Warsaw University of Technology

Faculty of Electrical Engineering

Diploma thesis
Bachelor's

In the field of study of Electrical Engineering
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Design of a medium voltage distribution network

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1. Thesis abstract

Design of a medium voltage distribution network

The main objective of the present work is the design and study of a medium voltage distribution network. The study consisted of designing with the help of PowerWorld a distribution network with a main generator and a network of loads that are connected at different nodes of the circuit. To this we must add several renewable energy sources at various points in the system. Using PowerWorld, we will simulate the system in different usage scenarios and compare voltages and currents to see how the system works and to be able to detect any possible anomalies.

Keywords: distribution network, RES (renewable energy source), voltages, currents, PowerWorld, simulations.

Projektowanie sieci rozdzielczej średniego napięcia

Głównym celem niniejszej pracy jest zaprojektowanie i zbadanie sieci dystrybucyjnej średniego napięcia. Badanie polegało na zaprojektowaniu za pomocą programu PowerWorld sieci dystrybucyjnej, w której znajduje się generator główny oraz sieć odbiorników, które są przyłączone w różnych węzłach obwodu. Do tego musimy dodać kilka odnawialnych źródeł energii w różnych punktach systemu. Używając oprogramowania PowerWorld przeprowadzimy symulację systemu w różnych scenariuszach użytkowania i porównamy napięcia i prądy, aby zobaczyć jak działa system i wykryć ewentualne anomalie.

Słowa kluczowe: sieć dystrybucyjna, OZE (odnawialne źródło energii), napięcia, prądy, PowerWorld, symulacje.

Diseño de una red de distribución de media tensión

El objetivo principal del presente trabajo es el diseño y el estudio de una red de distribucion de media tension. El estudio consistió en diseñar con la ayuda de PowerWorld una red de distribución que cuente con un generador principal y una red de cargas que se conectan en diferentes nodos del circuito. A esto le debemos añadir varias fuentes de energía renovable en varios puntos del sistema. Utilizando el programa PowerWorld simularemos el sistema en distintos escenarios de uso y compararemos tensiones y corrientes para ver el funcionamiento del sistema y poder detectar alguna posible anomalía.

Palabras clave: red de distribución, RES (fuente de energía renovable), tensiones, corrientes, PowerWorld, simulaciones.

2. Statement on the autorship of the thesis

I declare that this work is original, authentic, personal, that the corresponding sources have been cited and that in its execution the legal provisions that protect current copyright were respected. The ideas, doctrines, results and conclusions that I have reached are my sole responsibility.

3. Table of contents

4. References

In the drafting of this project, all the current regulations applicable in Spain were considered, and in particular:

- Royal Decree 1955/2000 of 1 December 2000, which regulates the transmission, distribution, marketing, supply and authorisation procedure for electrical energy installations.

- Low and Medium Voltage Electrotechnical Regulations and complementary Technical Instructions, approved by Royal Decree 842/2002, of 2 August.

5. General characteristics

The nominal distribution voltage will be three-phase with distributed neutral and directly connected to earth, with a transformer that will reduce the voltage from 110 kV to 20 kV.

The distribution networks in question are three-phase overhead networks for low medium voltage, fed at one end by means of twisted insulated cables made up of three phase conductors (aluminium) and a neutral conductor, the latter being self-supporting and made of hard aluminium alloy (Almelec).

The value of the loads has been randomised in the range of 5-30 kW and 0-18 kvar and a higher load of 300 kW and 200 kvar as we do not have enough time to be able to carry out a more accurate study.

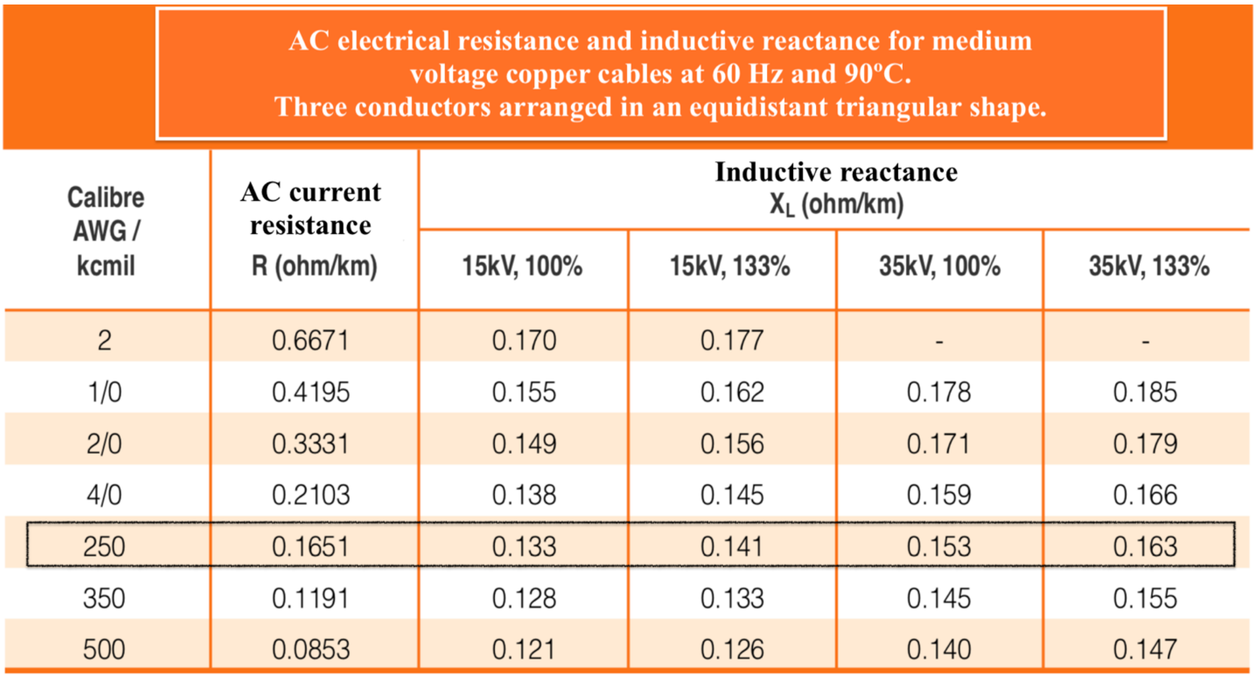
In the distribution system we have placed a main generator with higher generating capacity and 4 renewable energy sources. We have set up the main generator with a main supply power of 10 MW. RES 1 has been associated with a small field of wind generators totalling 3 MW, while RES 2, 3 and 4 have been associated with small wind generators with a power of 0.5 MW.

6. Type and parameters of materials used in the project

• Conductors (transmission lines):

The conductors to be used in the projected overhead medium voltage networks will be of insulated aluminium of the stranded bundled type with self-supporting neutral. A table with the type of conductor used is shown below:

Table 6.1. Type of conductor used



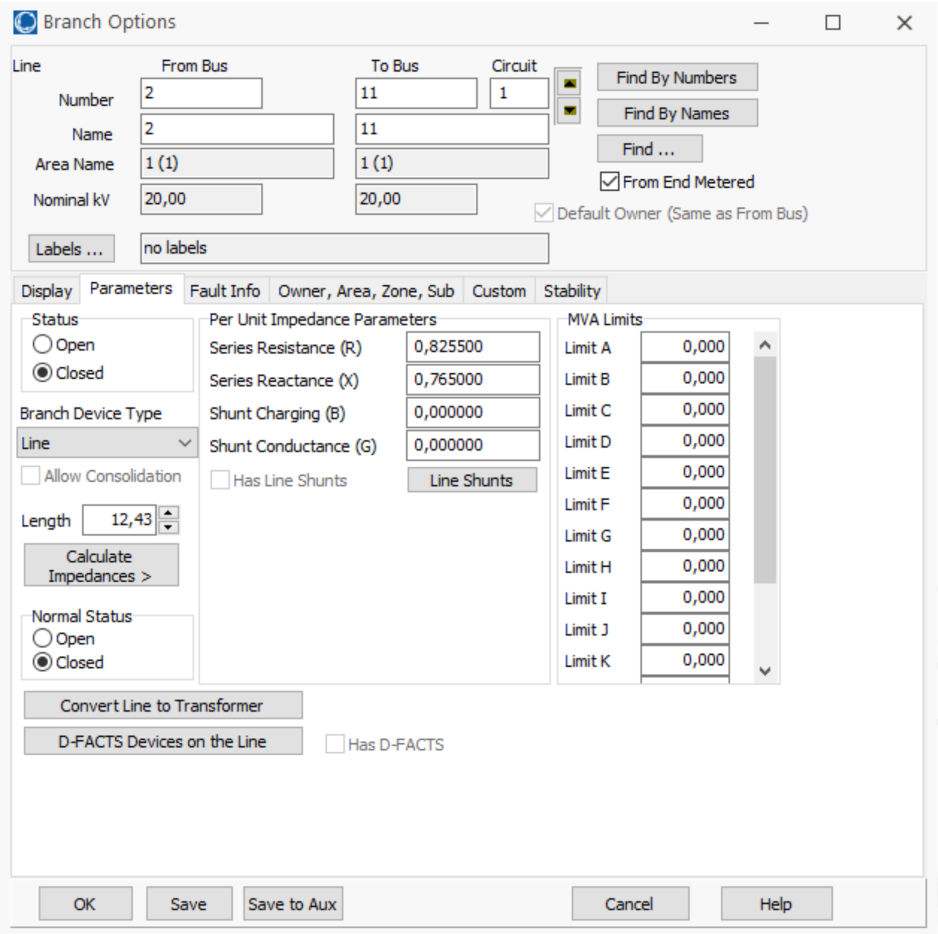
AC electrical resistance and inductive reactance for medium voltage copper cables at 60 Hz and 90ºC. Three conductors arranged in an equidistant triangular shape.

Calibre AWG / kcmil	AC current resistance R (ohm/km)	Inductive reactance X_L (ohm/km)			
		15kV, 100%	15kV, 133%	35kV, 100%	35kV, 133%
2	0.6671	0.170	0.177	-	-
1/0	0.4195	0.155	0.162	0.178	0.185
2/0	0.3331	0.149	0.156	0.171	0.179
4/0	0.2103	0.138	0.145	0.159	0.166
250	0.1651	0.133	0.141	0.153	0.163
350	0.1191	0.128	0.133	0.145	0.155
500	0.0853	0.121	0.126	0.140	0.147

Therefore, the cable used has the following nominal resistance and reactance values per kilometre:

$$\begin{cases} R = 0{,}1651 \ \dfrac{\Omega}{km} \\ X_L = 0{,}153 \ \dfrac{\Omega}{km} \end{cases}$$

Below we can see the options for one of the distribution lines, in which to calculate the impedances we entered the distance and the previous unit values per kilometre and the programme automatically calculated the R and X for us. We can see that this is the line that goes from bus-bar 2 to bus-bar 11, whose initial nominal voltage is 20 kV and its length is 20 km.



