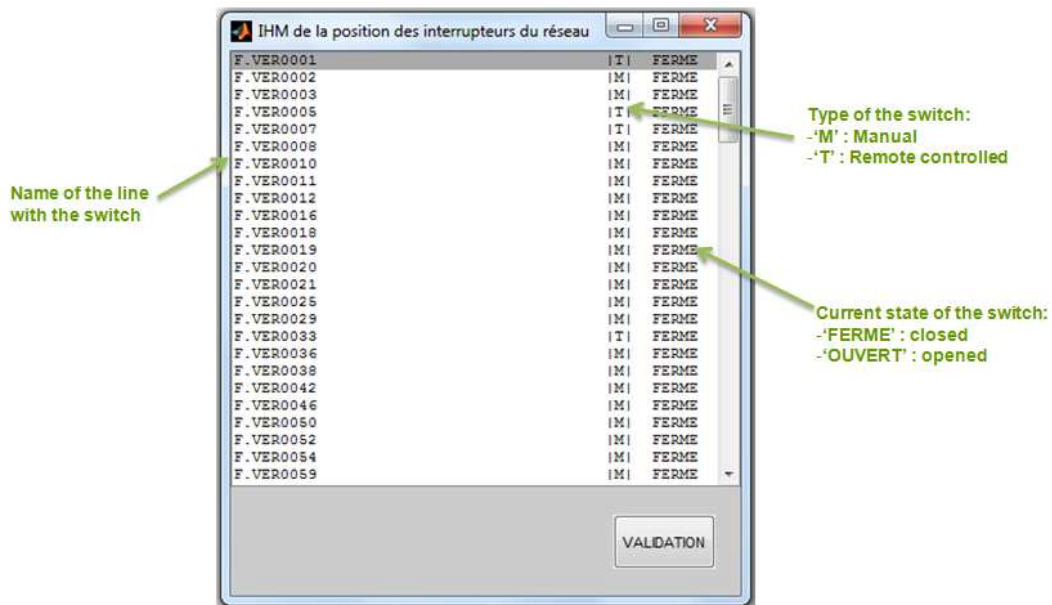


Figure 36: HMI of switches changes

3.3. SELECT THE ESTIMATED AREA

Four different options are proposed to the user to define the zone in which DSE is applied.

3.3.1. Zone between remote controlled switches

It is possible to define a zone between remote controlled switches as the zone in which the DSE is going to be applied. To do so, one has to choose the <Selection of the estimation area> and select 'Zone between switches' (Figure 37).

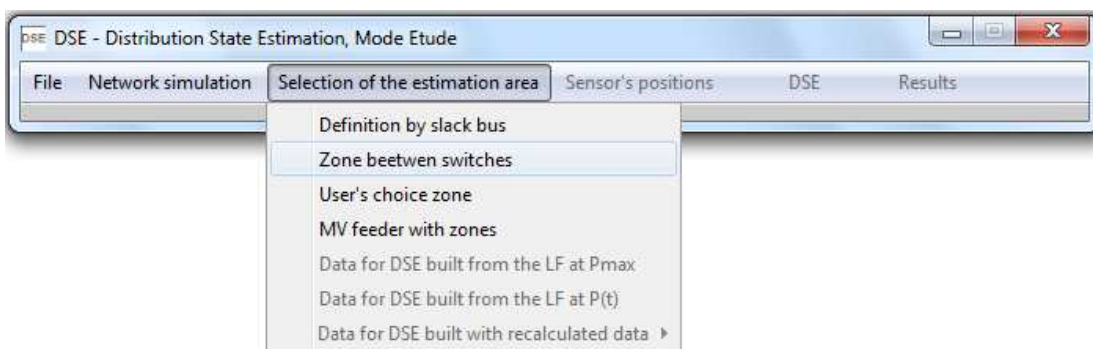


Figure 37: Defining treated zone between remote controlled switches

Once the user has selected this option, the network HMI and a new window will open (Figure 38). The new HMI shows all zones between remote controlled switches (switches are not included in the zones). Each one of these zones has a number to identify it and allows its definition. The number of the zone that is going to be defined as the estimated zone has to be defined in the new figure.

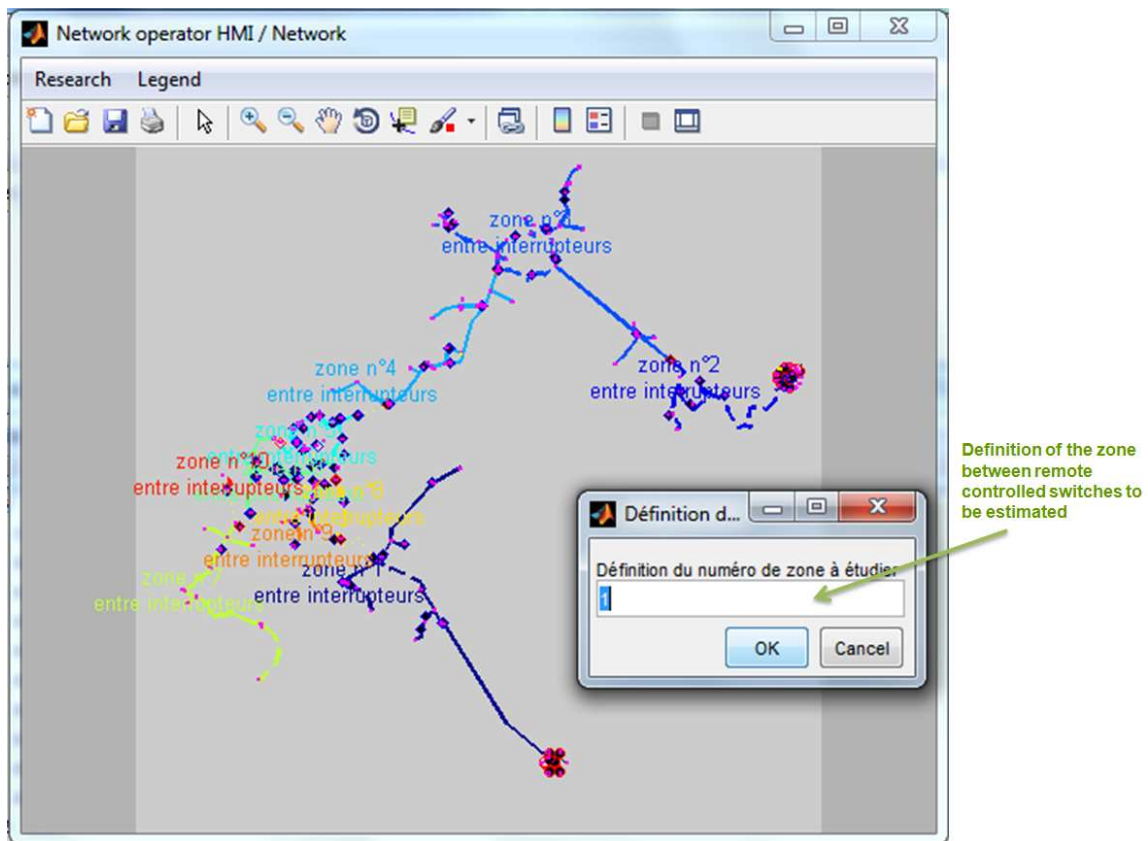


Figure 38: Choosing the zone between remote controlled switches

3.3.2. Zone downstream a node

In this case, the estimated zone is defined as all elements connected downstream the chosen node. To do so one has to choose the <Selection of the estimation area> and select 'Definition by slack bus' (Figure 39).

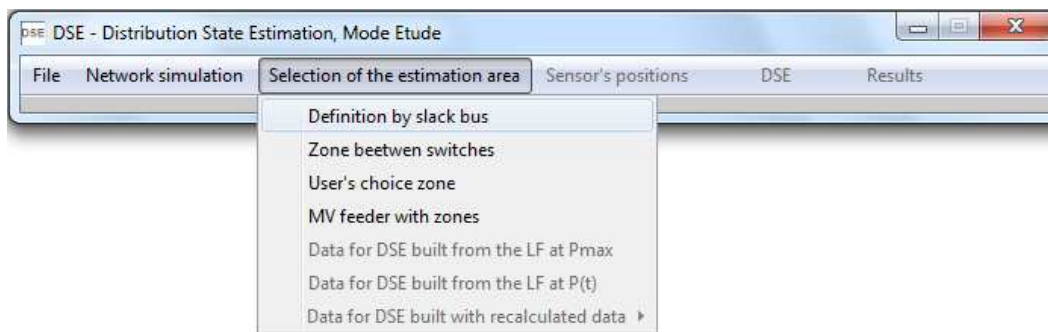


Figure 39: Defining treated zone downstream a node

Once the option has been selected, the network HMI and a new window are opened. In the new window, the user has to select the node that is going to be defined as the slack bus of the zone and that will define the zone as all elements connected downstream (Figure 40).

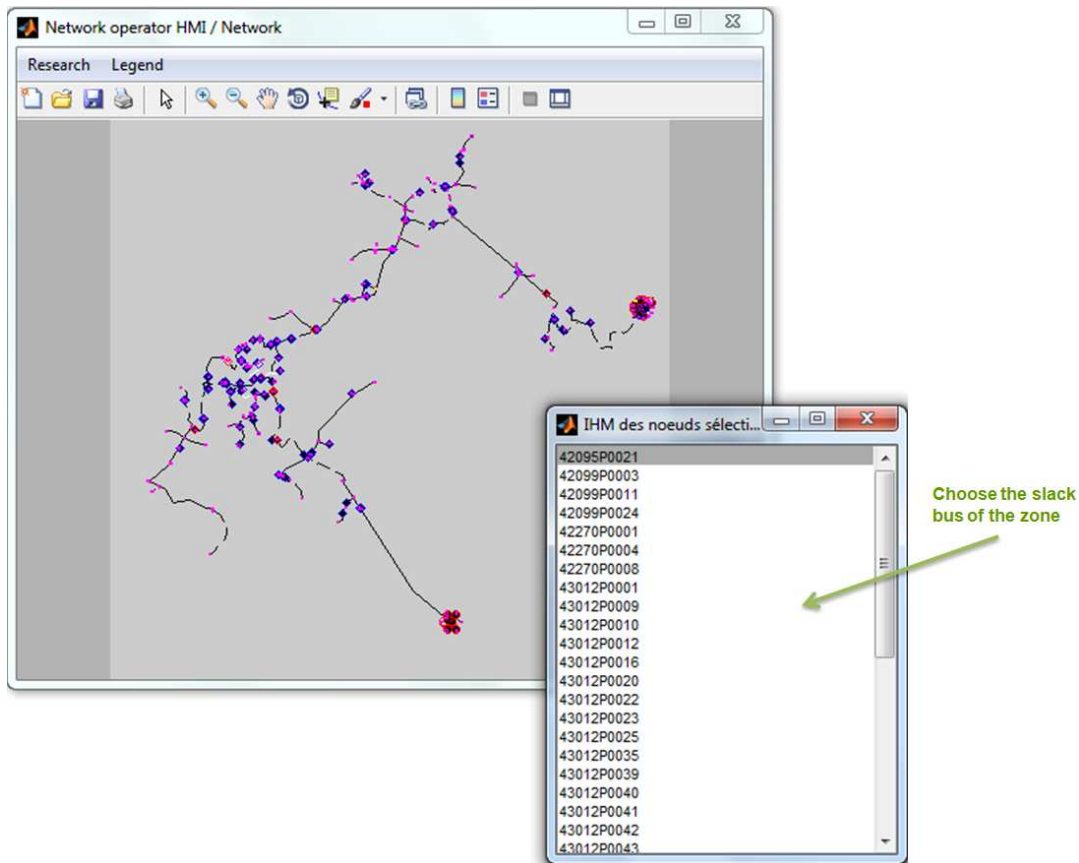


Figure 40: Choosing the node to define the zone downstream

3.3.3. User's definition zone

It is possible to define the zone to be estimated directly by defining border lines/cables and one node in the zone. To do so, one has to choose the <Selection of the estimation area> and select 'User's choice zone' (Figure 41).

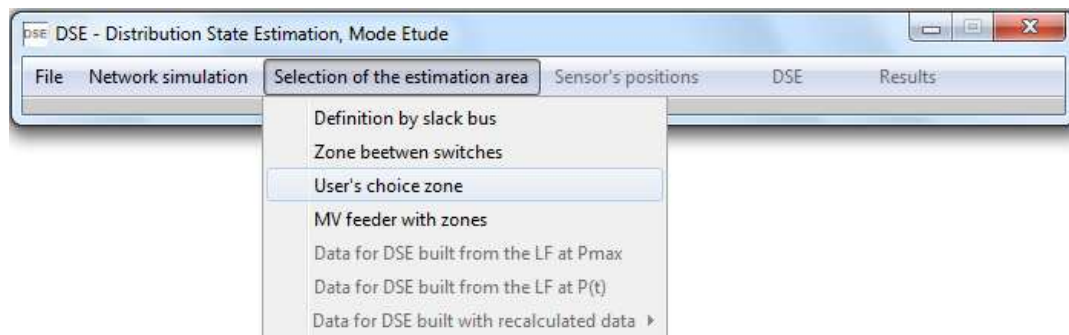


Figure 41: Defining treated zone by user's choice

Once the user has selected this option, the network HMI and a new window will open (Figure 42). In this new window the user has to specify:

- The names of the zone limits (as many as the user wants),
- The name of one node which is part of the defined zone,
- If the user wants to change the slack bus (by default is the closest node to the MV busbar), the name of the new slack bus.