Line

From Bus: Number 2; Name 2; Area Name 1 (1); Nominal kV 20,00

To Bus: Number 11; Name 11; Area Name 1 (1); Nominal kV 20,00

Circuit 1

☑ From End Metered

☑ Default Owner (Same as From Bus)

Labels: no labels

Status
○ Open
● Closed

Branch Device Type: Line

☐ Allow Consolidation

Length 12,43

Normal Status
○ Open
● Closed

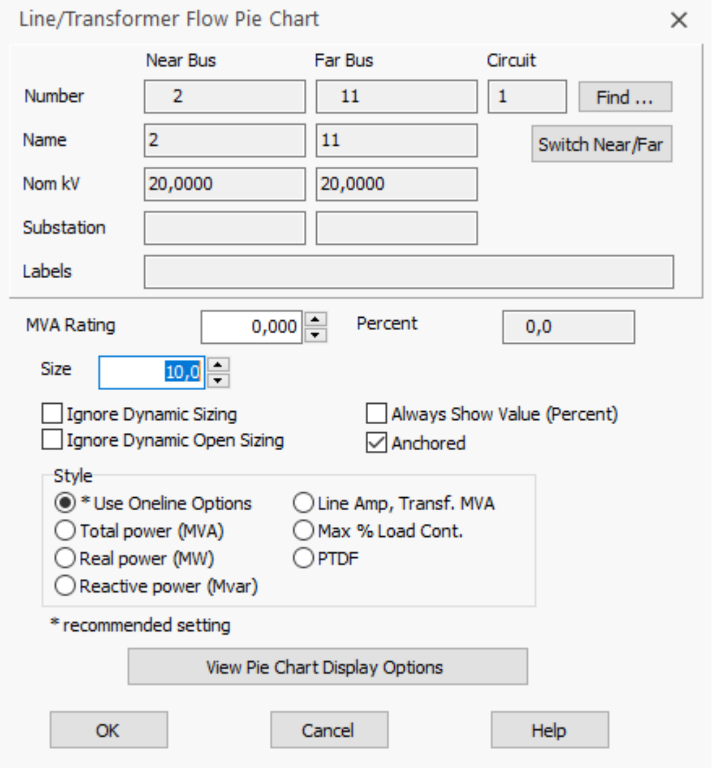
Per Unit Impedance Parameters
Series Resistance (R) 0,825500
Series Reactance (X) 0,765000
Shunt Charging (B) 0,000000
Shunt Conductance (G) 0,000000
☐ Has Line Shunts

MVA Limits
Limit A 0,000
Limit B 0,000
Limit C 0,000
Limit D 0,000
Limit E 0,000
Limit F 0,000
Limit G 0,000
Limit H 0,000
Limit I 0,000
Limit J 0,000
Limit K 0,000

☐ Has D-FACTS

Figure 6.1. Branch options

The distribution lines include meters with which we can control different parameters as shown in the picture on the right:



Near Bus: Number 2; Name 2; Nom kV 20,0000; Substation

Far Bus: Number 11; Name 11; Nom kV 20,0000; Substation

Circuit 1

Labels

MVA Rating 0,000

Percent 0,0

Size 10,0

☐ Ignore Dynamic Sizing
☐ Ignore Dynamic Open Sizing
☐ Always Show Value (Percent)
☑ Anchored

Style
● * Use Oneline Options
○ Total power (MVA)
○ Real power (MW)
○ Reactive power (Mvar)
○ Line Amp, Transf. MVA
○ Max % Load Cont.
○ PTDF

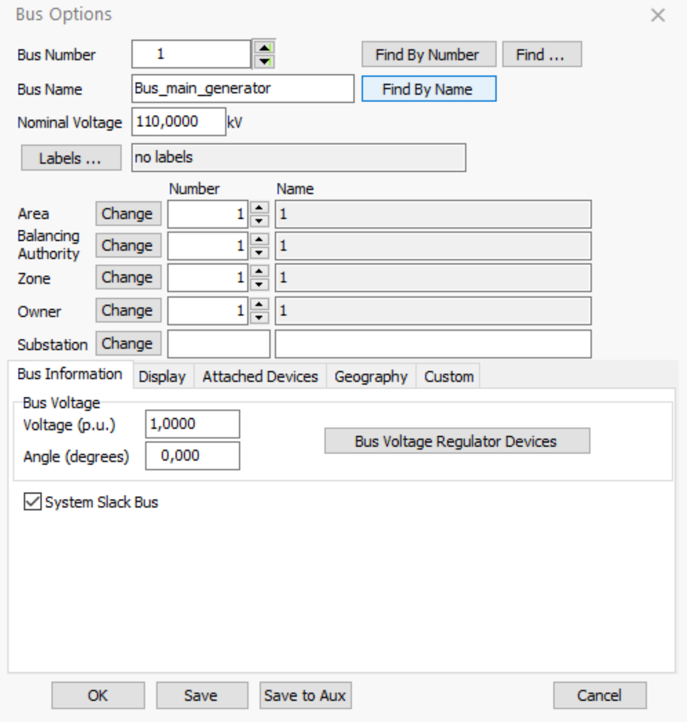
* recommended setting

Figure 6.2. Line/Transformer Flow Pie Chart

- **Bus-bars:**

In this project, we have worked with different nominal voltages on the bus-bars, 20 and 110 kV and have set both 1 per-unit values on the bus voltage without any phase shift.

The parameters of the 20 kV bus-bar entered in the powerworld simulator are shown below:


Bus Options

Bus Number: 1

Bus Name: Bus_main_generator

Nominal Voltage: 110,0000 kV

Labels ...: no labels

	Number	Name
Area	1	1
Balancing Authority	1	1
Zone	1	1
Owner	1	1
Substation		

Bus Voltage

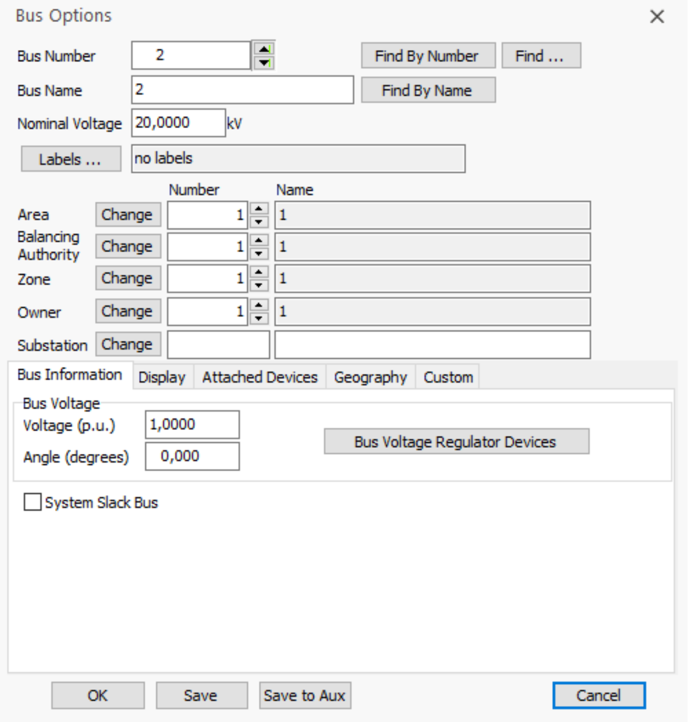
Voltage (p.u.): 1,0000

Angle (degrees): 0,000

☑ System Slack Bus

Figure 6.3. Bus Options

While the parameters of the 110 kV bus-bar are as follows:


Bus Options

Bus Number: 2

Bus Name: 2

Nominal Voltage: 20,0000 kV

Labels ...: no labels

	Number	Name
Area	1	1
Balancing Authority	1	1
Zone	1	1
Owner	1	1
Substation		

Bus Voltage

Voltage (p.u.): 1,0000

Angle (degrees): 0,000

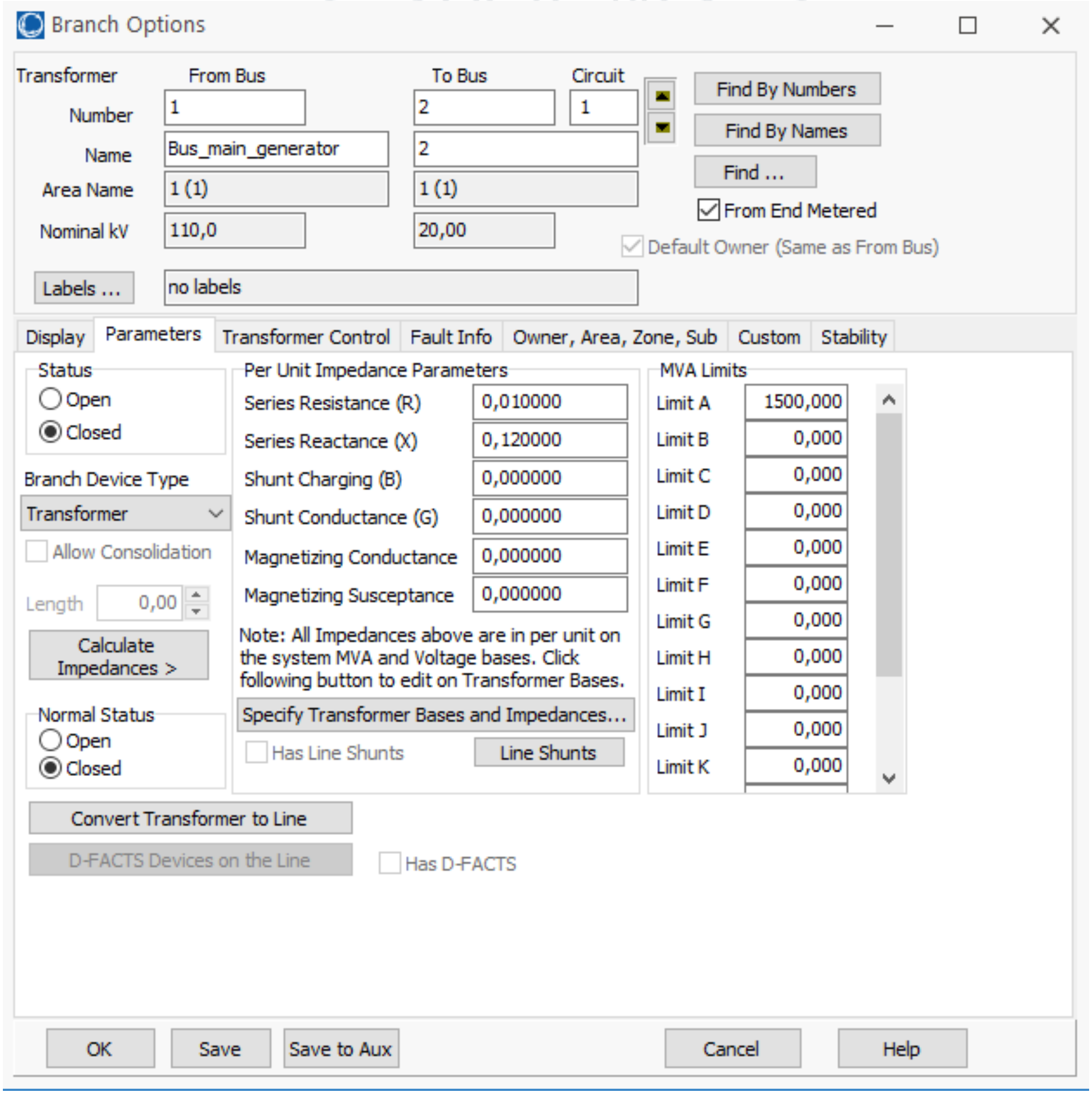
☐ System Slack Bus

Figure 6.4. Bus Options

- **Transformer:**

In the project, we have used a single transformer to dissipate the 110 kV voltage from the high-voltage distribution lines to 20 kV, suitable for possible medium-voltage consumption.

The transformer parameters that have been entered into the simulator are the initial ones, and are as follows:



Transformer	From Bus	To Bus	Circuit
Number	1	2	1
Name	Bus_main_generator	2	
Area Name	1 (1)	1 (1)	
Nominal kV	110,0	20,00	

☑ From End Metered
☑ Default Owner (Same as From Bus)

Labels: no labels

Status: ○ Open ● Closed

Branch Device Type: Transformer

☐ Allow Consolidation

Length: 0,00

Normal Status: ○ Open ● Closed

Per Unit Impedance Parameters

Series Resistance (R)	0,010000
Series Reactance (X)	0,120000
Shunt Charging (B)	0,000000
Shunt Conductance (G)	0,000000
Magnetizing Conductance	0,000000
Magnetizing Susceptance	0,000000

Note: All Impedances above are in per unit on the system MVA and Voltage bases. Click following button to edit on Transformer Bases.

☐ Has Line Shunts

MVA Limits

Limit A	1500,000
Limit B	0,000
Limit C	0,000
Limit D	0,000
Limit E	0,000
Limit F	0,000
Limit G	0,000
Limit H	0,000
Limit I	0,000
Limit J	0,000
Limit K	0,000

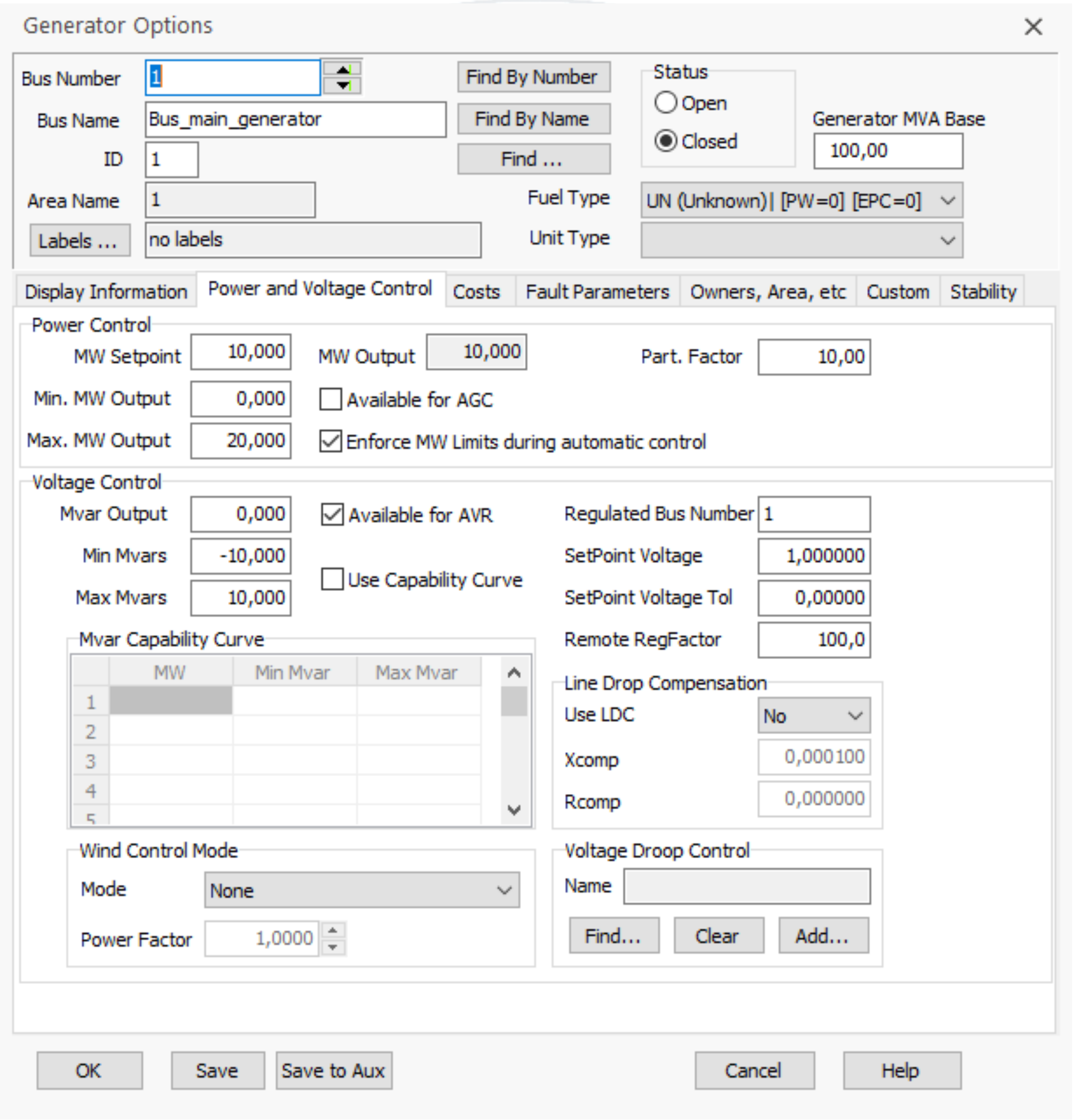
☐ Has D-FACTS

Figure 6.5. Branch Options

- **Generators:**

In this project, we have used two types of transformers, a main one and a secondary transformer simulating renewable energy sources such as solar panels or in our case windmills.

The power control and voltage control values entered in the main generator are as follows:



Bus Number: 1
Bus Name: Bus_main_generator
ID: 1
Area Name: 1
Labels ...: no labels
Status: ○ Open ● Closed
Generator MVA Base: 100,00
Fuel Type: UN (Unknown)| [PW=0] [EPC=0]
Unit Type:

Power Control
MW Setpoint: 10,000
MW Output: 10,000
Part. Factor: 10,00
Min. MW Output: 0,000
☐ Available for AGC
Max. MW Output: 20,000
☑ Enforce MW Limits during automatic control

Voltage Control
Mvar Output: 0,000
☑ Available for AVR
Regulated Bus Number: 1
Min Mvars: -10,000
SetPoint Voltage: 1,000000
☐ Use Capability Curve
Max Mvars: 10,000
SetPoint Voltage Tol: 0,00000
Remote RegFactor: 100,0

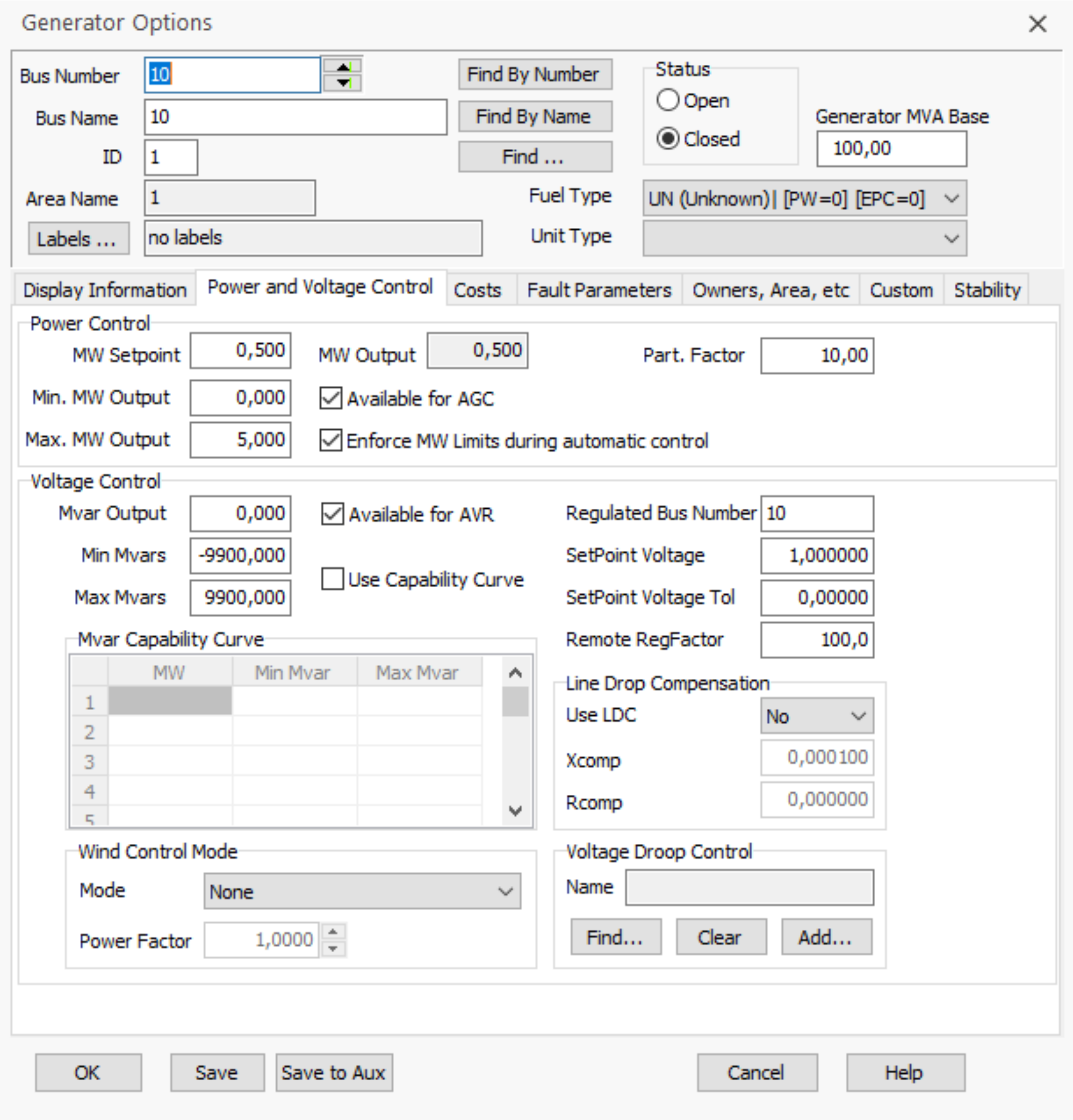
Line Drop Compensation
Use LDC: No
Xcomp: 0,000100
Rcomp: 0,000000

Wind Control Mode
Mode: None
Power Factor: 1,0000

Voltage Droop Control
Name:

Figure 6.6. Generator Options

While the power control and voltage control values entered in the RES are as follows:


Generator Options

Bus Number 10
Bus Name 10
ID 1
Area Name 1
Labels ... no labels

Status
○ Open
● Closed

Generator MVA Base 100,00
Fuel Type UN (Unknown)| [PW=0] [EPC=0]
Unit Type

Power and Voltage Control

Power Control
MW Setpoint 0,500
MW Output 0,500
Part. Factor 10,00
Min. MW Output 0,000
☑ Available for AGC
Max. MW Output 5,000
☑ Enforce MW Limits during automatic control

Voltage Control
Mvar Output 0,000
☑ Available for AVR
Regulated Bus Number 10
Min Mvars -9900,000
☐ Use Capability Curve
SetPoint Voltage 1,000000
Max Mvars 9900,000
SetPoint Voltage Tol 0,00000
Remote RegFactor 100,0

Mvar Capability Curve

	MW	Min Mvar	Max Mvar
1			
2			
3			
4			
5			

Line Drop Compensation
Use LDC No
Xcomp 0,000100
Rcomp 0,000000

Wind Control Mode
Mode None
Power Factor 1,0000

Voltage Droop Control
Name

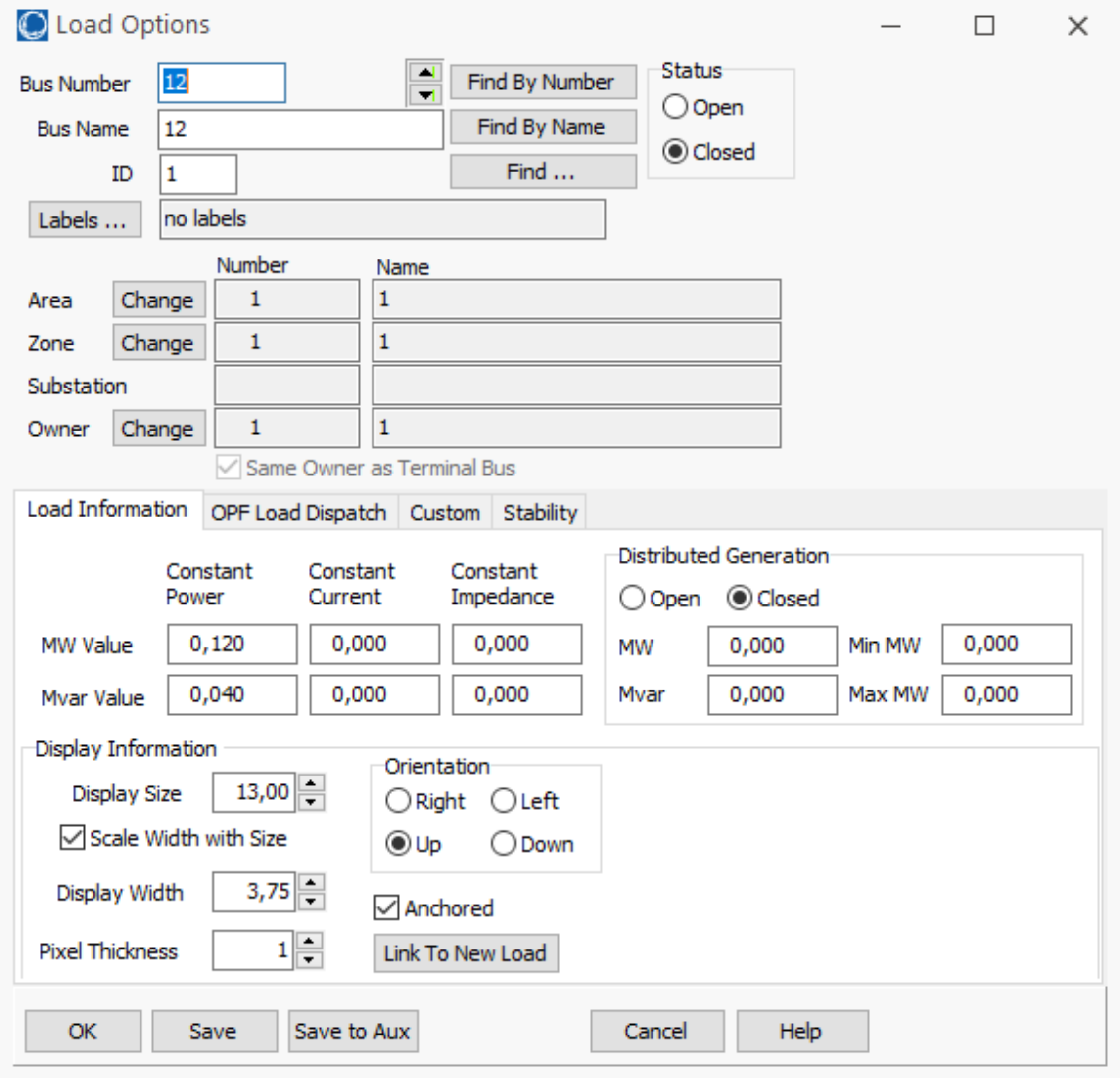
Figure 6.7. Generator Options

In one of the RES we set the active power setpoint to 3 MW while in the other three we introduced 0.5 MW.