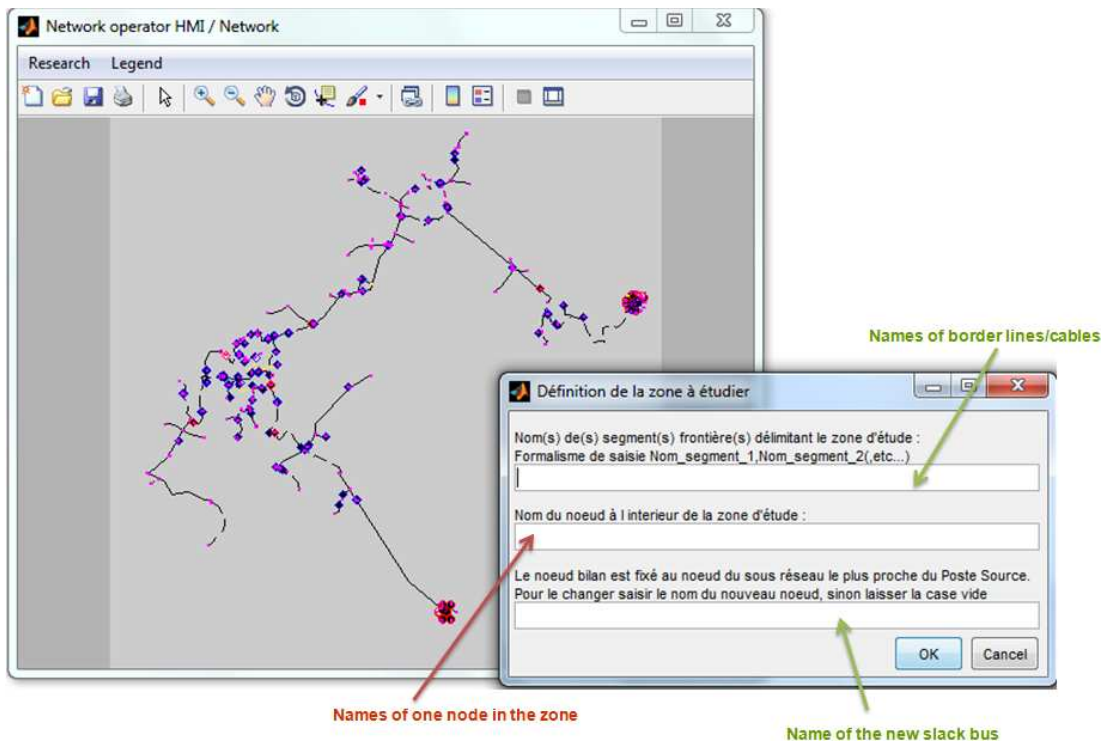


Figure 42: Choosing zone limits and node in the zone

3.3.4. MV feeder with the zonal approach

In this case, an entire MV feeder is going to be chosen and divided into zones so the zonal approach can be applied. To do so, one has to choose the <Selection of the estimation area> and select 'MV feeder with zones' (Figure 43).

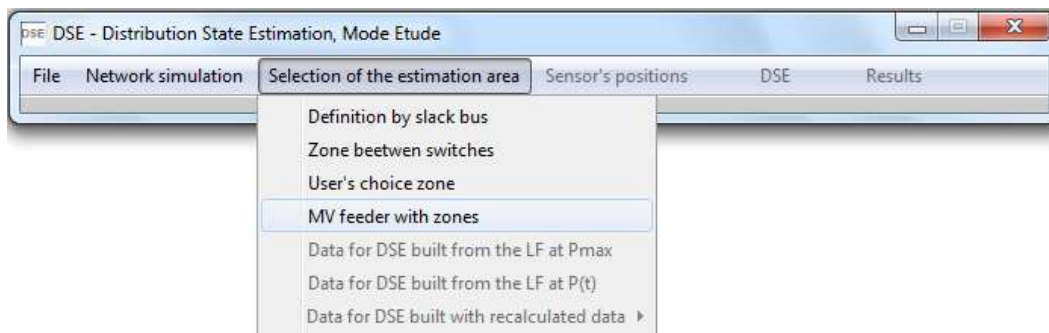


Figure 43: Defining treated zone as an MV feeder with the zonal approach

Once the user has selected the MV feeder definition, a first window allowing the definition of the parameters used for the zonal approach is going to appear (Figure 44). In this figure five aspects have to be defined:

- Visualization of each zone of the MV feeder:
 - False: the network HMI will only have the final situation,
 - True: the network HMI will change each time the algorithm detects a new zone.

- Load connected to the slack bus of a zone:
 - False: a node with a load directly connected cannot be defined as the slack bus of the zone⁶,
 - True: all nodes, even with loads directly connected, can be defined as slack buses. In this case, the load is going to be measured by a PQ sensor.
- Type of configuration:
 - Series: in this case, only a PQV sensor at the beginning of each node is necessary.
 - Parallel: In this case, a PQV sensor is placed at the beginning of each zone.
- Use of existing voltage sensors: In the series configuration, the use of voltage sensors on border nodes has to be defined.
 - True: The measured voltage is going to be used for the estimation of both zones directly connected to the border node.
 - False: The measured voltage is only used for the first zone. The second zone uses the estimated voltage on the border node.
- DSE to be applied: definition of the algorithm to be applied
 - WLS: for the moment, only the WLS algorithm is available.

Figure 44: Choosing parameters of zonal approach

Once the user has defined all required parameters, the network HMI will open and the user can define the number of the MV feeder to be estimated with the zonal approach (Figure 45). The number of the MV feeder in which the zonal approach is applied has to be defined in the new figure.

⁶ As the slack bus is going to be defined automatically, this option doesn't consider as remote controlled switches the switches with a load directly connected.

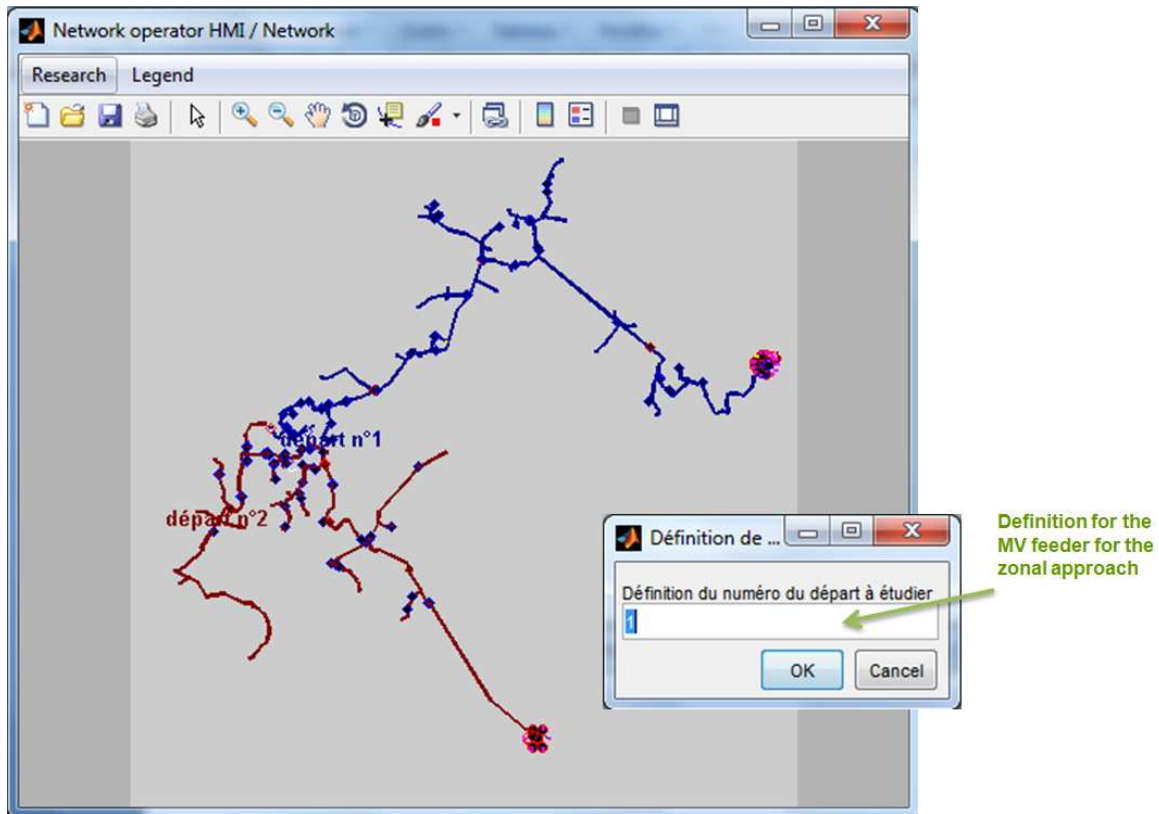


Figure 45: Defining the MV feeder to be divided into zones

3.4. CHOOSE DATE FOR DSE

Once the zone in which the DSE is applied is defined, it is important to define the real state of the network that is considered. Two different options are available:

- Network with the maximum load (Pmax),
- Network with the load curve (P(t)).

For each one of these states, two different options are available depending the way used for calculating the electrical values:

- Direct load flow results: in this case, all results are gathered directly from the internal variables of the PSAT load flow,
- Recalculated data: in this case, the only information directly gathered from the load flow is the voltage vector (magnitudes and phases). The other electrical values are recalculated from this vector and the admittance matrix.

3.4.1. Load flow at Pmax

To choose the results of load flow at the maximum load without any recalculation as the real state of the network, one has to choose the <Selection of the estimation area> menu and select 'Data for DSE built from the LF at Pmax' (Figure 46).

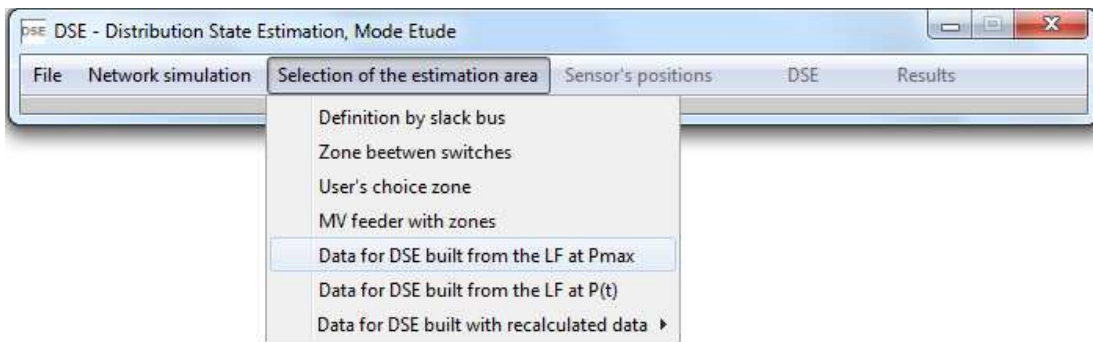


Figure 46: Choosing load flow at Pmax as the real state of the network

To choose the results of load flow at the maximum load with the recalculation of electrical values as the real state of the network, one has to choose the <Selection of the estimation area> menu and select 'Data for DSE built with recalculated data' and 'Recalculated data with LF at Pmax' (Figure 47).

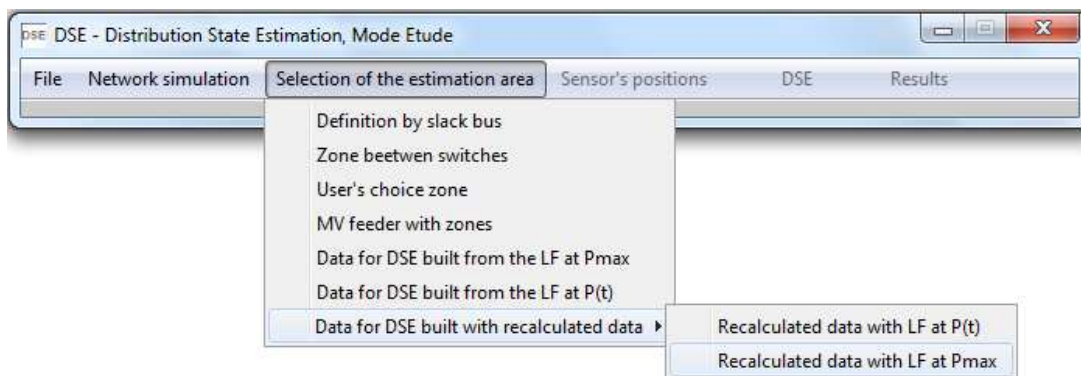


Figure 47: Choosing load flow at Pmax with recalculated values as the real state of the network

3.4.2. Load flow at P(t)

To choose the results of load flow with the load curve P(t) with no recalculation as the real state of the network, one has to choose the <Selection of the estimation area> menu and select 'Data for DSE built from the LF at P(t)' (Figure 48).

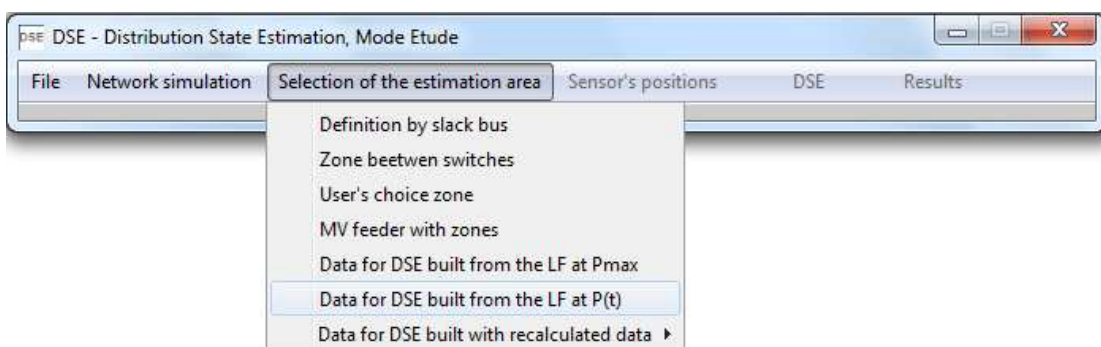


Figure 48: Choosing load flow at P(t) as the real state of the network

To choose the results of load flow with the load curve P(t) and with the recalculation of electrical values as the real state of the network, one has to choose the <Selection of the

estimation area> menu and select **'Data for DSE built with recalculated data'** and **'Recalculated data with LF at P(t)'** (Figure 49).

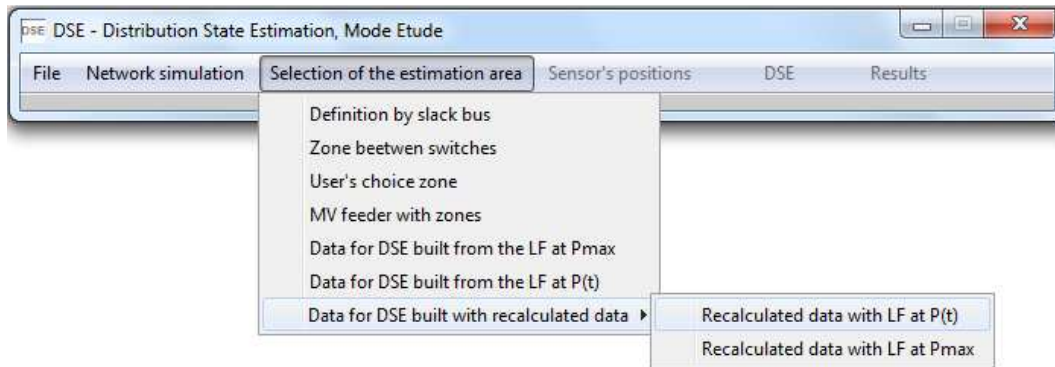


Figure 49: Choosing load flow at P(t) with recalculated values as the real state of the network

3.5. SENSORS PLACEMENT IN THE MV NETWORK

The DSE tool allows the simulation of real sensors in the network even if they don't exist in the real network.