- **Loads:**

The value of the loads has been randomised in the range of 5-30 kW and 0-18 kvar and a higher load of 300 kW and 200 kvar as we do not have enough time to be able to carry out a more accurate study.

The following is an example of one of the loads, whose active power is 12 kW and reactive power is 4 kvar. This load is connected to bus-bar number twelve.



Bus Number: 12
Bus Name: 12
ID: 1
Labels: no labels
Status: ○ Open ● Closed

	Number	Name
Area	1	1
Zone	1	1
Substation		
Owner	1	1

☑ Same Owner as Terminal Bus

	Constant Power	Constant Current	Constant Impedance
MW Value	0,120	0,000	0,000
Mvar Value	0,040	0,000	0,000

Distributed Generation: ○ Open ● Closed
MW: 0,000
Min MW: 0,000
Mvar: 0,000
Max MW: 0,000

Display Information
Display Size: 13,00
☑ Scale Width with Size
Display Width: 3,75
Pixel Thickness: 1

Orientation: ○ Right ○ Left ● Up ○ Down
☑ Anchored

Figure 6.8. Load Options

7. Distribution system scheme

Below is the distribution system with all data included designed with graphic design software.

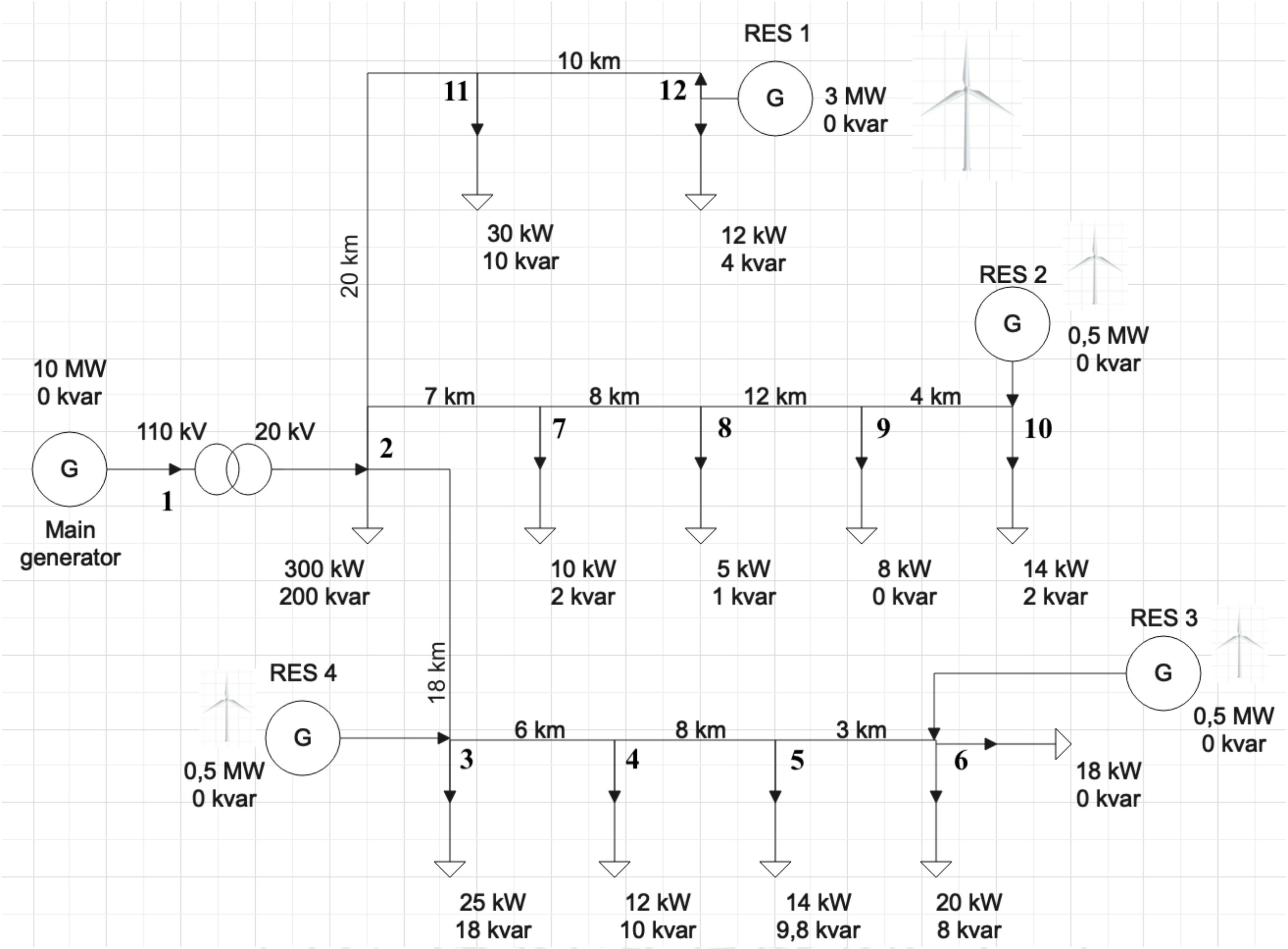


Figure 7.1. Distribution system with a design software

The same distribution system implemented in the powerworld is:

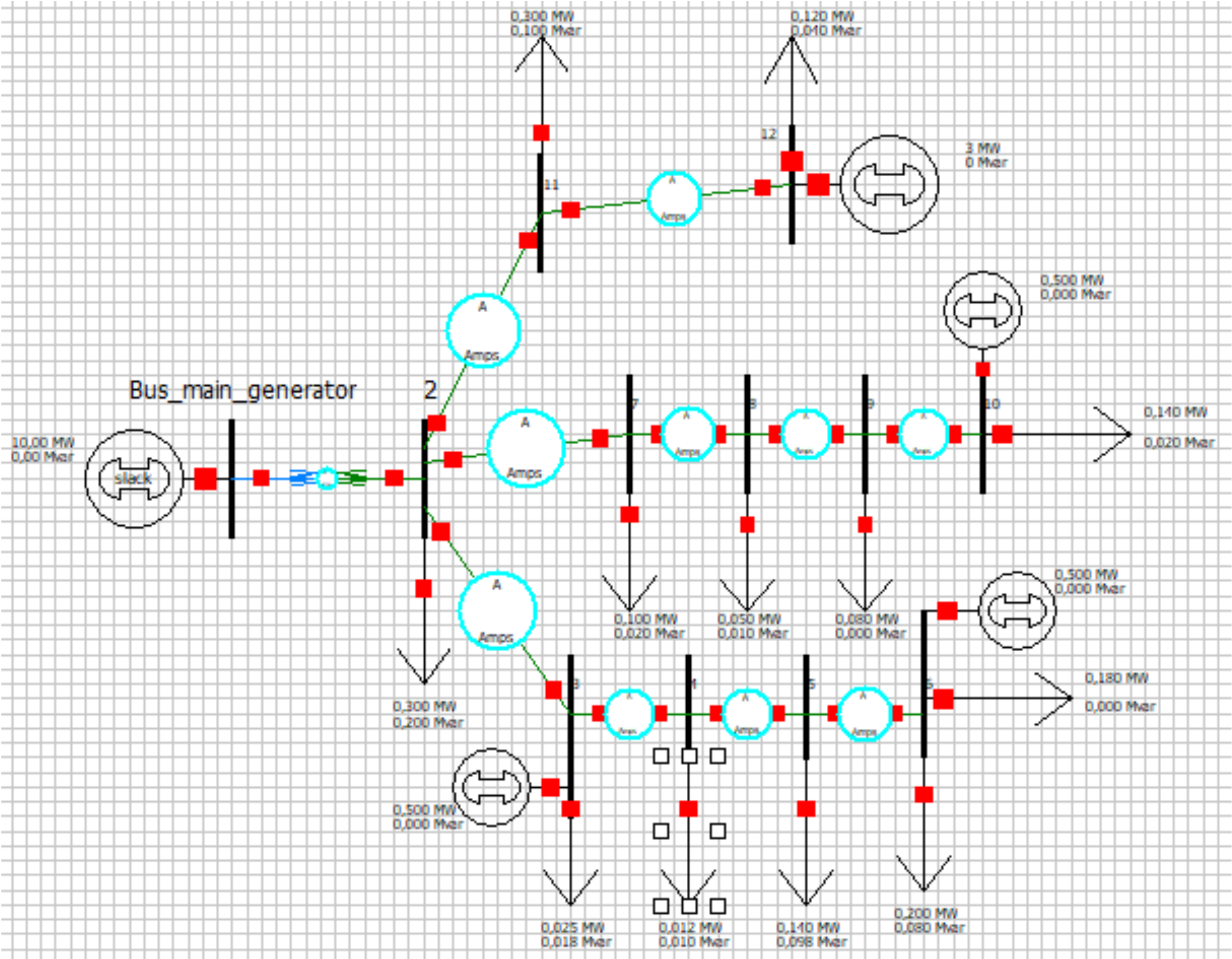


Figure 7.2. Distribution system with PowerWorld

8. Simulations and voltage/current results

The first simulation below shows the main generator connected and the rest of the generators deactivated.

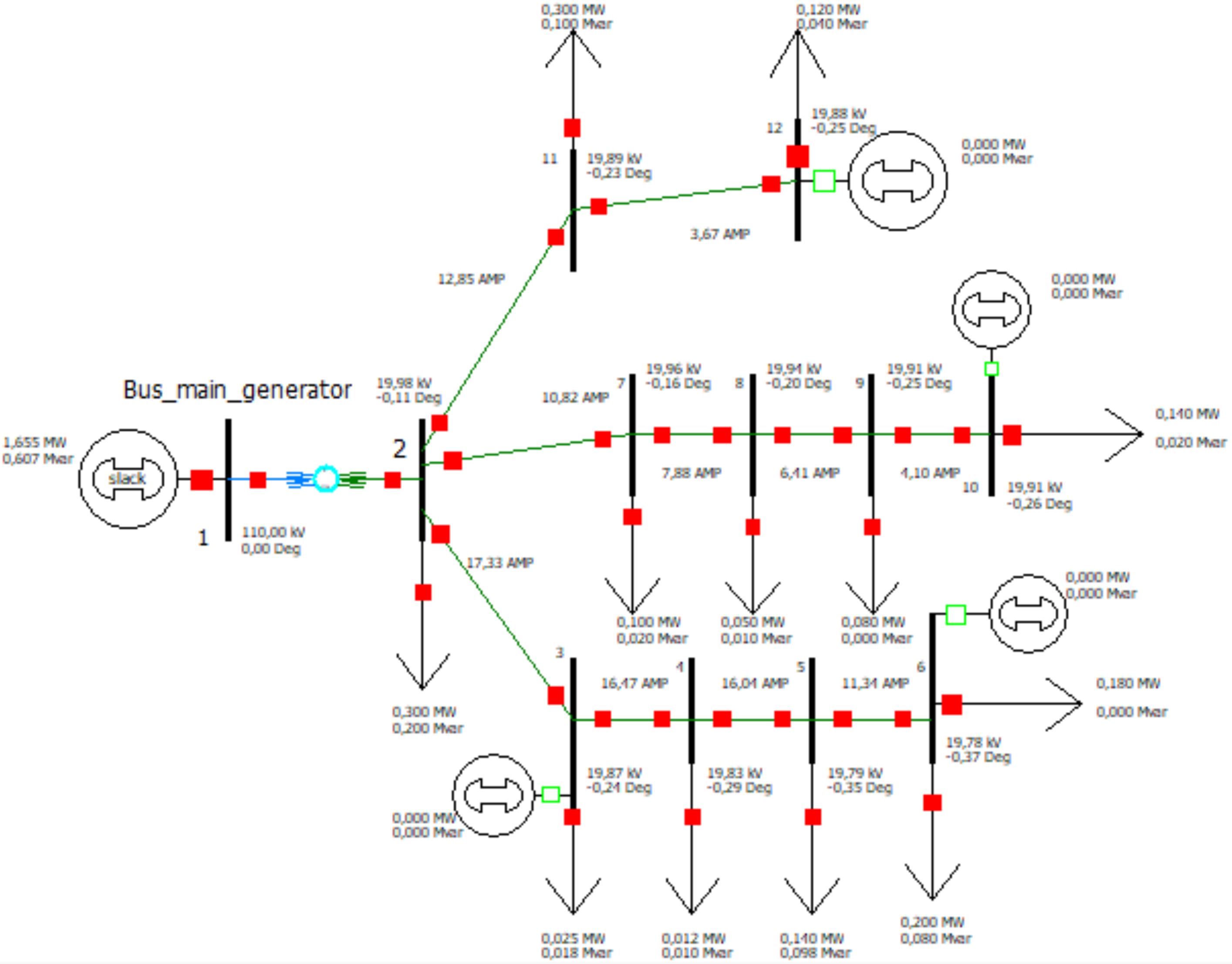


Figure 8.1. Simulation case a)

The power consumed by the generators is:

Table 8.1.1. Power consumed case a)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	1,655	0,607
RES 1	0	0
RES 2	0	0
RES 3	0	0
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 8.1.2. Voltage and offset case a)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,98	-0,11
3	19,87	-0,24
4	19,83	-0,29
5	19,79	-0,35
6 (end of bottom line)	19,78	-0,37
7	19,96	-0,16
8	19,94	-0,20
9	19,91	-0,25
10 (end of middle line)	19,91	-0,26
11	19,89	-0,23
12 (end of top line)	19,88	-0,25

The current flowing through the distribution lines is:

Table 8.1.3. Current case a)

	Length (km)	Current (A)
2-3	18	17,33
3-4	6	16,47
4-5	8	16,04
5-6	3	11,34
2-7	7	10,82
7-8	8	7,88
8-9	12	6,41
9-10	4	4,10
2-11	20	12,85
11-12	10	3,67

The following simulation shows the main generator connected and the main renewable energy source switched on, which is the generetaor situated in the end of the top line.