3.5.1. Define sensors configuration

To define sensors configuration, one has to select the **<Sensor's positions>** menu and the **'Define sensor's positions'** (Figure 50). This option allows the placement of new sensors without resetting sensors already existing. If the zonal approach has been chosen, this option places the required sensors for the chosen configuration (series or parallel) and deletes sensors already positioned into the network.

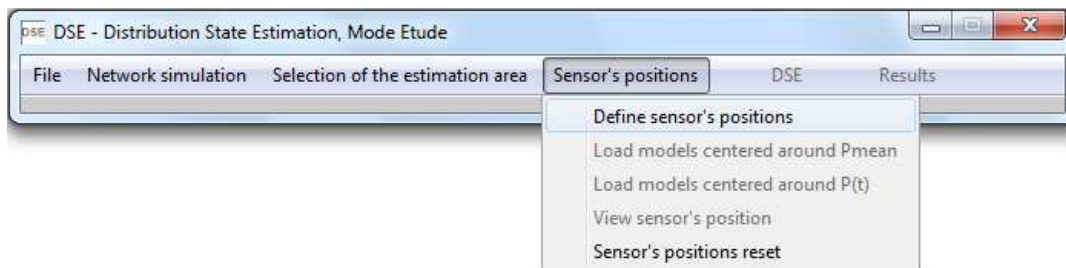


Figure 50: Defining sensor's positions

A new HMI is opened to define the default accuracies used for sensors and pseudo-measurements (Figure 51).

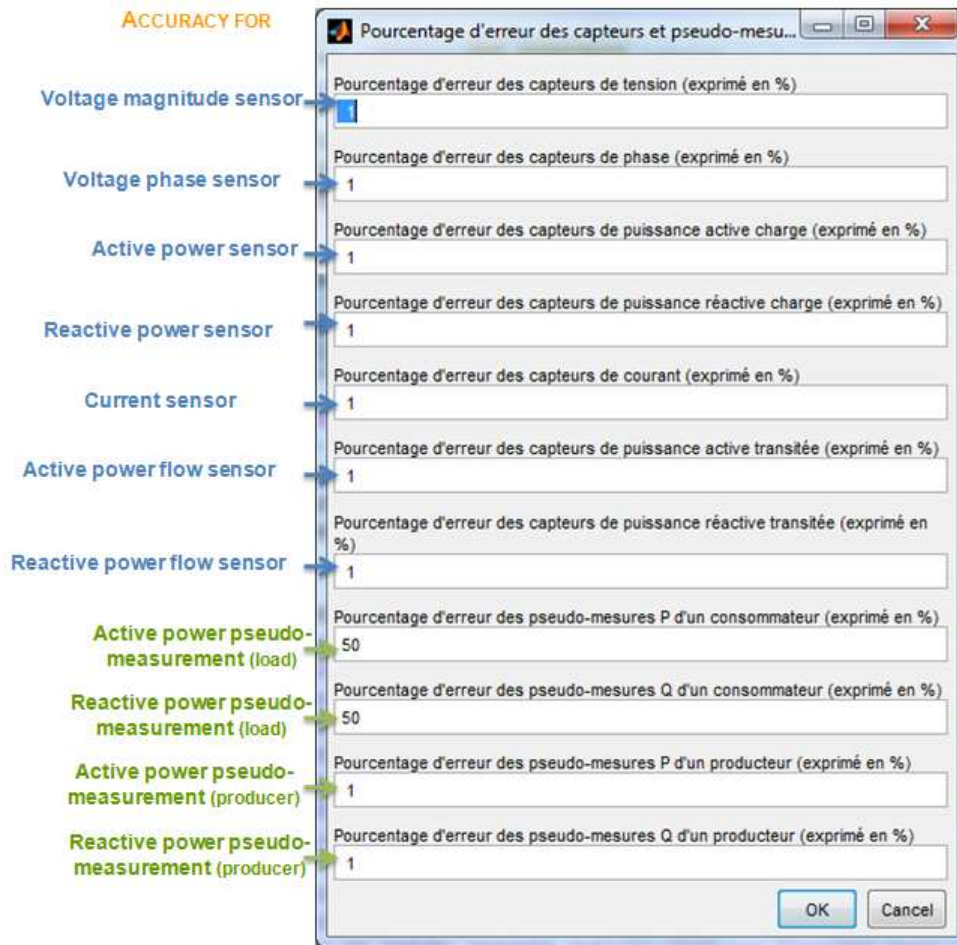


Figure 51: Defining sensor's accuracies

After choosing the default value of accuracies, the sensor configuration HMI will appear (Figure 52). This HMI is divided in three parts:

1. General part of the HMI,
2. Part for sensors placement at nodes,
3. Part for sensors placement on lines/cables.

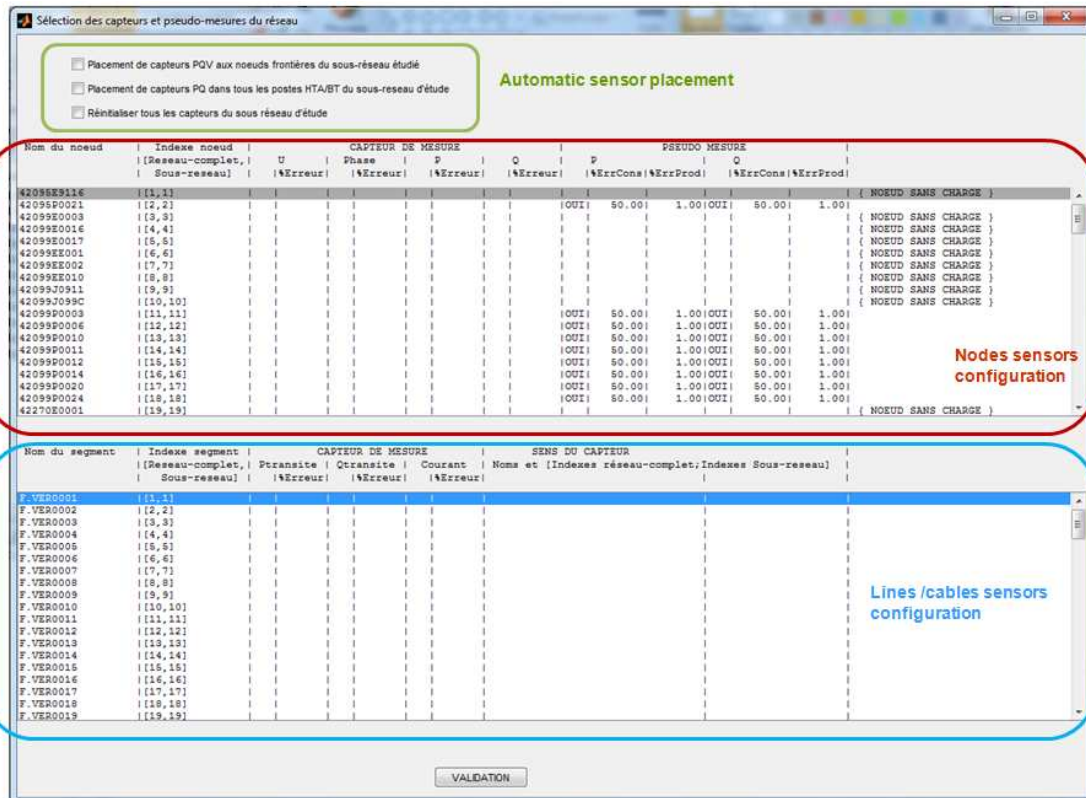


Figure 52: HMI for sensors placement

The general part of the sensors HMI (Figure 53) allows a quick placement of the sensors in the network. Three options are available in this part of the HMI:

1. Placement of a PQV sensor on each border node of the chosen zone,
2. Placement of PQ sensors at each load of the chosen zone,
3. Reset all sensors: in this case all sensors are deleted. After this reset, it may be necessary to place new sensors in order to run the estimation.

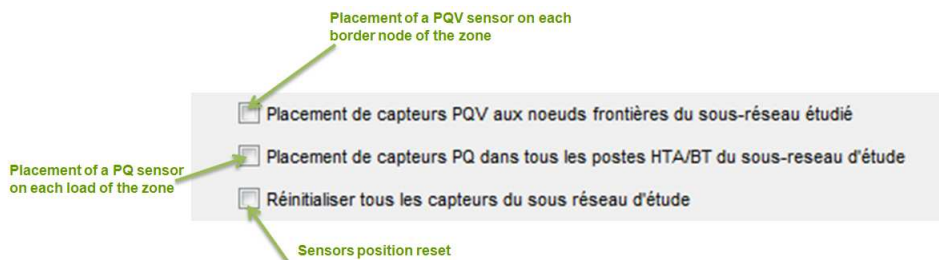


Figure 53: General part of the sensors HMI

The “node placement” part of the sensors HMI (Figure 54) summarizes all sensors connected to each one of the nodes.

Nom du noeud	Indice noeud [Réseau-complet, Sous-réseau]	CAPTEUR DE MESURE				PSEUDO MESURE				Type of the node
		U [%Erreur]	Phase [%Erreur]	P [%Erreur]	Q [%Erreur]	P [%ErrCons|%ErrProd]	Q [%ErrCons|%ErrProd]			
42099E0016	[[1,1]]									{ NOEUD SANS CHARGE }
42099E0021	[[2,2]]									{ NOEUD SANS CHARGE }
42099E0008	[[3,3]]									{ NOEUD SANS CHARGE }
42099E0016	[[4,4]]									{ NOEUD SANS CHARGE }
42099E0017	[[5,5]]									{ NOEUD SANS CHARGE }
42099E0001	[[6,6]]									{ NOEUD SANS CHARGE }
42099E0002	[[7,7]]									{ NOEUD SANS CHARGE }
42099E0010	[[8,8]]									{ NOEUD SANS CHARGE }
42099J0911	[[9,9]]									{ NOEUD SANS CHARGE }
42099J099C	[[10,10]]									{ NOEUD SANS CHARGE }
42099P0003	[[11,11]]					50.00	1.00	50.00	1.00	{ NOEUD SANS CHARGE }
42099P0006	[[12,12]]					50.00	1.00	50.00	1.00	{ NOEUD SANS CHARGE }
42099P0010	[[13,13]]					50.00	1.00	50.00	1.00	{ NOEUD SANS CHARGE }
42099P0011	[[14,14]]					50.00	1.00	50.00	1.00	{ NOEUD SANS CHARGE }
42099P0012	[[15,15]]					50.00	1.00	50.00	1.00	{ NOEUD SANS CHARGE }
42099P0014	[[16,16]]					50.00	1.00	50.00	1.00	{ NOEUD SANS CHARGE }
42099P0020	[[17,17]]					50.00	1.00	50.00	1.00	{ NOEUD SANS CHARGE }
42099P0024	[[18,18]]					50.00	1.00	50.00	1.00	{ NOEUD SANS CHARGE }
42270E0001	[[19,19]]									{ NOEUD SANS CHARGE }

Figure 54: “Node placement” part of the sensors HMI

For each node, the following information are available:

- Node name,
- Node index : in the complete network reference and in the zone reference,
- Real sensors:
 - Voltage magnitude sensor: if there is a sensor and its accuracy,
 - Voltage phase sensor: if there is a sensor and its accuracy,
 - Active power sensor: if there is a sensor and its accuracy,
 - Reactive power sensor: if there is a sensor and its accuracy.
- Pseudo-measurements:
 - Active power pseudo-measurement: if there is a pseudo-measurement and the accuracy of the model for loads and generators,
 - Reactive power pseudo-measurement: if there is a pseudo-measurement and the accuracy of the model for loads and generators.
- Type of the node: this information allows the identification of required sensors/ pseudo-measurements in some nodes. The possibilities are:
 - “Noeud sans charge”: node without a load. No power sensor or pseudo-measurement can be placed on this node. If there is one power sensor or pseudo-measurement, an error will be detected once the user validates its selection and the sensors HMI will be opened.
 - “Noeud frontiere”: border nodes. These nodes have been considered as having a load (to simulate the power flowing out of the zone) even if it is possible to have a node without any load. A sensor or a pseudo-measurement has to be placed at this node in order to not have an error. If there is no load or power flowing going out of the zone by this border node, the sensor or the pseudo-measurement will be deleted in a further step.
 - “Noeud bilan du sous reseau”: slack bus of the node. It is necessary to have a power sensor or a pseudo-measurement to be able to run the DSE.

It is possible to change the sensors connected to one node, their characteristics or the information regarding pseudo-measurements. To do so, one has to click on the line of the node and a new HMI will appear (Figure 55). In this new HMI, it is possible to:

- Define a new sensor: voltage magnitude, voltage phase angle, active power or reactive power.
- Define or modify the accuracy of the sensor.
- Define the statistical model used to define the error of sensors: for the moment only the Gaussian model is available.
- Define a new pseudo-measurement.
- Define or modify the accuracy of pseudo-measurements for loads or generators;
- Define the statistical model used to define the error of pseudo-measurements: for the moment only the Gaussian model is available.

If a PQ sensor and a PQ pseudo-measurement are available on the same node, only the PQ sensor is kept.