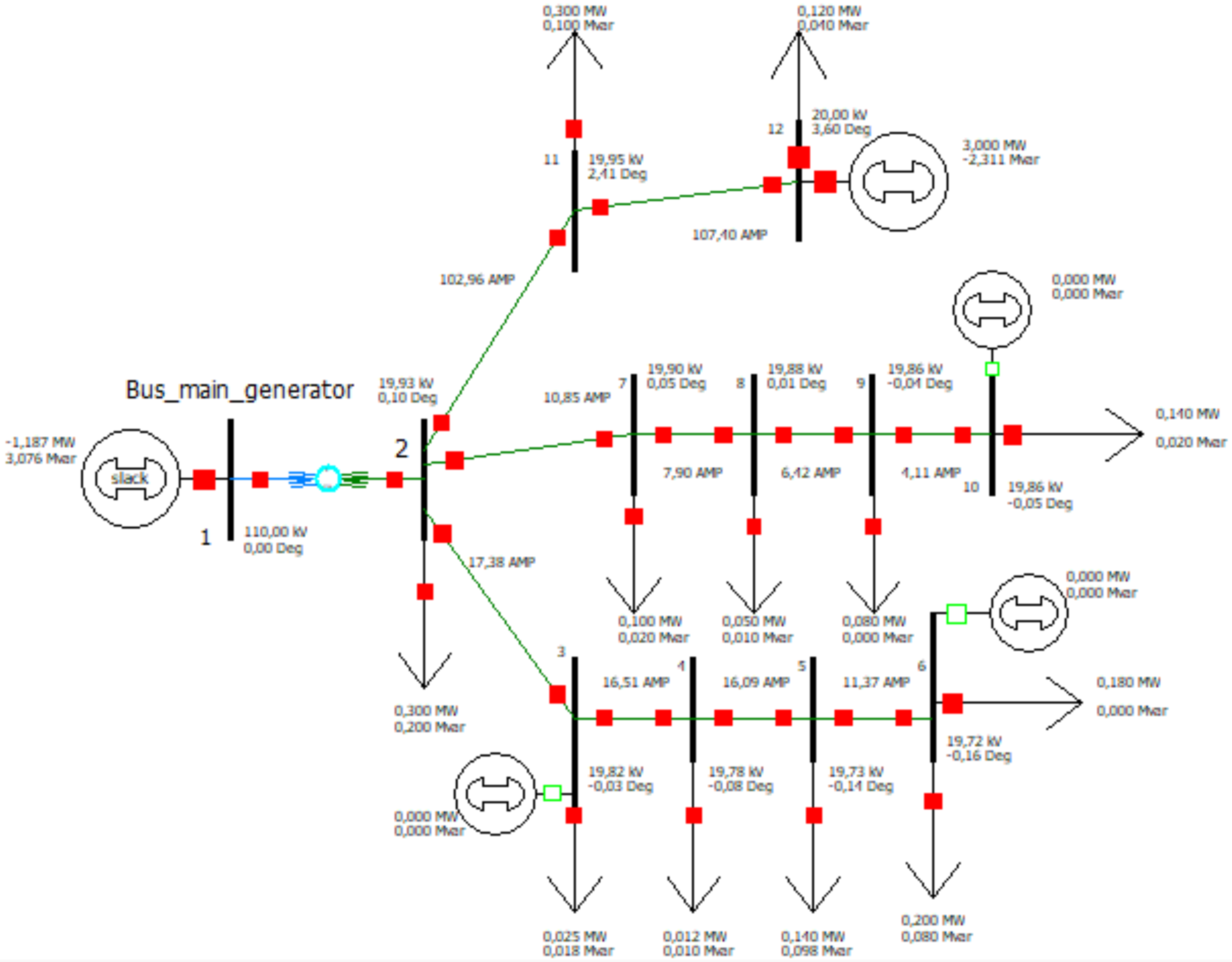


Figure 8.2. Simulation case b)

The power consumed by the generators is:

Table 8.2.1. Power consumed case b)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-1,187	3,076
RES 1	3,000	-2,311
RES 2	0	0
RES 3	0	0
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 8.2.2. Voltage and offset case b)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,93	0,10
3	19,82	-0,03
4	19,78	-0,08
5	19,73	-0,14
6 (end of bottom line)	19,72	-0,16
7	19,90	0,05
8	19,88	0,01
9	19,86	-0,04
10 (end of middle line)	19,86	-0,05
11	19,95	2,41
12 (end of top line)	20,00	3,60

The current flowing through the distribution lines is:

Table 8.2.3. Current case b)

	Length (km)	Current (A)
2-3	18	17,38
3-4	6	16,51
4-5	8	16,09
5-6	3	11,37
2-7	7	10,85
7-8	8	7,90
8-9	12	6,42
9-10	4	4,11
2-11	20	102,96
11-12	10	107,40

The following simulation shows the main generator connected, the main renewable energy source switched on, which is the generetaor situated in the end of the top line and the RES 4 switched on too, which is the only generator is not connected in the final of the line.

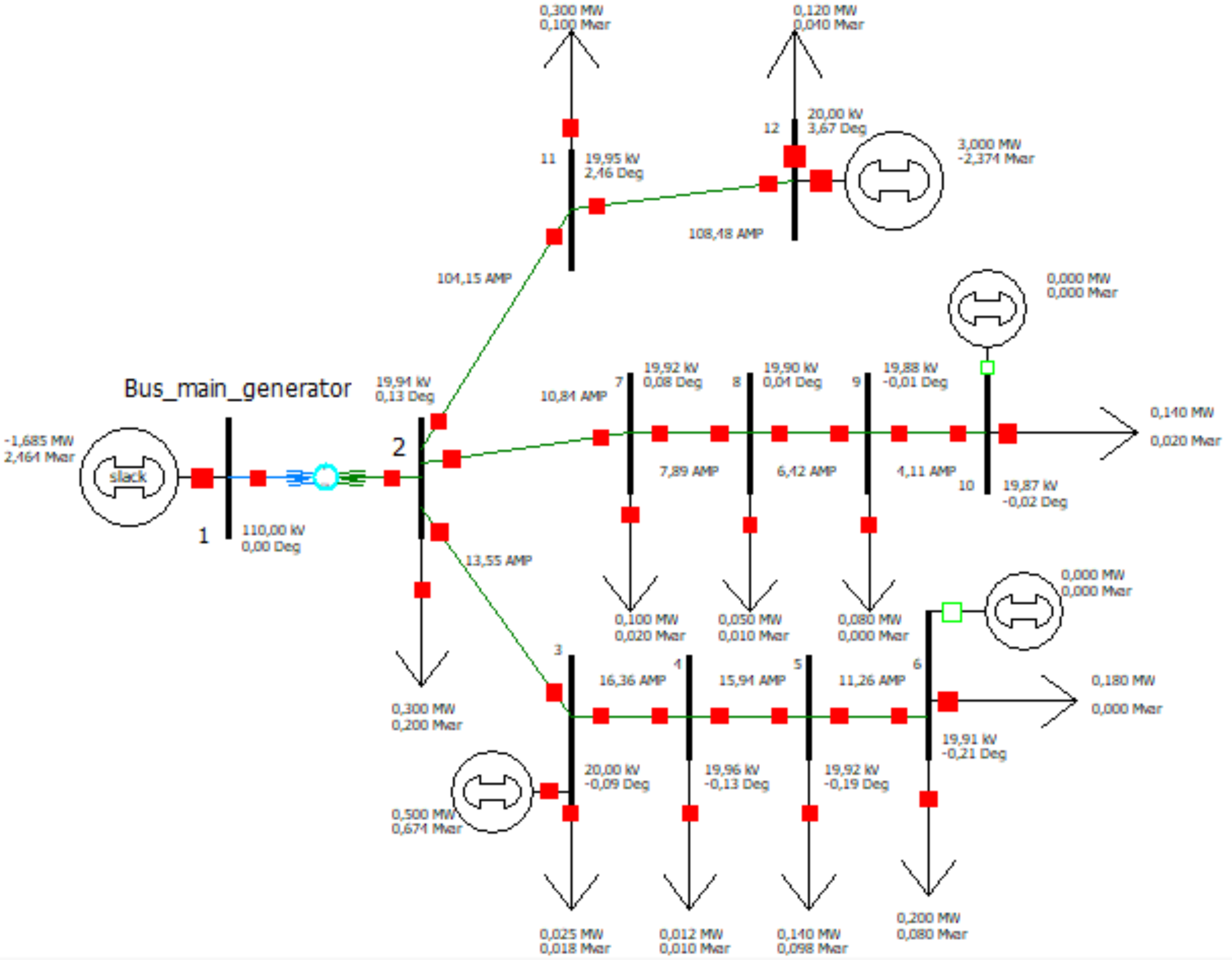


Figure 8.3. Simulation case c)

The power consumed by the generators is:

Table 8.3.1. Power consumed case c)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-1,685	2,464
RES 1	3,000	-2,374
RES 2	0	0
RES 3	0	0
RES 4	0,500	0,674

The voltage and its offset in the bus-bars is:

Table 8.3.2. Voltage and offset case c)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,94	0,13
3	20,00	-0,09
4	19,96	-0,13
5	19,92	-0,19
6 (end of bottom line)	19,91	-0,21
7	19,92	0,08
8	19,90	0,04
9	19,88	-0,01
10 (end of middle line)	19,87	-0,02
11	19,95	2,46
12 (end of top line)	20,00	3,67

The current flowing through the distribution lines is:

Table 8.3.3. Current case c)

	Length (km)	Current (A)
2-3	18	13,55
3-4	6	16,36
4-5	8	15,94
5-6	3	11,26
2-7	7	10,84
7-8	8	7,89
8-9	12	6,42
9-10	4	4,11
2-11	20	104,15
11-12	10	108,48

The following simulation shows the main generator connected and all the RES, which are in the end of the line, are switched on. The only RES is switched off is the RES 4, which is the only generator is not connected in the final of the line.

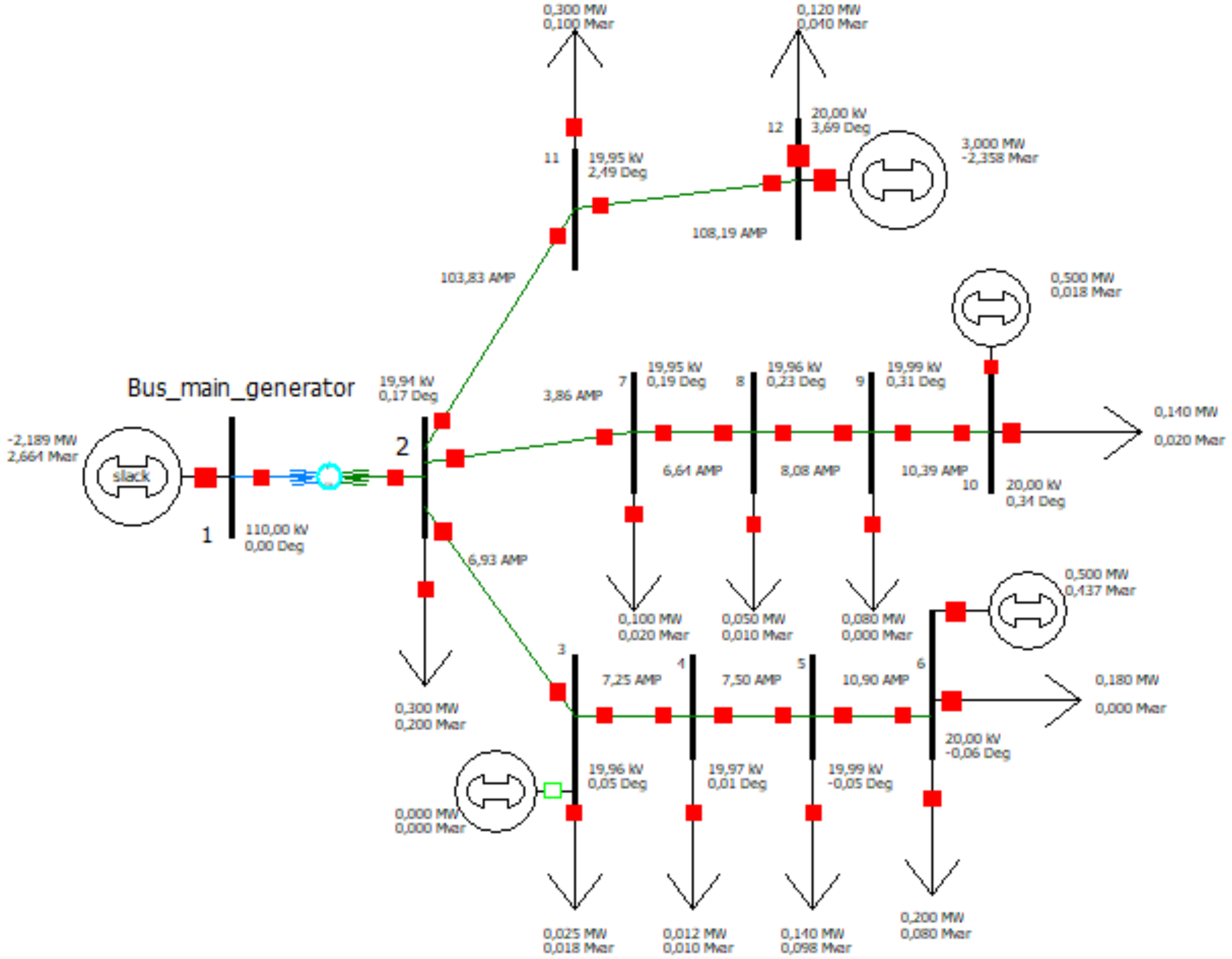


Figure 8.4. Simulation case d)

The power consumed by the generators is:

Table 8.4.1. Power consumed case d)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-2,189	2,664
RES 1	3,000	-2,358
RES 2	0,500	0,018
RES 3	0,500	0,427
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 8.4.2. Voltage and offset case d)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,94	0,17
3	19,96	0,05
4	19,97	0,01
5	19,99	-0,05
6 (end of bottom line)	20,00	-0,06
7	19,95	0,19
8	19,96	0,23
9	19,99	0,31
10 (end of middle line)	20,00	0,34
11	19,95	2,49
12 (end of top line)	20,00	3,69

The current flowing through the distribution lines is:

Table 8.4.3. Current case d)

	Length (km)	Current (A)
2-3	18	6,93
3-4	6	7,25
4-5	8	7,50
5-6	3	10,90
2-7	7	3,86
7-8	8	6,64
8-9	12	8,08
9-10	4	10,39
2-11	20	103,83
11-12	10	108,19

The following simulation shows the main generator connected and only the RES 2 and RES 3 are switched on, which are the generators of the middle and bottom end of lines.

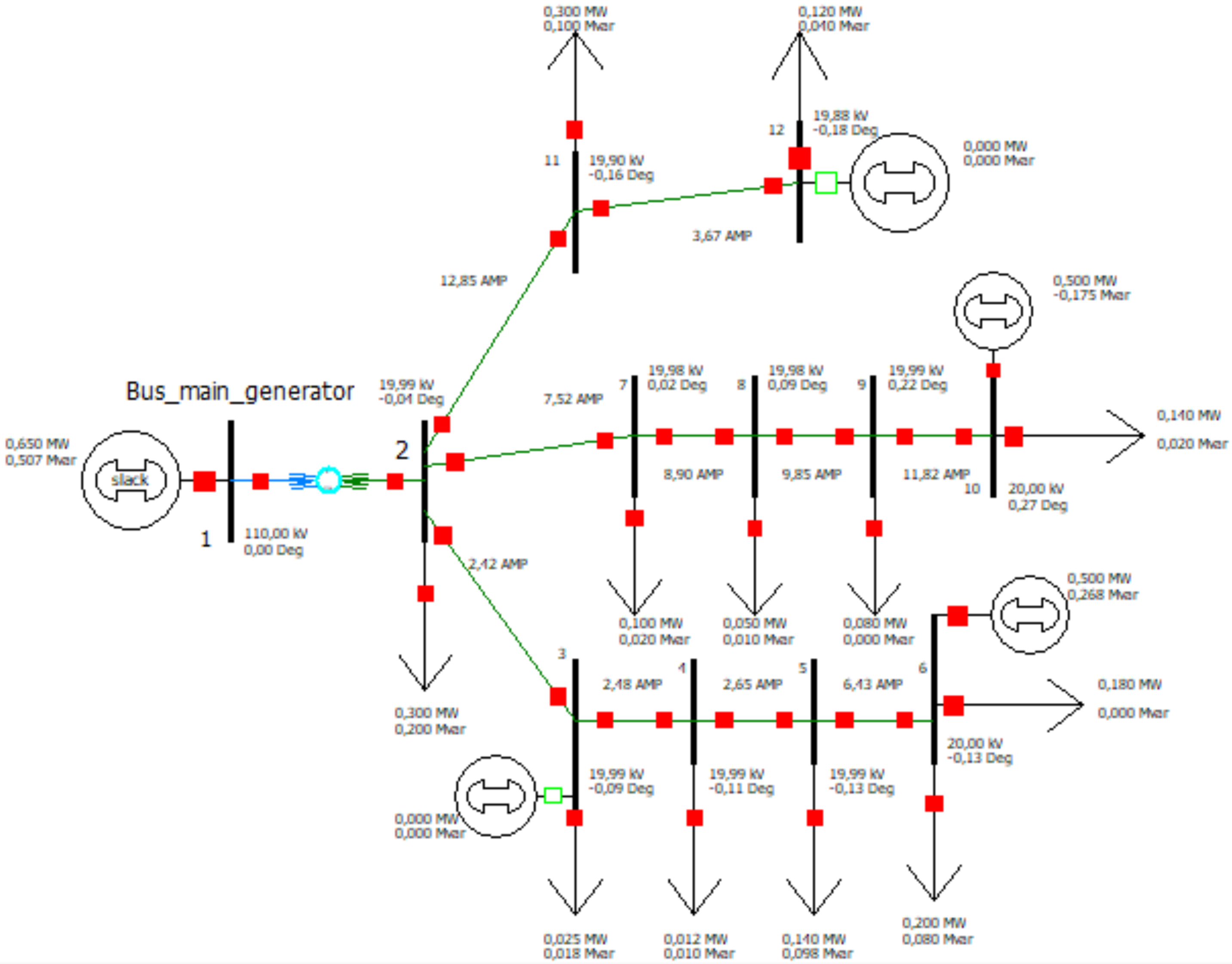


Figure 8.5. Simulation case e)

The power consumed by the generators is:

Table 8.5.1. Power consumed case e)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	0,650	0,507
RES 1	0	0
RES 2	0,500	-0,175
RES 3	0,500	0,268
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 8.5.2. Voltage and offset case e)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,99	-0,04
3	19,99	-0,09
4	19,99	-0,11
5	19,99	-0,13
6 (end of bottom line)	20,00	-0,13
7	19,98	0,02
8	19,98	0,09
9	19,99	0,22
10 (end of middle line)	20,00	0,27
11	19,90	-0,16
12 (end of top line)	19,88	-0,18

The current flowing through the distribution lines is:

Table 8.5.3. Current case e)

	Length (km)	Current (A)
2-3	18	2,42
3-4	6	2,48
4-5	8	2,65
5-6	3	6,43
2-7	7	7,52
7-8	8	8,90
8-9	12	9,85
9-10	4	11,82
2-11	20	12,85
11-12	10	3,67

The following simulation shows the main generator connected and all the RES switch on, too.

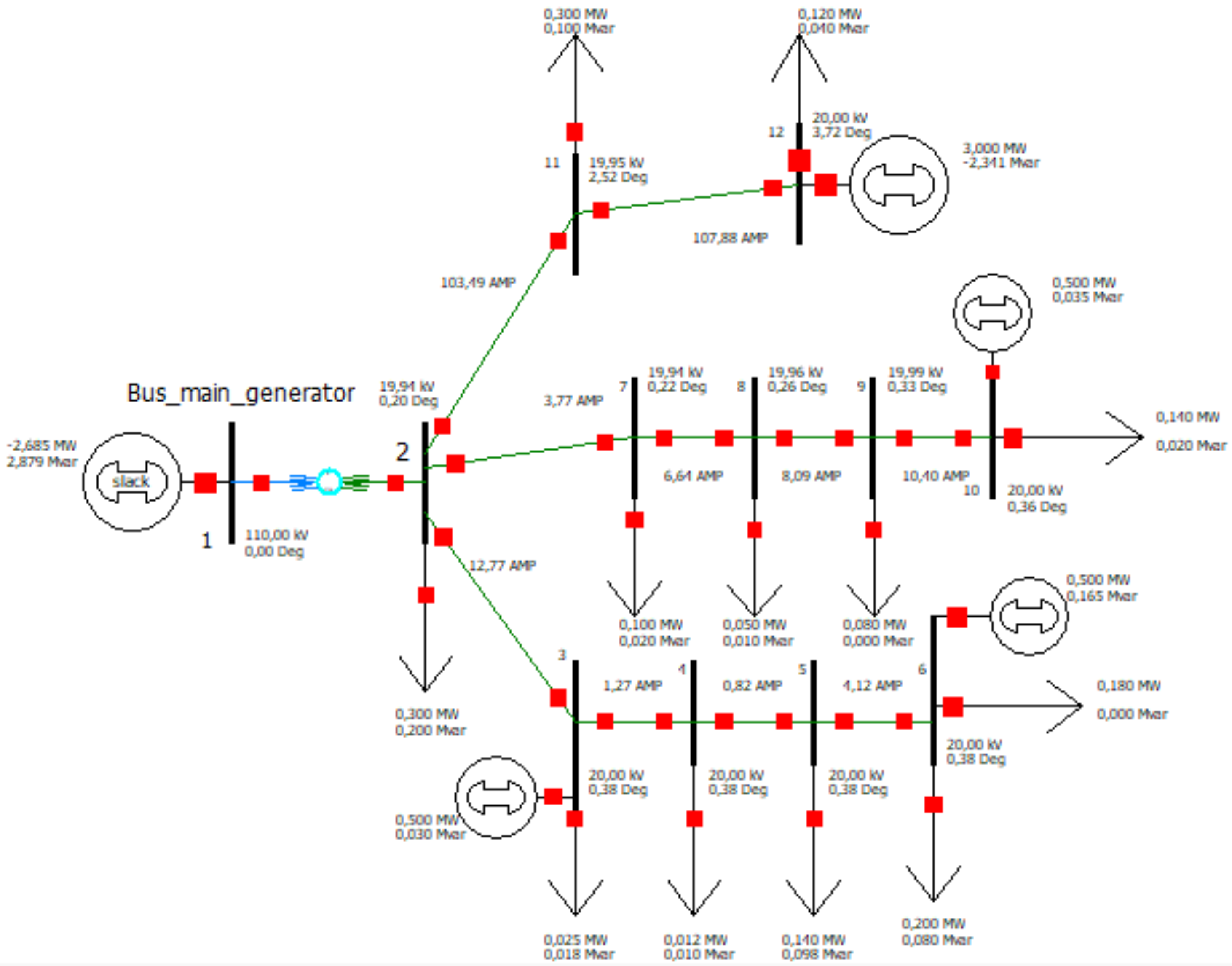


Figure 8.6. Simulation case f)

The power consumed by the generators is:

Table 8.6.1. Power consumed case f)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-2,685	2,879
RES 1	3,000	-2,341
RES 2	0,500	0,035
RES 3	0,500	0,165
RES 4	0,500	0,030

The voltage and its offset in the bus-bars is:

Table 8.6.2. Voltage and offset case f)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,94	0,20
3	20,00	0,38
4	20,00	0,38
5	20,00	0,38
6 (end of bottom line)	20,00	0,38
7	19,94	0,22
8	19,96	0,26
9	19,99	0,33
10 (end of middle line)	20,00	0,36
11	19,95	2,52
12 (end of top line)	20,00	3,72

The current flowing through the distribution lines is:

Table 8.6.3. Current case f)

	Length (km)	Current (A)
2-3	18	12,77
3-4	6	1,27
4-5	8	0,87
5-6	3	4,12
2-7	7	3,77
7-8	8	6,64
8-9	12	8,09
9-10	4	10,40
2-11	20	103,49
11-12	10	107,88

The following simulation shows the case where the main generator breaks down or there is a problem in its supply line, so only the RES are connected.