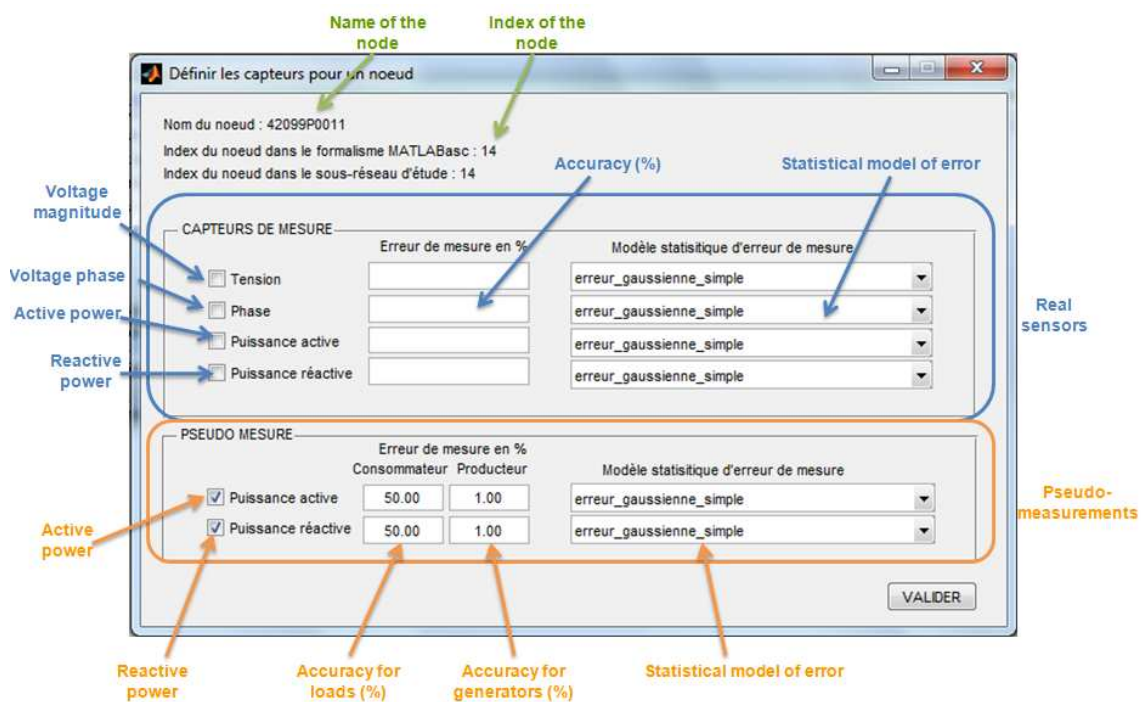


Figure 55: HMI of sensors configuration at one node

The “line/cable placement” part of the sensors HMI (Figure 56) summarizes all sensors connected to each line/cable of the chosen zone.

Nom du segment	Indexe segment [Réseau-complet, Sous-réseau]	CAPTEUR DE MESURE			SENS DU CAPTEUR	
		Ptransite [%Erreur]	Qtransite [%Erreur]	Courant [%Erreur]	Noms et [Indexes réseau-complet; Indexes Sous-réseau]	
F.VER0001	[1, 1]					
F.VER0002	[12, 2]					
F.VER0003	[3, 3]					
F.VER0004	[4, 4]					
F.VER0005	[5, 5]					
F.VER0006	[6, 6]					
F.VER0007	[7, 7]					
F.VER0008	[8, 8]					
F.VER0009	[9, 9]					
F.VER0010	[10, 10]					
F.VER0011	[11, 11]					
F.VER0012	[12, 12]					
F.VER0013	[13, 13]					
F.VER0014	[14, 14]					
F.VER0015	[15, 15]					
F.VER0016	[16, 16]					
F.VER0017	[17, 17]					
F.VER0018	[18, 18]					
F.VER0019	[19, 19]					

Figure 56: “Line/cable placement” part of the sensors HMI

For each line/cable, the following information are available:

- Line/cable name,
- Line/cable index : in the complete network reference and in the zone reference,
- Real sensors:
 - Active power flow sensor: if there is a sensor and its accuracy,
 - Reactive power flow sensor: if there is a sensor and its accuracy,
 - Current sensor: if there is a sensor and its accuracy,
 - Direction of the sensor: this parameter indicates if the sensor measures the flow from node N1 to node N2 or from node N2 to node N1.

It is possible to add a new sensor by clicking on the line where the sensor is added. In this case, a new HMI will open (Figure 57). In this new HMI it is possible to:

- Add/ delete sensors associated to one line/cable,
- Modify the accuracy of each sensor,
- Change the direction of the sensor measurement (from N1 to N2 or vice-versa). To do this, one has to add the sensor, validate its choice and then open the HMI of the line to change the direction.

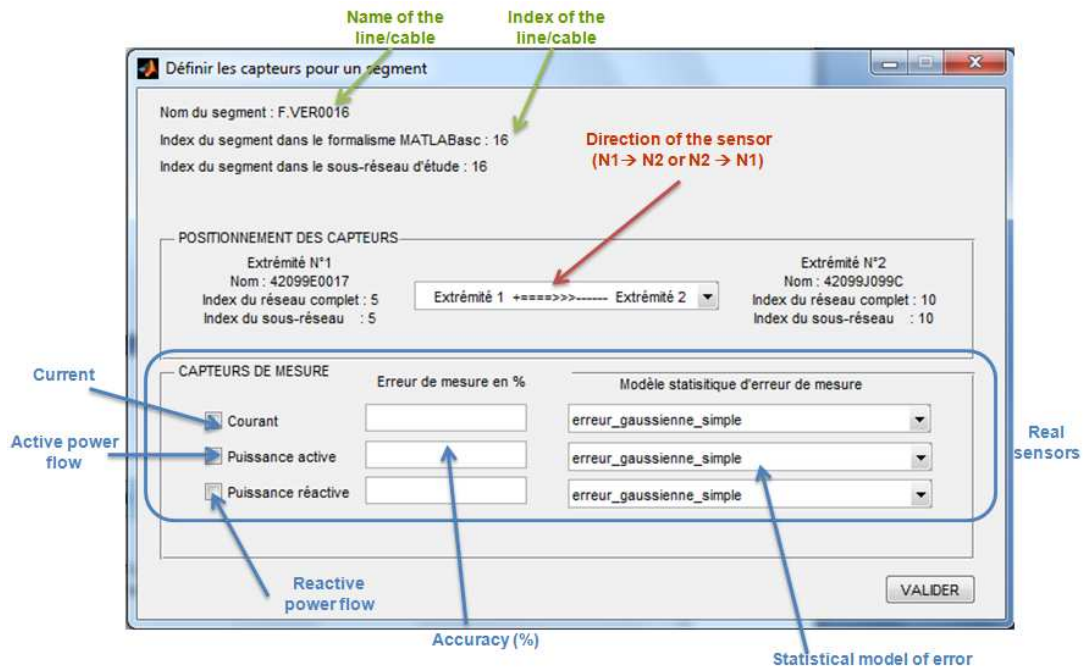


Figure 57: HMI of sensors configuration at one line/cable

3.5.2. Change mean value for pseudo-measurements

It is possible to change the mean value of the statistical model used to define pseudo-measurements. To center load models on the mean value, one has to select the <Sensor's positions> menu and the 'Load models centered around Pmean' (Figure 58).

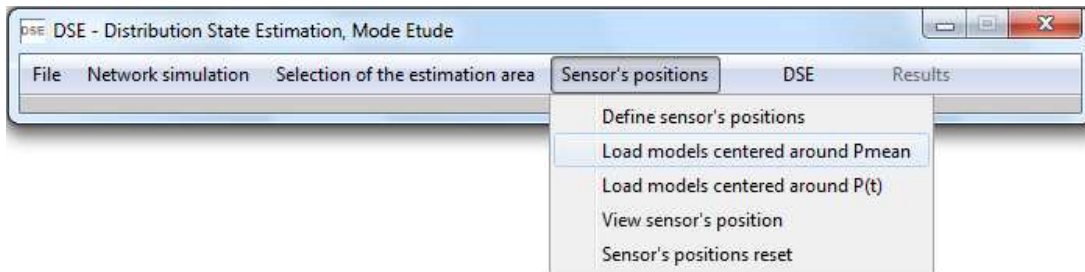


Figure 58: Changing mean value of pseudo-measurements to the mean value

To center load models on the real value (P_{max} or $P(t)$ depending on the users choice), one has to select the <Sensor's positions> menu and the 'Load models centered around $P(t)$ ' (Figure 59).

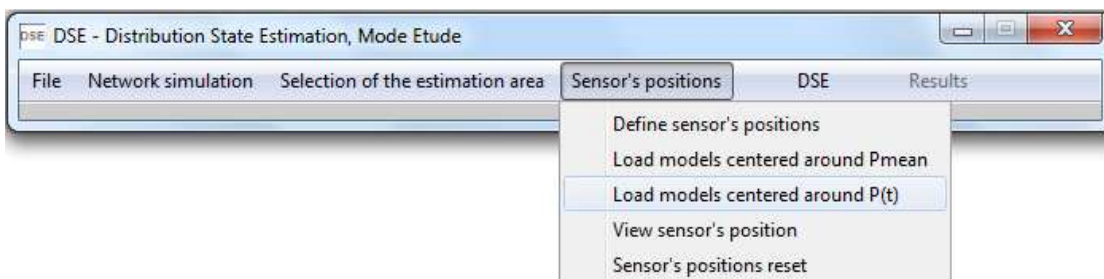


Figure 59: Changing mean value of pseudo-measurements to the real value

3.5.3. View sensors' position

It is possible to get a view of the sensors taken into account by the DSE algorithm. To do so, one has to select the <Sensor's positions> menu and the 'View sensor's position' (Figure 60).

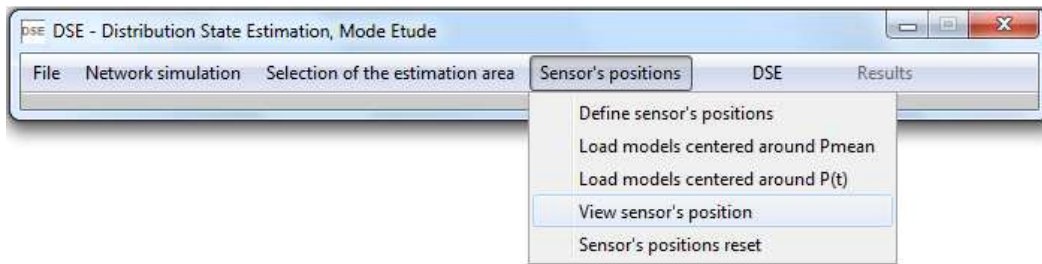


Figure 60: View of sensors position

In this case, a new network HMI will be opened with all available sensors and pseudo-measurements (Figure 61). For each type of sensor, a different color is used in the network representation:

- Voltage magnitude : blue,
- Voltage phase angle: red,
- Active and reactive power on a node: red,
- Current in lines/cables: violet,
- Active and reactive power flowing in lines/cables: green.

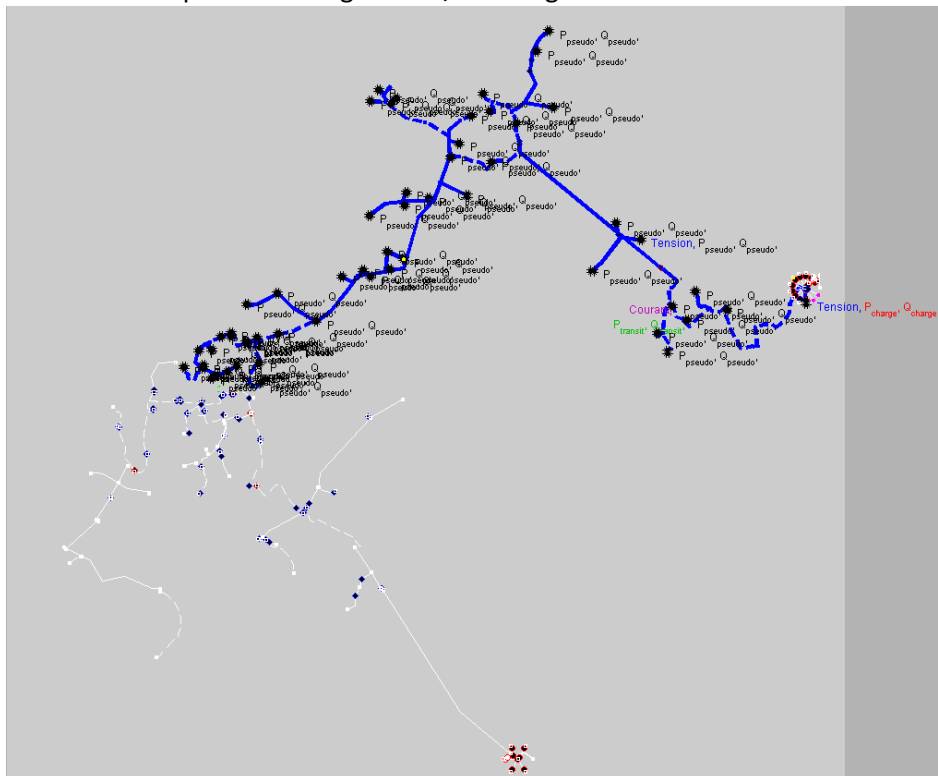


Figure 61: Network HMI with available sensors

3.5.4. Reset sensors information

It is possible to reset sensors information so sensors added previously are deleted and the initial configuration is set by default. To reset all sensors configuration, one has to select the <Sensor's positions> menu and the 'Sensor's positions reset' (Figure 62).

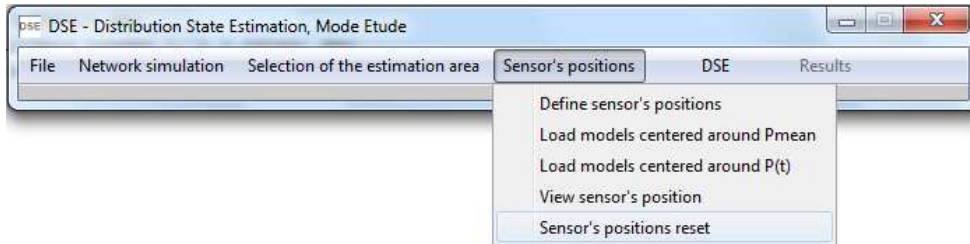


Figure 62: Resetting sensors placement

3.6. RUN THE DES ALGORITHM

3.6.1. Create noise measurements

To run DSE algorithms, it is necessary to generate noisy measurements used as inputs by the algorithms. To do so, one has to select the <DSE> menu and the 'Number of estimation to be run' (Figure 63).



Figure 63: Defining parameters to generate noisy measurements

A new window will be opened to define the parameters used to create noisy measurements (Figure 64). These parameters are:

- Number of estimations to be run,
- Initialization of the random (§2.4.1).



Figure 64: Choosing the parameters to create noisy measurements

3.6.2. Start the DSE calculation

To run the DSE algorithm, one has to select the <DSE> menu and the 'Run DSE' (Figure 65). For the moment, the only DSE algorithm available is the WLS.

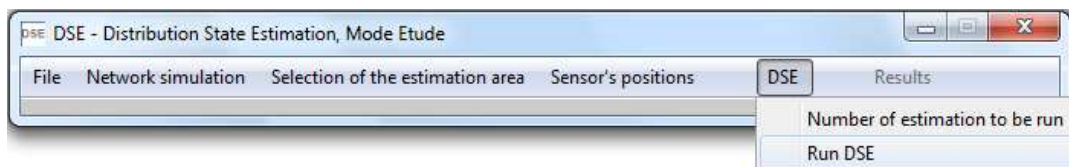


Figure 65: Running DSE algorithm

3.7. ANALYSIS RESULTS

Once the DSE algorithm has been run and the results are available, some analysis options are proposed to the user.

3.7.1. Numerical analysis

The numerical analysis allows the calculation of all electrical values from the estimated voltages and the admittance matrix and the calculation of the estimated error. At the end of this phase an Excel file is generated containing all the estimation results (Figure 14). To run this numerical analysis, one has to select the <Results> menu and the 'Numerical results' (Figure 66).



Figure 66: Getting numerical results

As explained in paragraph §2.5.2, some statistics are done regarding the results with less error than a defined value. Once the numerical results option has been chosen, it is necessary to define the accepted error. In Figure 67, the accepted errors for different electrical variables are defined and in Figure 68 the user can choose to compare the current results with other results (for example with other sensors configuration).

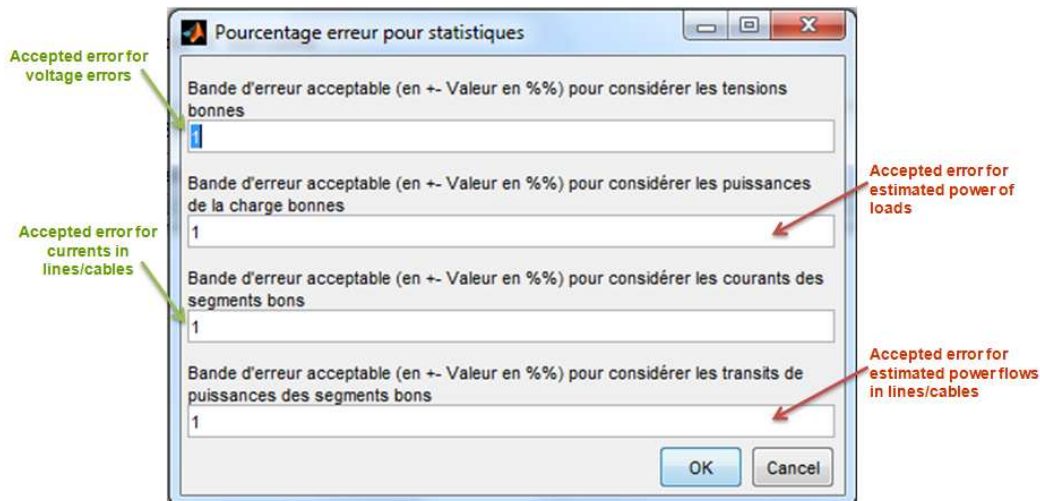


Figure 67: Defining the accuracy to run the statistical analysis

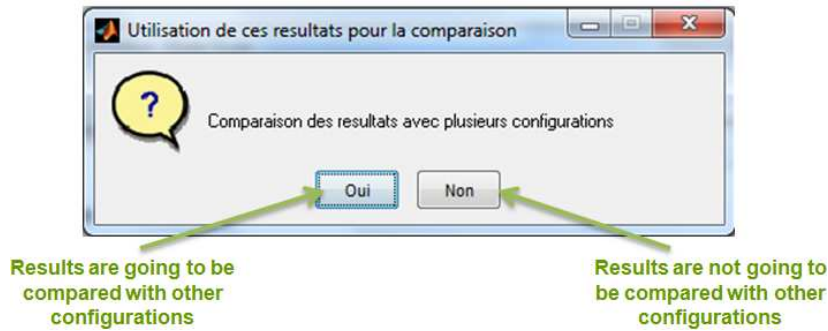


Figure 68: Choosing the comparison with other sensors configuration

3.7.2. Graphical analysis: ellipses

To have a visual representation of errors of voltages and power on nodes, it is possible to draw the ellipses described in §0. To do so, one has to select the <Results> menu and the 'Graphic results' (Figure 69). Questions regarding the accepted error (Figure 67) and the comparison with other configurations (Figure 68) have to be answered by the user as for numerical results.



Figure 69: Getting results with the ellipses

Before creating one figure per node, it is important to define the saving parameters of the ellipses. In fact, it is proposed to the user to decide if the ellipses are going to be saved and in which format. To do so, a new figure is created (Figure 70).

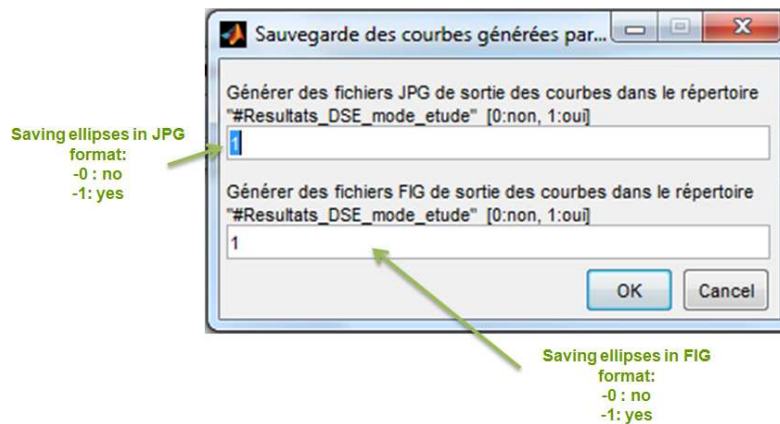


Figure 70: Choosing ellipses saving parameters

3.7.3. DSE results in the network HMI

Once all the electrical values have been calculated (with the numerical or the graphical analysis), it is possible to integrate the results of one estimation on the network HMI. To do so, one has to select the <Results> menu and the 'Introduction of DSE results in network HMI' (Figure 71).

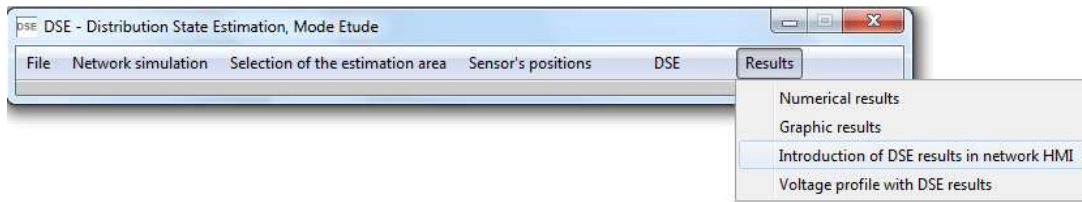


Figure 71: Introduction of DSE results into the network HMI

A new window appears so the user can indicate the number of the estimation that it is going to be integrated in the network HMI (Figure 72). If the zonal approach has been applied, a second window will appear to decide whether the MV feeder or the zonal results are integrated in the network HMI (Figure 73).

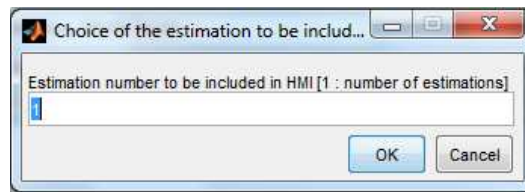


Figure 72: Choosing the “estimation” to be integrated into the HMI

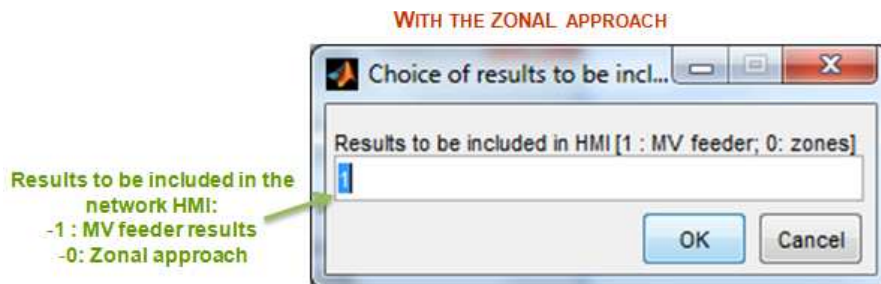


Figure 73: Choosing the MV feeder or the zonal approach to be integrated into the HMI

Once these choices have been made, something similar to Figure 16 is obtained.

3.7.4. Voltage profiles

The DSE tool allows the comparison of the real voltage profile and the estimated one. To compare both of them, one has to select the <Results> menu and the ‘Voltage profile with DSE results’ (Figure 74).



Figure 74: Integration of DSE results on voltage profiles

The questions in Figure 72 and in Figure 73 have to be answered by the user before getting the result in a similar manner as the results presented in Figure 17.

4. CASE STUDY

Once all options proposed by the DSE tool explained, two case studies are presented to show the use of the tool in the complete way.

4.1. USER'S DEFINITION ZONE

This case study presents the definition of the zone by choosing zone limits and a node inside the zone. The Network used for this case study is a French rural network. This network has one primary substation, two HV/MV transformers and 11 MV feeders. Its characteristics are summarized in Table 1.

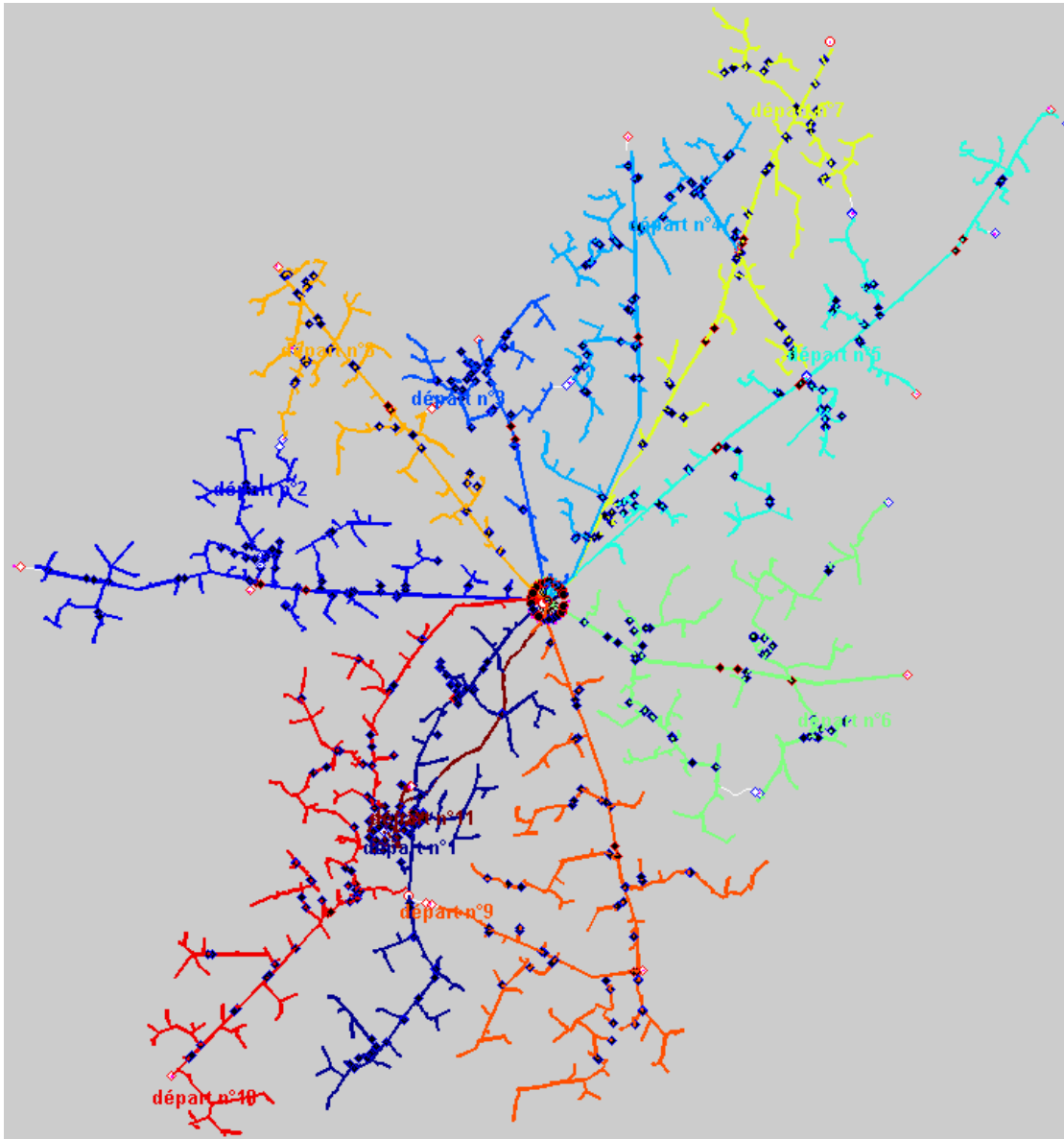


Figure 75 : Network topology

MV feeder	HV/MV substation	HV/MV transformer	Maximal Transit (kVA)	Length (km)	Overhead length (km)	Number of LV clients	Maximal voltage drop (%)
Feeder_1	Sub_1	T_HV_MV_1	2833.7	62.79	56.19	918	1.91%
Feeder_2	Sub_1	T_HV_MV_1	2942.4	74.43	70.29	1053	2.75%
Feeder_3	Sub_1	T_HV_MV_1	3528.4	36.23	30.44	1141	2.10%
Feeder_4	Sub_1	T_HV_MV_2	3442.2	66.55	60.72	1327	3.83%
Feeder_5	Sub_1	T_HV_MV_2	3761	70.63	63.50	1701	5.12%
Feeder_6	Sub_1	T_HV_MV_2	3049.1	79.35	75.38	1327	3.83%
Feeder_7	Sub_1	T_HV_MV_1	2902.6	68.57	61.76	1357	3.30%
Feeder_8	Sub_1	T_HV_MV_2	2119.6	54.89	52.08	1204	1.70%
Feeder_9	Sub_1	T_HV_MV_2	2392.1	86.06	84.54	891	2.25%
Feeder_10	Sub_1	T_HV_MV_2	2521.3	83.71	77.44	857	3.98%
Feeder_11	Sub_1	T_HV_MV_1	5079.3	22.61	3.07	1511	2.40%