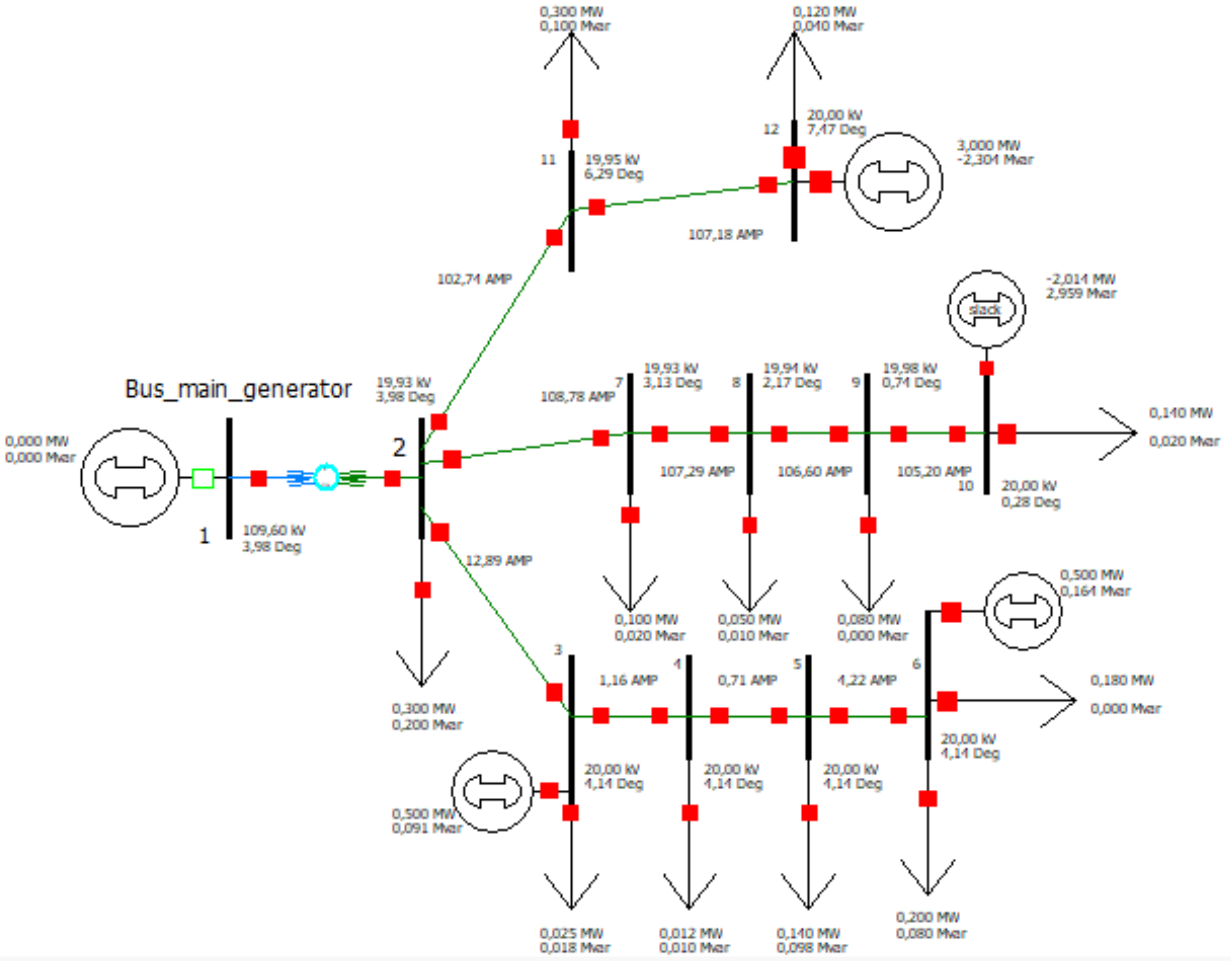


Figure 8.7. Simulation case g)

The power consumed by the generators is:

Table 8.7.1. Power consumed case g)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	0	0
RES 1	3,000	-2,304
RES 2	-2,014	2,959
RES 3	0,500	0,164
RES 4	0,500	0,091

The voltage and its offset in the bus-bars is:

Table 8.7.2. Voltage and offset case g)

	Voltage (kV)	Offset (deg)
1 (transformer input)	109,60	3,98
2 (transformer output)	19,93	3,98
3	20,00	4,14
4	20,00	4,14
5	20,00	4,14
6 (end of bottom line)	20,00	4,14
7	19,93	3,13
8	19,94	2,17
9	19,98	0,74
10 (end of middle line)	20,00	0,28
11	19,95	6,29
12 (end of top line)	20,00	7,47

The current flowing through the distribution lines is:

Table 8.7.3. Current case g)

	Length (km)	Current (A)
2-3	18	12,89
3-4	6	1,16
4-5	8	0,71
5-6	3	4,22
2-7	7	108,78
7-8	8	107,29
8-9	12	106,60
9-10	4	105,20
2-11	20	102,74
11-12	10	107,18

9. Simulations with the RES unable to regulate voltage

The first simulation below shows the main generator connected and the rest of the generators deactivated.

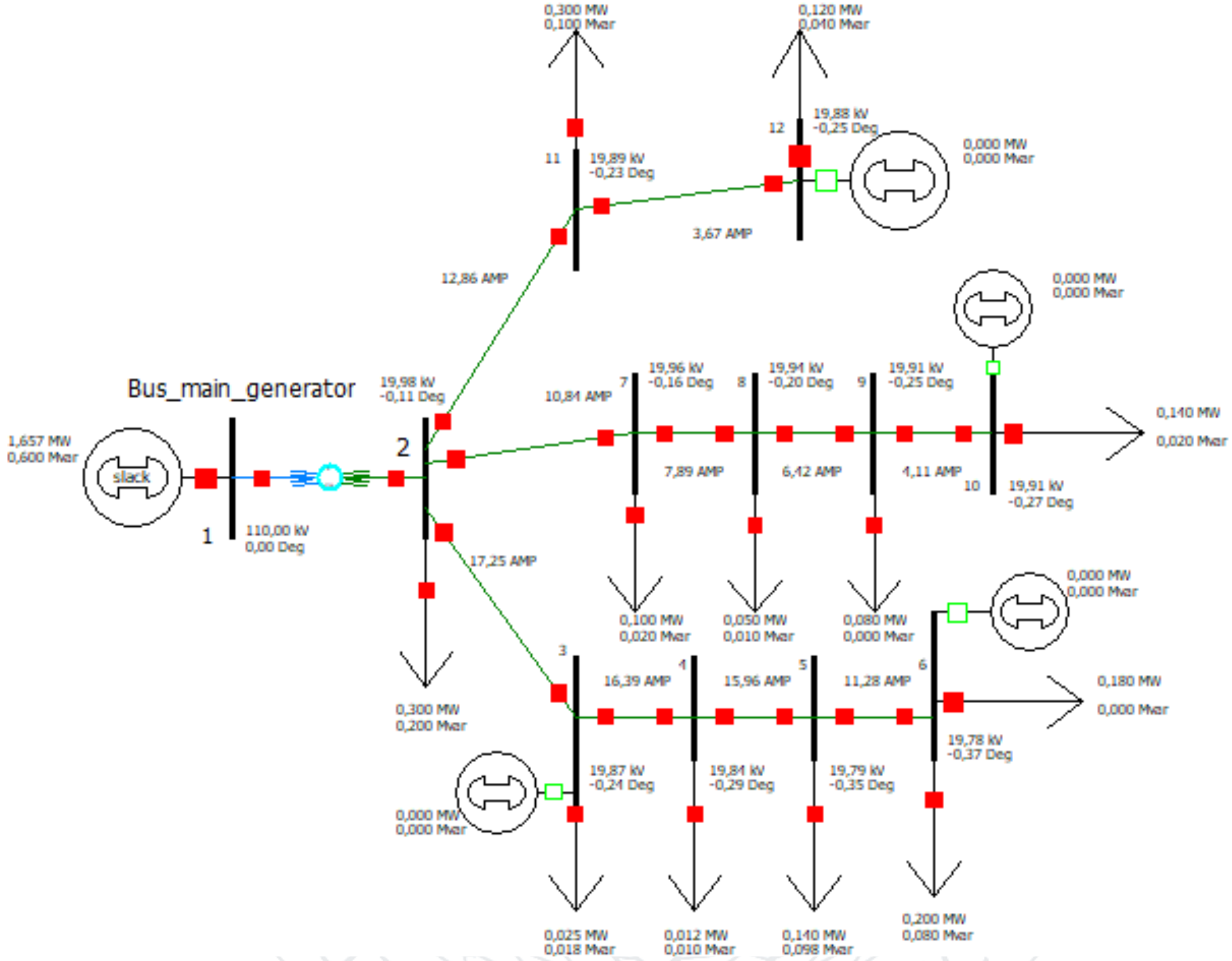


Figure 9.1. Simulation case a)

The power consumed by the generators is:

Table 9.1.1. Power consumed case a)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	1,657	0,600
RES 1	0	0
RES 2	0	0
RES 3	0	0
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 9.1.2. Voltage and offset case a)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,98	-0,11
3	19,87	-0,24
4	19,84	-0,29
5	19,79	-0,35
6 (end of bottom line)	19,78	-0,37
7	19,96	-0,16
8	19,94	-0,20
9	19,91	-0,25
10 (end of middle line)	19,91	-0,27
11	19,89	-0,23
12 (end of top line)	19,88	-0,25

The current flowing through the distribution lines is:

Table 9.1.3. Current case a)

	Length (km)	Current (A)
2-3	18	17,25
3-4	6	16,39
4-5	8	15,96
5-6	3	11,28
2-7	7	10,84
7-8	8	7,89
8-9	12	6,42
9-10	4	4,11
2-11	20	12,86
11-12	10	3,67

The following simulation shows the main generator connected and the main renewable energy source switched on, which is the generetaor situated in the end of the top line.

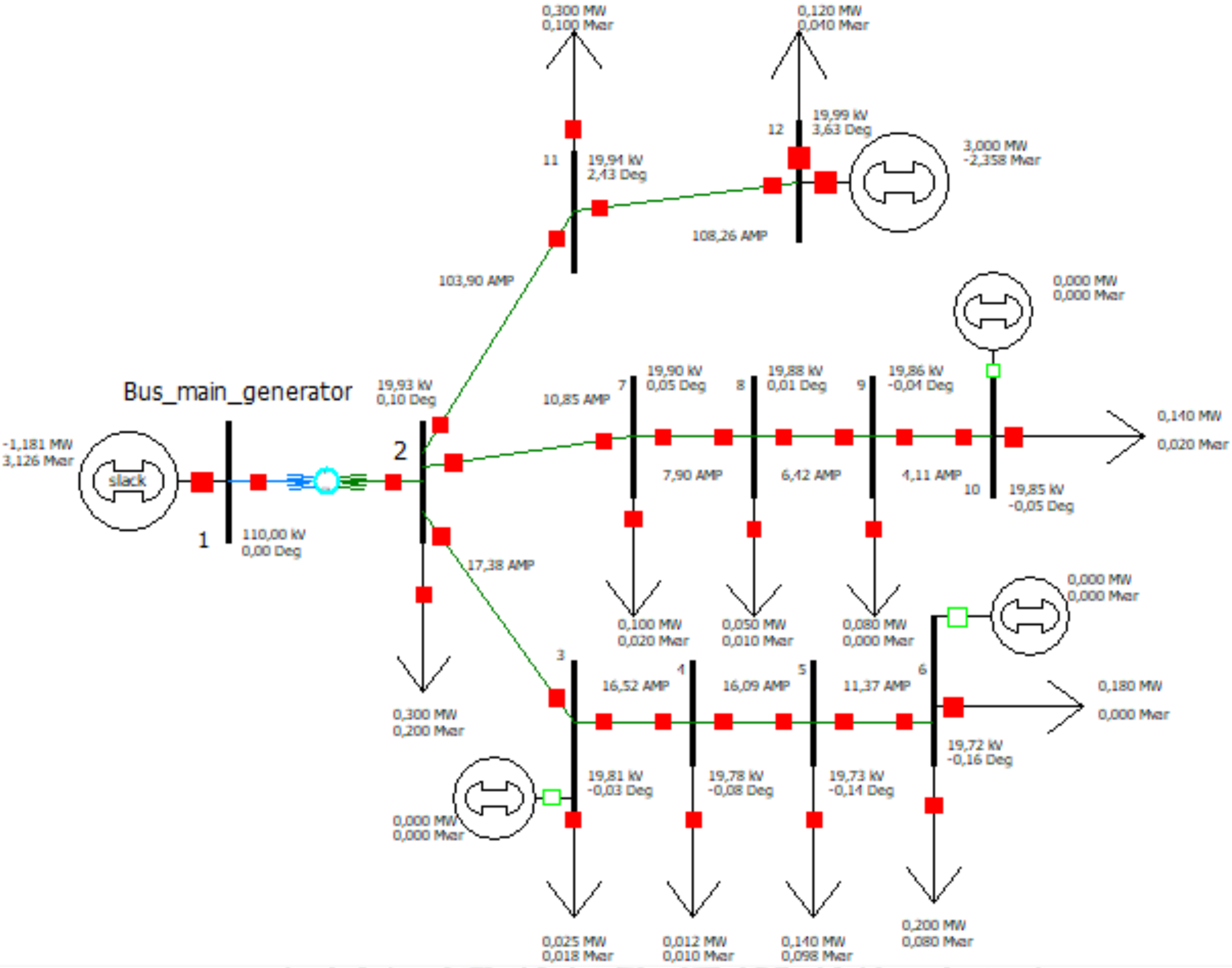


Figure 9.2. Simulation case b)