Table 1 : Network characteristics

As explained in §3.2.1, some parameters for the load flow calculations have to be set in the initialization phase. In this case, the parameters used are:

- There are no generators in the network,
- The h ratio is settled at 3000 hours,
- All HV/MV transformers are regulated and their set point is 20.4kV,
- There is no capacitor bank connected to the network,
- The date for the P(t) load flow is 03/07 14:00
- The load profiles are:

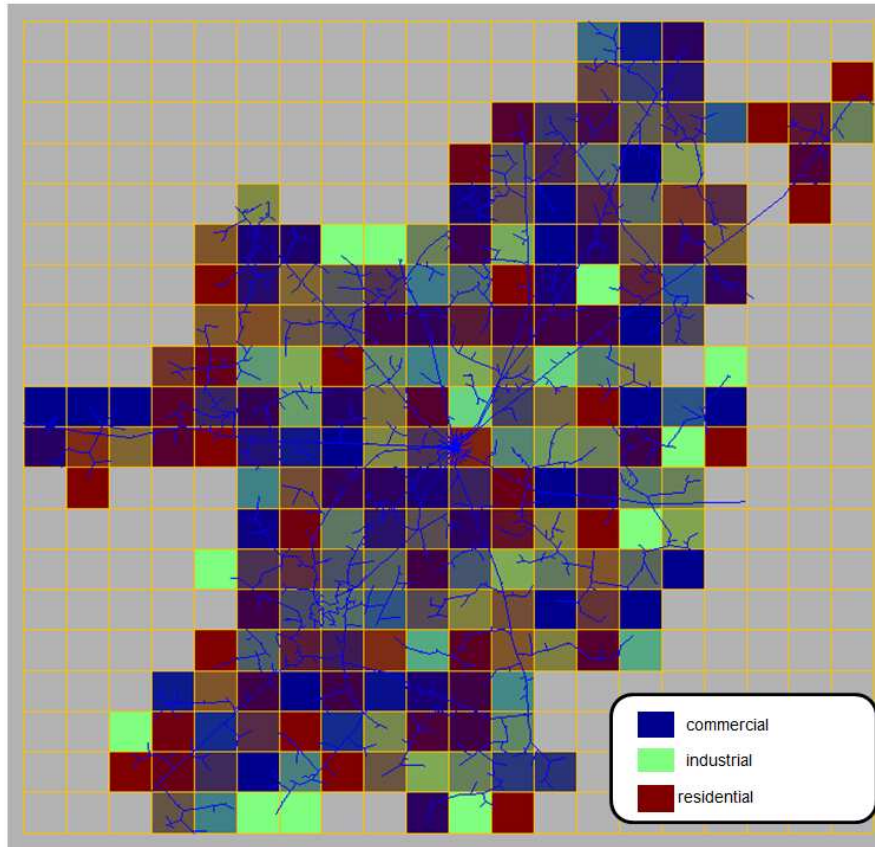


Figure 76: Load profiles

The option retained to define the zone to be estimated is ‘**User’s choice zone**’ and the chosen parameters to define the zone are:

- Border lines/cables: AUBIG2287,AUBIG2126 and AUBIG2182,
- Node in the zone: 49232E0035,
- New slack bus of the zone: no information is given so the closest node to the MV busbar.

Once these options are chosen, the chosen zone is represented in Figure 77. In this figure, the chosen zone is in red and the zone limits are in green.

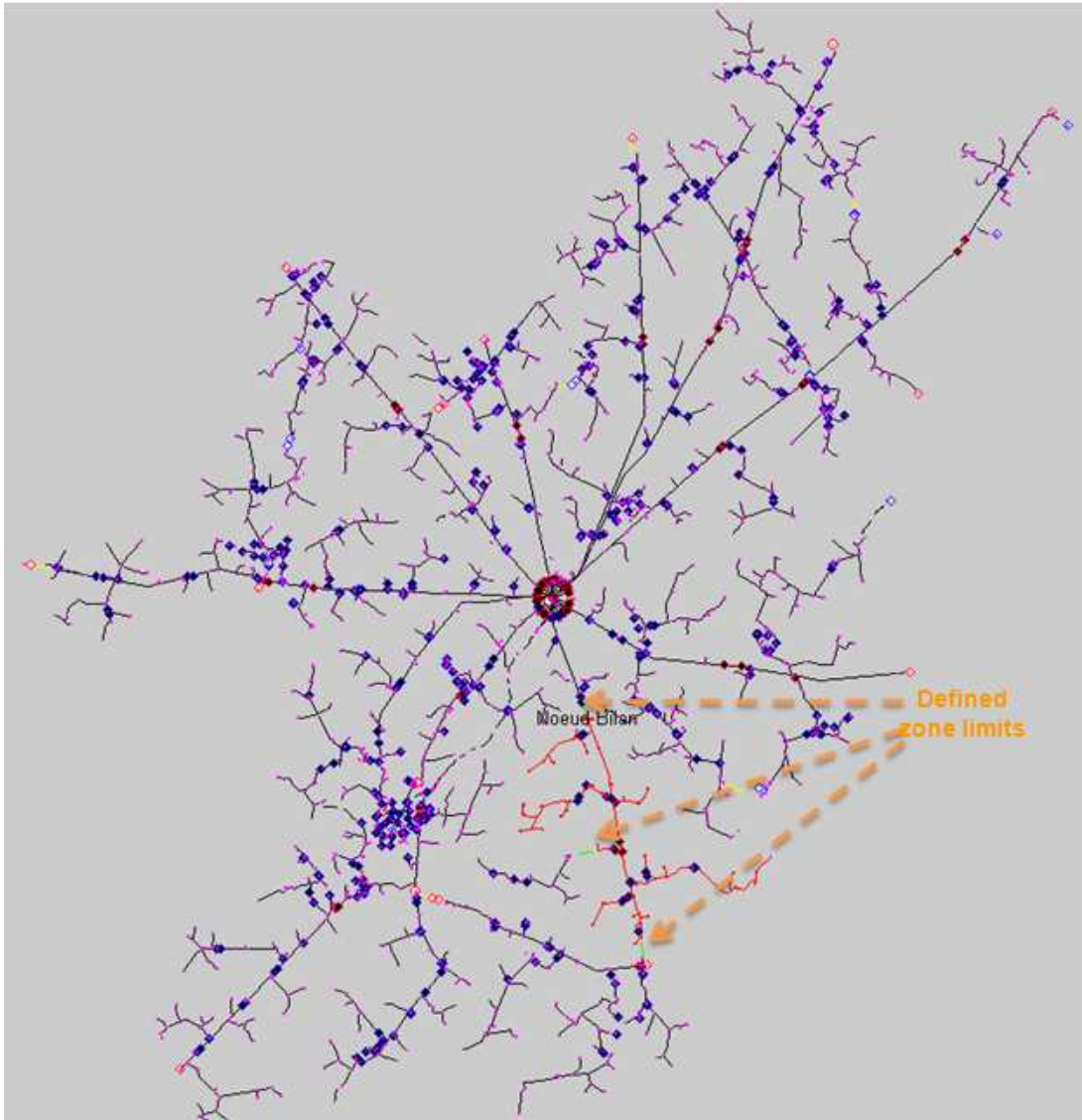


Figure 77 : Choice of the zone

The load flow results used to define the real state of the network are the results with the loads at the maximum value. The sensor configuration used for this study is composed of:

- PQV sensor at the beginning of the MV feeder,
- PQ sensor for each load.

All sensors are modeled with an accuracy of 1%. This sensor configuration is represented in Figure 78.

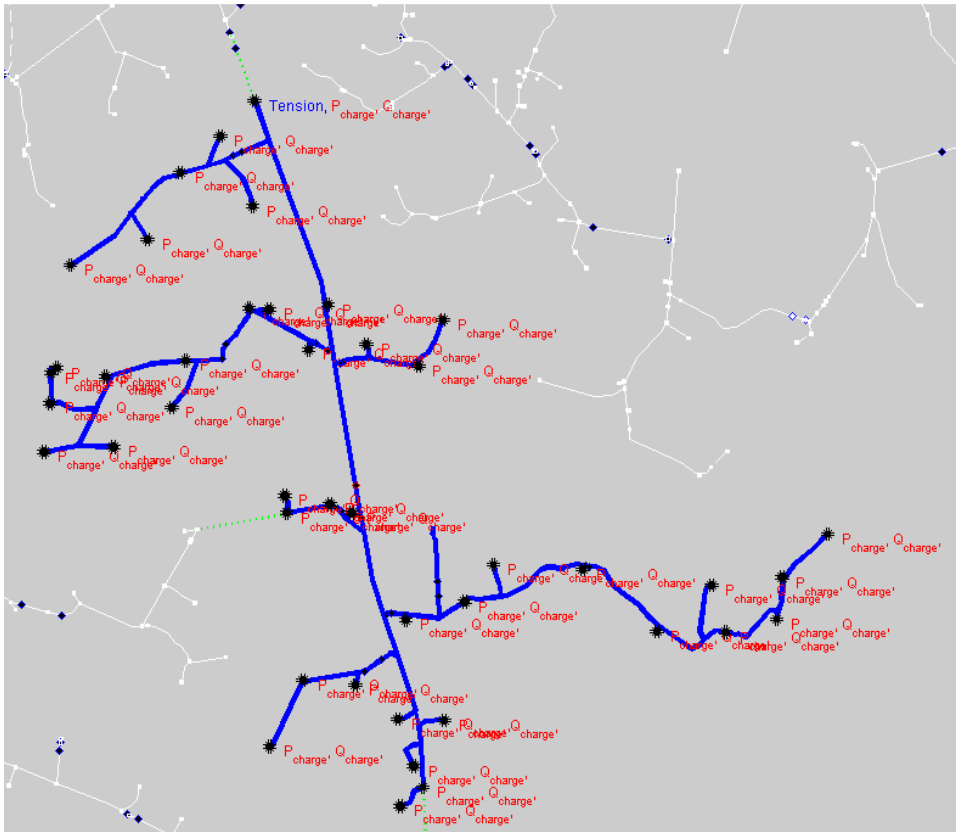


Figure 78: Sensors configuration for the chosen zone

With this sensor configuration, the DSE algorithm is applied to obtain the estimated variables. The estimated voltage profiles are illustrated in Figure 79. In this figure, it is possible to see how the estimated voltage profile doesn't begin at the busbar but in the middle of the MV feeder as the chosen zone doesn't integrate the busbar.

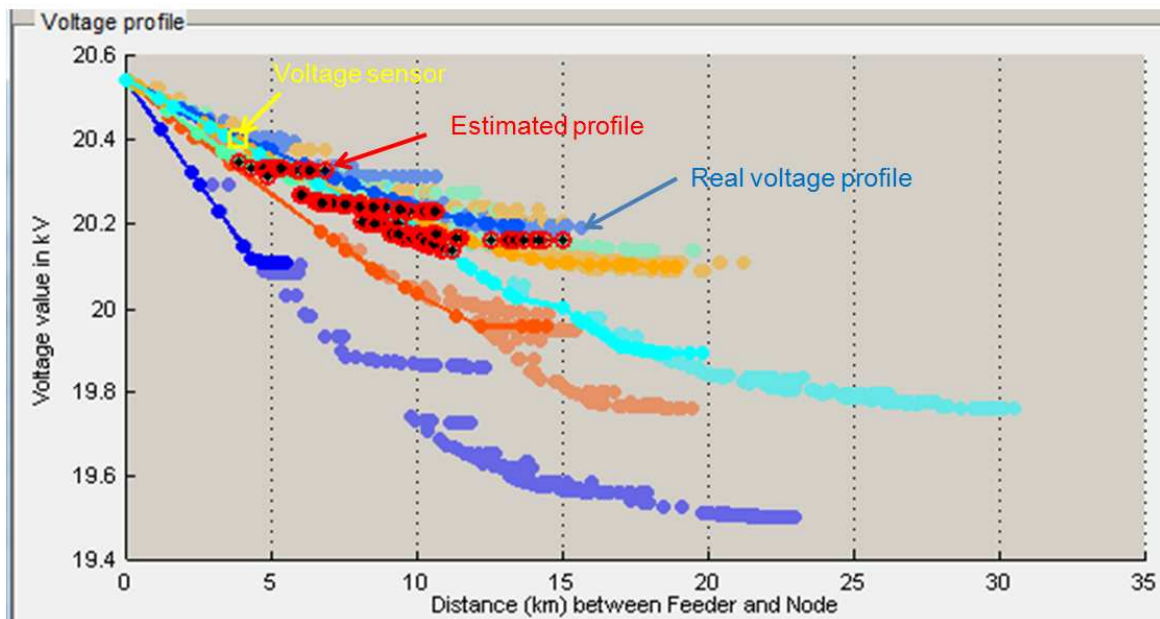


Figure 79: Voltage profile in the zone

4.2. ZONAL APPROACH

In this case, the zonal approach is applied to a network to show all possibilities and to show a comparison between the results obtained taking into account the entire MV feeder and the zonal approach.

The network used for the simulations with the zonal approach is a French semi-urban network (Figure 80). Its characteristics are summarized in Table 2.

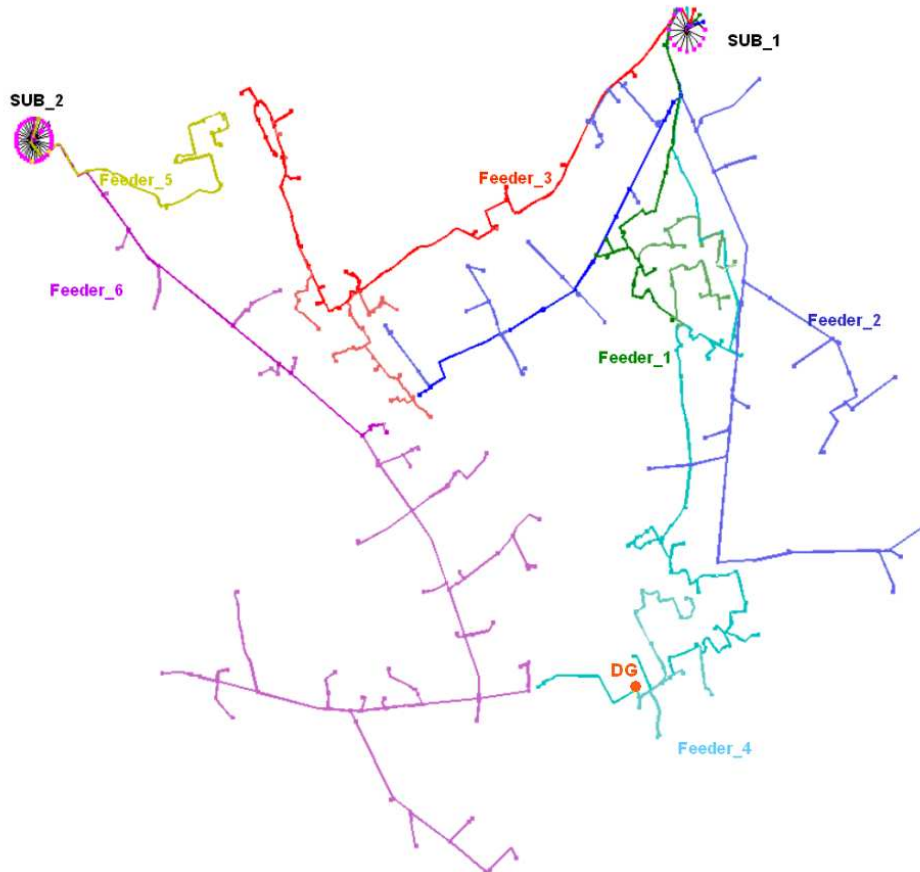


Figure 80 : Network topology

MV feeder	HV/MV substation	HV/MV transformer	Maximal Transit (kVA)	Length (km)	Overhead length (km)	Number of LV clients	Maximal voltage drop (%)
Feeder_1	Sub_1	T311	4020.6	12.543	0	1924	1.04%
Feeder_2	Sub_1	T311	965	27.256	24.324	204	0.32%
Feeder_3	Sub_1	T312	5906.5	19.176	0	1635	2.09%
Feeder_4	Sub_1	T312	5833.2	23.072	0	1694	3.94%
Feeder_5	Sub_2	T001	3400.2	6.147	0	54	0.60%
Feeder_6	Sub_2	T002	1712.5	27.790	24.393	343	1.65%

Table 2 : Network characteristics

As explained in §3.2.1, some parameters for the load flow calculations have to be set in the initialization phase. In this case, the parameters used are:

- All generators are considered as having a PQ behavior,
- The h ratio is settled at 3500 hours,
- The k ratio for the three generators is 0.17 as they are considered as being PV panels,
- All HV/MV transformers are regulated and their set point is 20.4kV,
- A capacitor bank of 2.5MVA is connected to the network and it can be used for the reactive power compensation,
- The date for the P(t) load flow is 12/10 10:00
- The load profiles are:

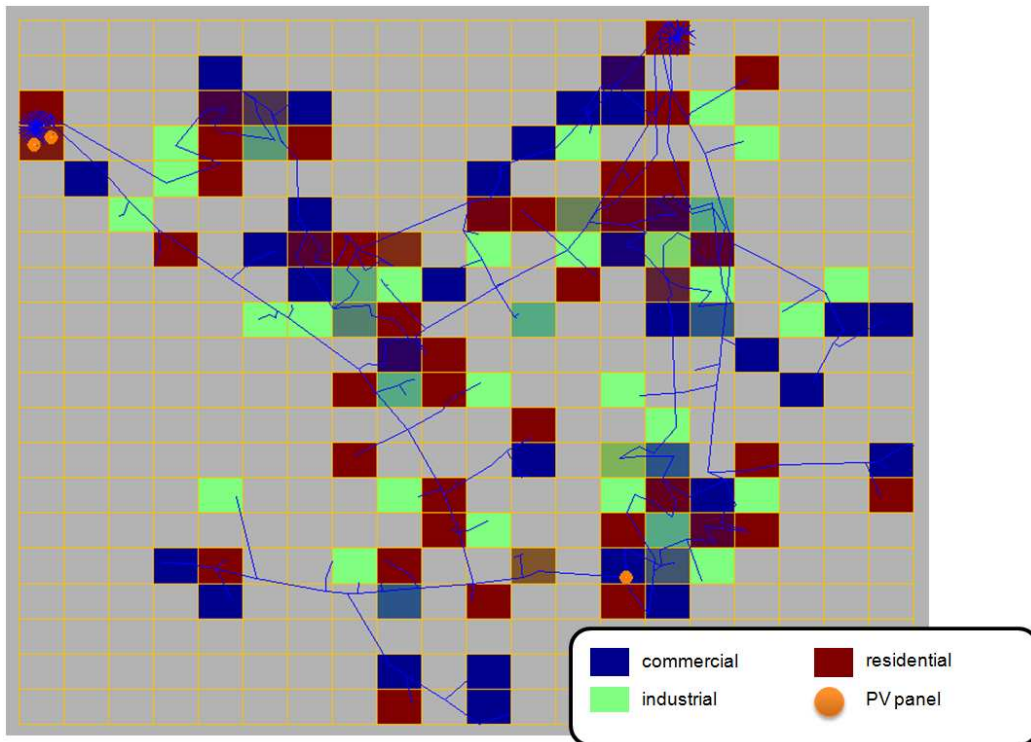


Figure 81: Load profiles

The option retained to define the zone to be estimated is ‘**MV feeder with zones**’ and the chosen parameters for the zonal approach are:

- Visualization of each zone in the HMI: False,
- Can the slack bus of each zone have a load directly connected: False,
- Type of configuration for the zonal estimation: Parallel,
- Use of existing voltage sensors for zone: True,
- DSE to be used: WLS.

Once these options are chosen, the MV feeder in which the zonal approach is going to be applied has to be chosen (Figure 82).

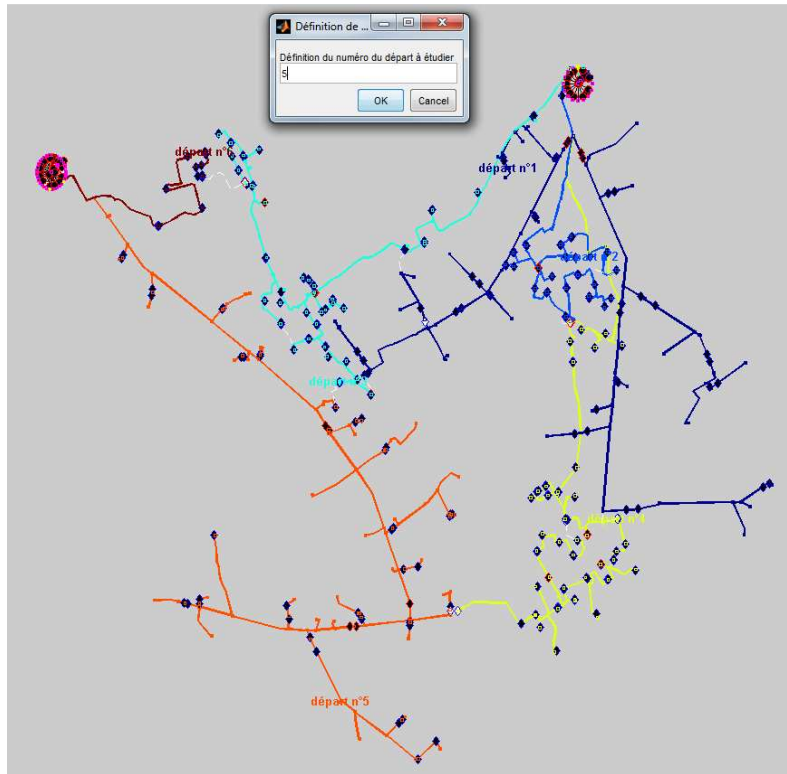


Figure 82 : Choice of the MV feeder

The MV feeder number 5 has been chosen and the zones between remote controlled switches are defined. In Figure 83, it is possible to identify the four zones into which the MV feeder has been split in.

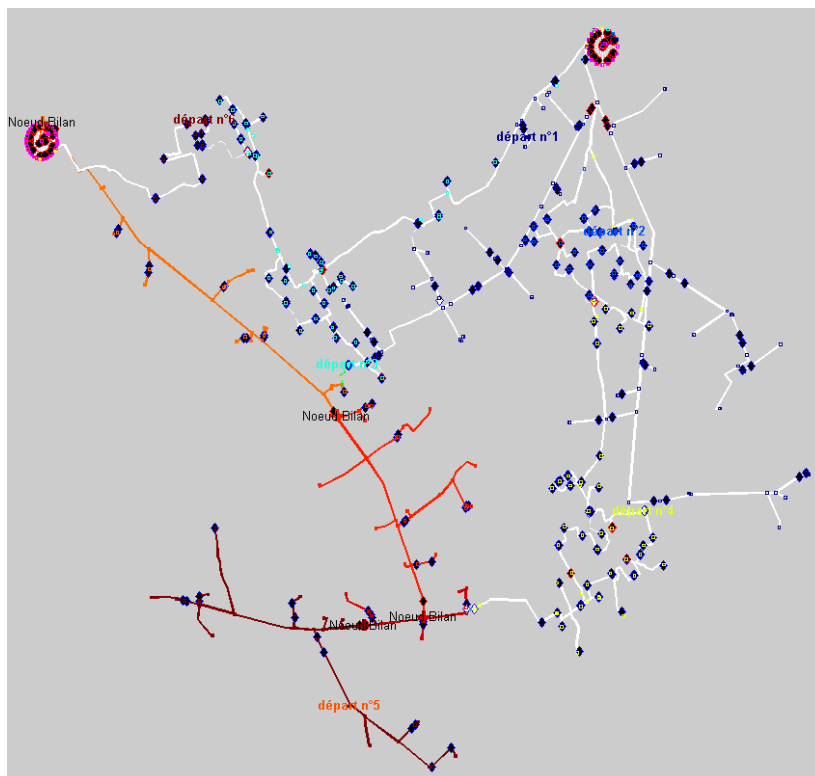


Figure 83 : Zones in the MV feeder

The load flow results used to define the real state of the network are the results with the load curve P(t).

The default sensors configuration is used for this case study. As the parallel approach has been chosen, a PQV sensor at the beginning of each zone has been placed. The PQ sensor is not associated to the node but to the first section of the zone as its goal is to measure the power entering the zone. This sensor configuration is represented in Figure 84. All sensors are modeled with an accuracy of 1%. The pseudo-measurements are centered on the mean value of the loads (maximum value* h ratio) with a Gaussian error of 50%.

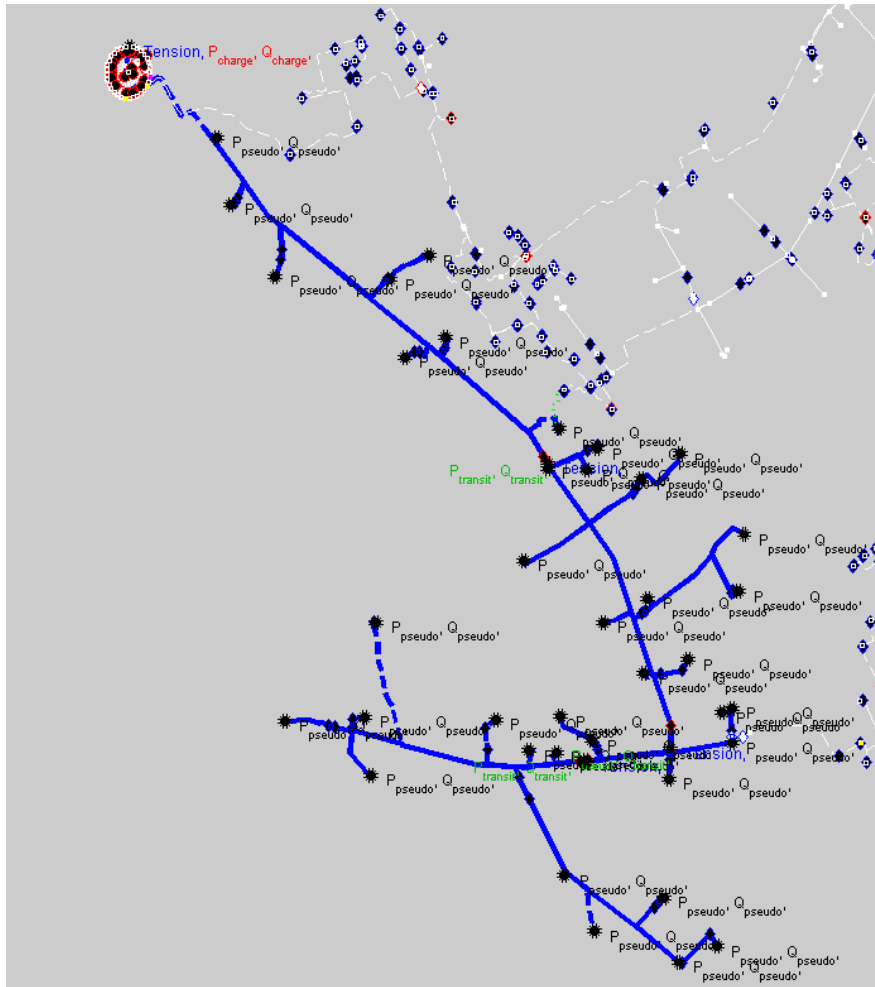


Figure 84: Sensors configuration for the zonal approach

With this sensor configuration, the DSE algorithm is applied to obtain the estimated variables. To compare the performances between the MV feeder and the zonal approach, both configurations are estimated and are going to be compared.

The estimated voltage profile obtained with the MV feeder configuration is represented in Figure 85 and with the zonal approach in Figure 86. It is possible to see that, the zonal approach introduces voltage gaps in the estimated voltage profile as zones are considered as independent.

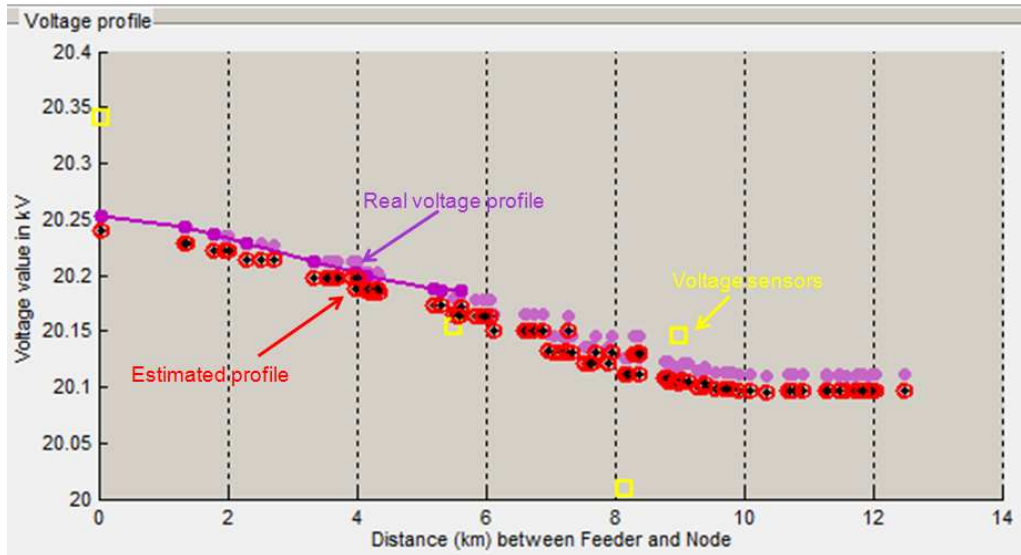


Figure 85: Voltage profile with the MV feeder configuration

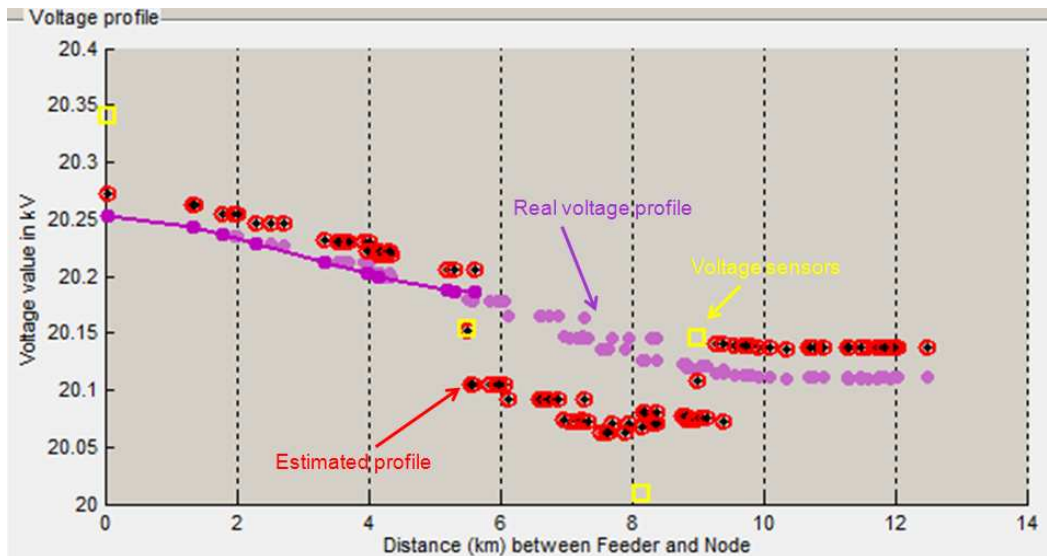


Figure 86: Voltage profile with the zonal approach

To solve this voltage gap problem, it is possible to use the direct results of DSE to determine the voltage drop in each zone. With this voltage drop information, one could generate for each zone the voltage profile of the MV feeder using DSE results of the zone and voltage drop for the other zones. At the end of this stage, as many voltage profiles as zones are available. The final voltage profile is the mean of all voltage profiles.

5. CONCLUSION

The structure of the developed tool is summarized in Figure 87. This structure facilitates the change of the DSE algorithm to introduce a different one (for example the PSO approach described in D.2.1.1).

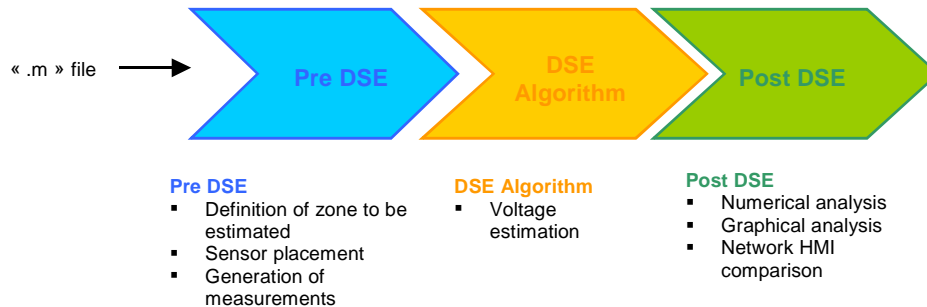


Figure 87: Architecture of MV network DSE tool

The « Pre DSE » block uses the “m” file description of the network to generate the inputs used by the DSE algorithms. In this phase, the real state of the network is defined with a load flow calculation, the zone that is going to be estimated is chosen and the sensors are placed in the network (the measurement noise is also simulated).

Once the DSE inputs are generated by the “Pre DSE”, the “DSE algorithm” is run and estimated voltages are obtained as outputs. The algorithm inside this block can be changed by another as the PSO if the inputs of both algorithms are identical.

Finally, the “Post DSE” block analyzes the estimation results. These analyses can be numerical or graphical and results can also be integrated in the network HMI.

This DSE software tool is made available to the partners of the HiperDNO project. It will be used to run case studies as part of the demonstration phase.

6. BIBLIOGRAPHY

[1] <http://www.uclm.es/area/gsee/web/Federico/psat.htm>

7. APPENDICES

7.1. APPENDIX 1. STRUCTURE OF “.M” FILES

The network information used by the DSE tool is described in a “.m” file and it is structured as described in Figure 88.

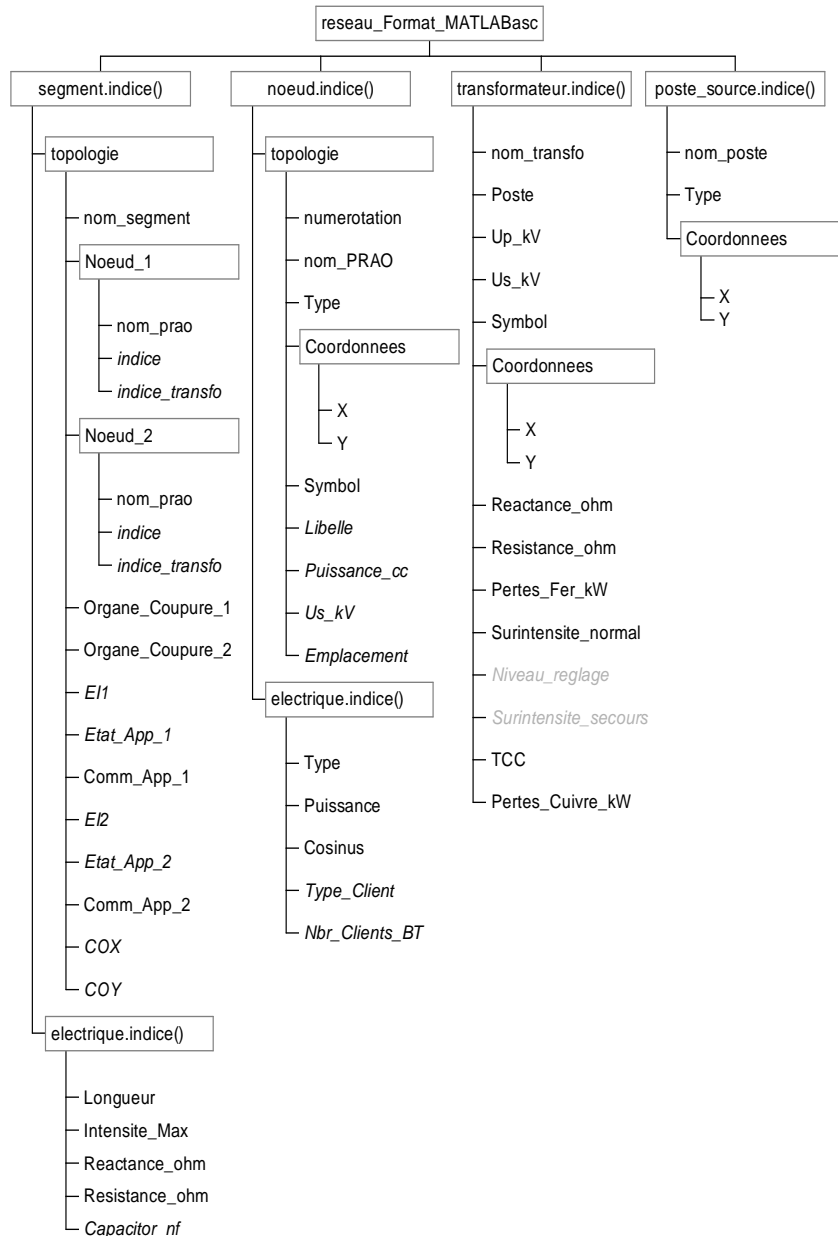


Figure 88 : Structure of the network in the « .m » file

7.2. APPENDIX 2. INPUTS OF DSE ALGORITHM

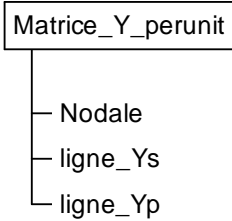
The four structures containing input information for the DSE algorithm are:

- Matrice_Y_perunit : structure with topological information
- data_from_donnees : structure with sensors and general information
- Vecteur_Z_mesure : structure with measurement information

- Grandeur_VIPQ : structure containing real state of the network

Some of the information contained in these structures are not used by the DSE algorithms but have been integrated into the structures as they are useful in previous steps of the DSE tool.

7.2.1. Matrice_Y_perunit



Name	Type	Description
Matrice_Y_perunit		
.Nodale	Matrix (Number of nodes, Number of nodes)	Matrix with admittances in pu between 2 nodes.
.ligne_Ys	Matrix (Number of nodes, Number of nodes)	Matrix with the value $\frac{1}{(R+j \cdot X) \cdot L}$ in pu between N1 and N2
.ligne_Yp	Matrix (Number of nodes, Number of nodes)	Matrix with the value $j \cdot pi \cdot 50 \cdot C \cdot L$ in pu between N1 and N2

7.2.2. data_from_donnees

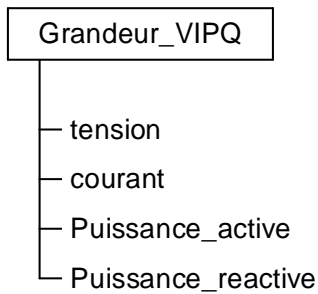
data_from_donnees

- TransitP
- segment_correspondant_TransitP_sous_reseau
- segment_correspondant_TransitP_reseau_complet
- TransitQ
- segment_correspondant_TransitQ_sous_reseau
- segment_correspondant_TransitQ_reseau_complet
- CapteurV
- CapteurPhase
- CapteurI
- segment_correspondant_I_sous_reseau
- segment_correspondant_I_reseau_complet
- CapteurP
- CapteurQ
- Ppseudo_mesure
- Qpseudo_mesure
- noeud_valeur_centrale_pseudo_mesures_etat_reseau
- noeud_valeur_centrale_pseudo_mesures_P_moy
- Noeud_mesure_virtuelle_contrainte
- liste_noeuds_non_virtuels
- delta_init
- noeud_reference
- nombre_estimation
- nombre_noeud
- SNB
- UNB
- Vinit

Name	Type	Description
data_from_donnees		
.TransitP	Matrix	Index of nodes of lines/cables with a active flow sensors
.Segment_correspondant_TransitP_sous_reseau	Matrix	Information regarding active flow sensors
.Segment_correspondant_TransitP_reseau_complet	Vector	Index of lines/cables (complete network) with a active flow sensors
.TransitQ	Matrix	Index of nodes of lines/cables with a reactive flow sensors
.Segment_correspondant_TransitQ_sous_reseau	Matrix	Information regarding reactive flow sensors
.Segment_correspondant_TransitQ_reseau_complet	Vector	Index of lines/cables (complete network) with a reactive flow sensors
.CapteurV	Vector	Index of nodes with a sensor for voltage magnitude
.CapteurPhase	Vector	Index of nodes with a sensor for voltage phase angle
.CapteurI	Matrix	Index of nodes of lines with a current sensor
.Segment_correspondant_I_sous_reseau	Matrix	Information regarding current sensors
.Segment_correspondant_I_reseau_complet	Vector	Index of lines/cables (complet network) with a current sensor
.CapteurP	Vector	Index of nodes with a sensor for active power
.CapteurQ	Vector	Index of nodes with a sensor for reactive power
.Ppseudo_mesure	Vector	Index of nodes with load model for active power
.Qpseudo_mesure	Vector	Index of nodes with load model for reactive power
.Nœud_valeur_centrale_pseudo_mesures_etat_reseau	Vector	Index of nodes with load model centred on real value
.Nœud_valeur_centrale_pseudo_mesures_P_moy	Vector	Index of nodes with load model centred on mean value
.Nœud_mesure_virtuelle_contrainte	Vector	Index of virtual nodes
.liste_nœuds_non_virtuels	Vector	Index of non virtual nodes

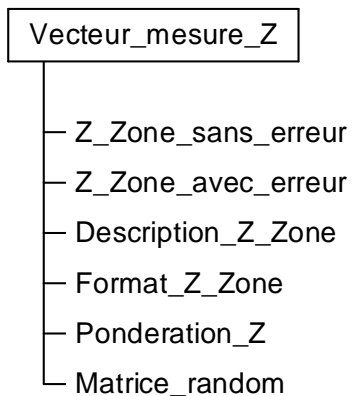
.delta_init	Double	Initial value of voltage phase angles
.nœud_reference	Int	Index of slack bus
.nombre_estimation	Int	Number of estimations to be done
.nombre_nœud	Int	Number of nodes
.SNB	Double	Power used for pu (in VA)
.UNB	Double	Voltage used for pu (in V)
.Vinit	Double	Initial value of voltages in pu

7.2.3. Grandeur_VIPQ



Name	Type	Description
GRANDEUR_VIPQ		
.tension	Vector	Voltages at different nodes
.courant	Vector	Current injections/ consumptions on nodes
.Puissance_active	Vector	Active power of each node
.Puissance_reactive	Vector	Reactive power of each node

7.2.4. Vecteur_Mesure_Z



Name	Type	Description
Vecteur_mesure_Z		
.Z_Zone_sans_erreur	Vector	Measured values (without noise)
.Z_Zone_avec_erreur	Matrix	Measured values (noisy)
.Description_Z_Zone	Matrix	Information about the type and the position of the measure
.Format_Z_Zone	Text	Pour for each sensor : « Node 1 : __ Node 2 : __ Type of measurement : __ »
.Ponderation_Z	Vector	Weighting factors
.Matrice_random	Vector	Random matrix (representing noise)