The power consumed by the generators is:

Table 9.2.1. Power consumed case b)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-1,181	3,126
RES 1	3,000	-2,358
RES 2	0	0
RES 3	0	0
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 9.2.2. Voltage and offset case b)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,93	0,10
3	19,81	-0,03
4	19,78	-0,08
5	19,73	-0,14
6 (end of bottom line)	19,72	-0,16
7	19,90	0,05
8	19,88	0,01
9	19,86	-0,04
10 (end of middle line)	19,85	-0,05
11	19,94	2,43
12 (end of top line)	19,99	3,63

The current flowing through the distribution lines is:

Table 9.2.3. Current case b)

	Length (km)	Current (A)
2-3	18	17,38
3-4	6	16,52
4-5	8	16,09
5-6	3	11,37
2-7	7	10,85
7-8	8	7,90
8-9	12	6,42
9-10	4	4,11
2-11	20	103,90
11-12	10	108,26

The following simulation shows the main generator connected, the main renewable energy source switched on, which is the generetaor situated in the end of the top line and the RES 4 switched on too, which is the only generator is not connected in the final of one if the lines.

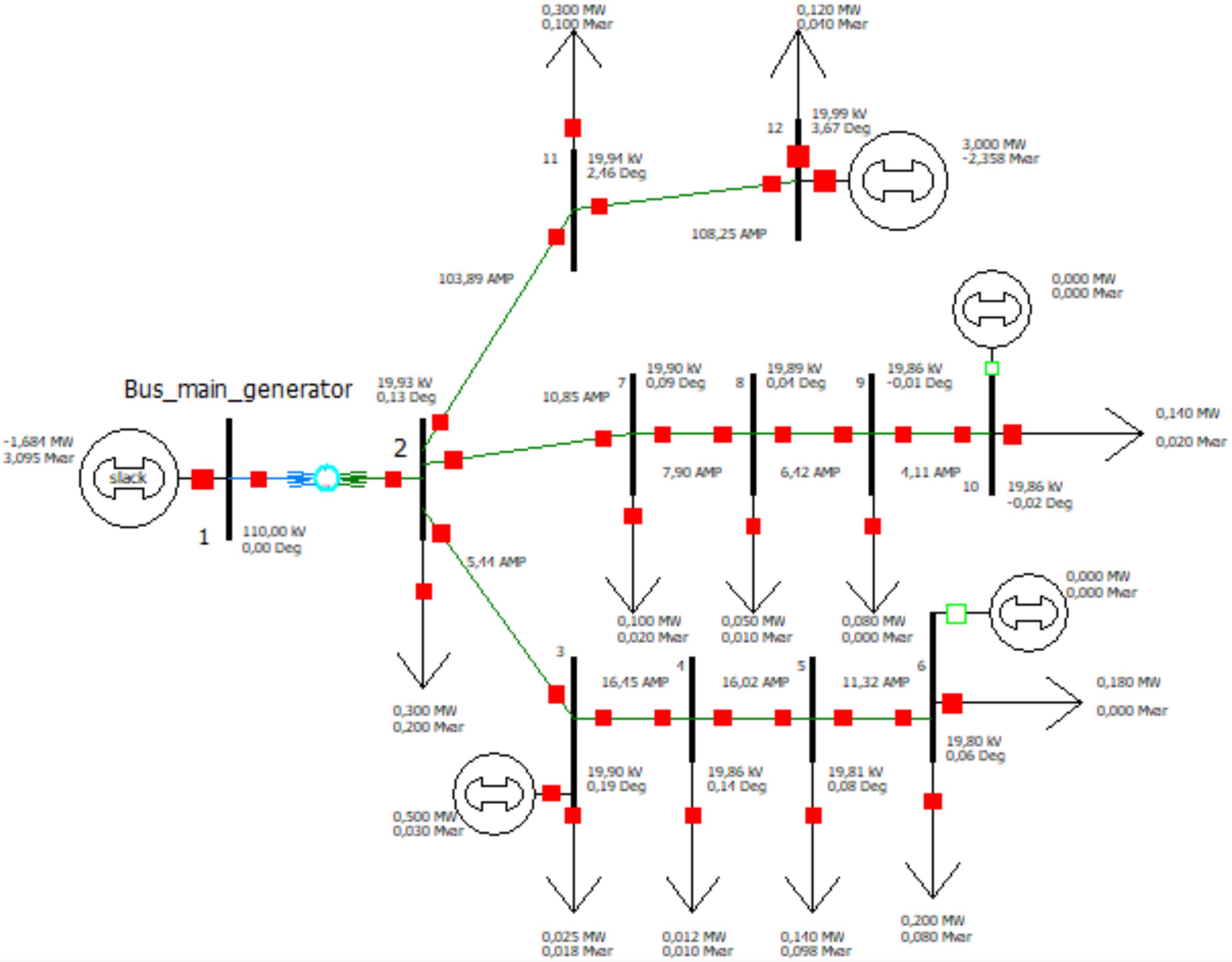


Figure 9.3. Simulation case c)

The power consumed by the generators is:

Table 9.3.1. Power consumed case c)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-1,684	3,095
RES 1	3,000	-2,358
RES 2	0	0
RES 3	0	0
RES 4	0,500	0,030

The voltage and its offset in the bus-bars is:

Table 9.3.2. Voltage and offset case c)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,93	0,13
3	19,90	0,19
4	19,86	0,14
5	19,81	0,08
6 (end of bottom line)	19,80	0,06
7	19,90	0,09
8	19,89	0,04
9	19,86	-0,01
10 (end of middle line)	19,86	-0,02
11	19,94	2,46
12 (end of top line)	19,99	3,67

The current flowing through the distribution lines is:

Table 9.3.3. Current case c)

	Length (km)	Current (A)
2-3	18	5,44
3-4	6	16,45
4-5	8	16,02
5-6	3	11,32
2-7	7	10,85
7-8	8	7,90
8-9	12	6,42
9-10	4	4,11
2-11	20	103,89
11-12	10	108,25

The following simulation shows the main generator connected and all the RES, which are in the end of the line, are switched on. The only RES is switched off is the RES 4, which is the only generator is not connected in the final of the line.

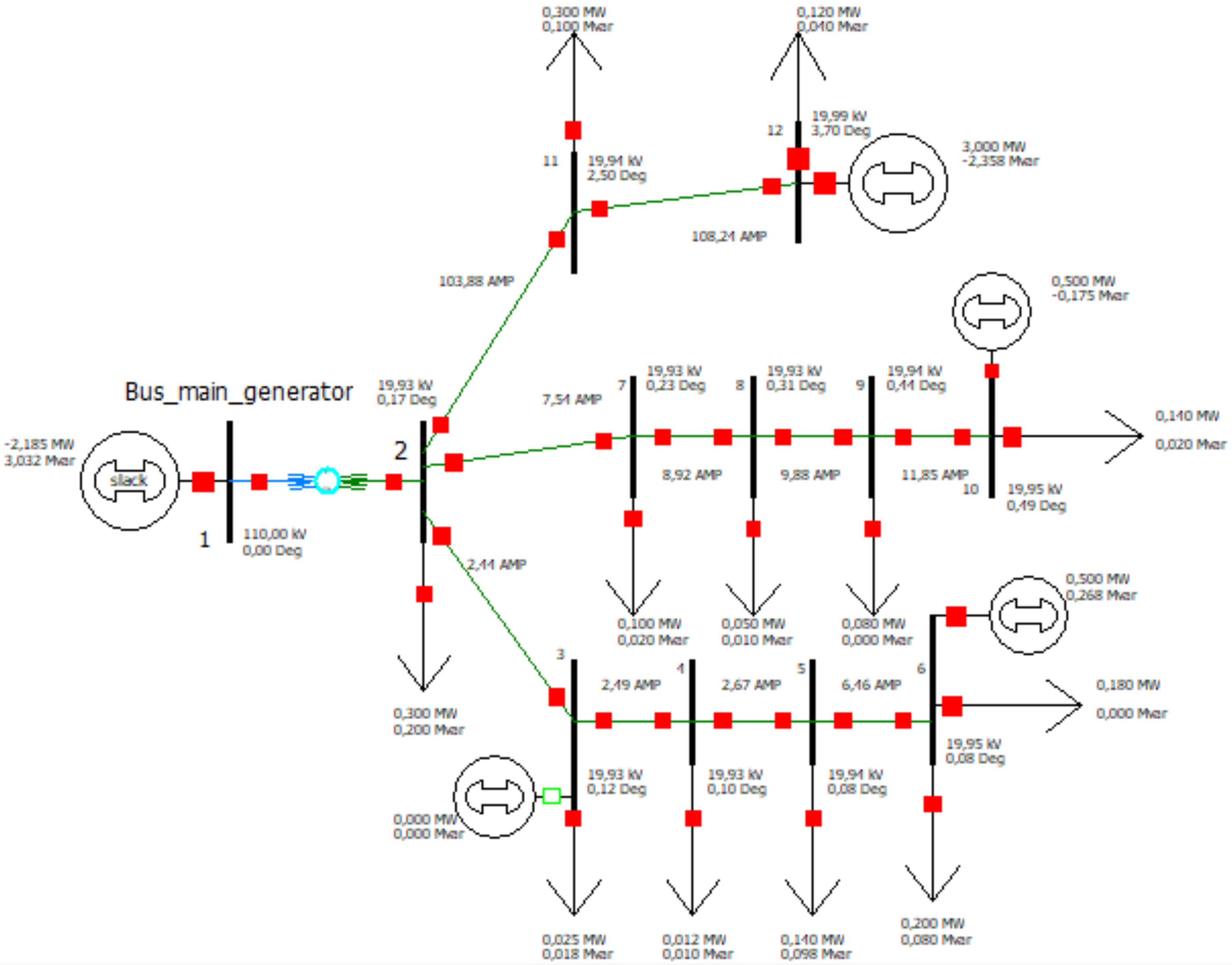


Figure 9.4. Simulation case d)

The power consumed by the generators is:

Table 9.4.1. Power consumed case d)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-2,185	3,032
RES 1	3,000	-2,358
RES 2	0,500	-0,175
RES 3	0,500	0,268
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 9.4.2. Voltage and offset case d)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,93	0,17
3	19,93	0,12
4	19,93	0,10
5	19,94	0,08
6 (end of bottom line)	19,95	0,08
7	19,93	0,23
8	19,93	0,31
9	19,94	0,44
10 (end of middle line)	19,95	0,49
11	19,94	2,50
12 (end of top line)	19,99	3,70

The current flowing through the distribution lines is:

Table 9.4.3. Current case d)

	Length (km)	Current (A)
2-3	18	2,44
3-4	6	2,49
4-5	8	2,67
5-6	3	6,46
2-7	7	7,54
7-8	8	8,92
8-9	12	9,88
9-10	4	11,85
2-11	20	103,88
11-12	10	108,24

The following simulation shows the main generator connected and only the RES 2 and RES 3 are switched on, which are the generators of the middle and bottom end of lines.

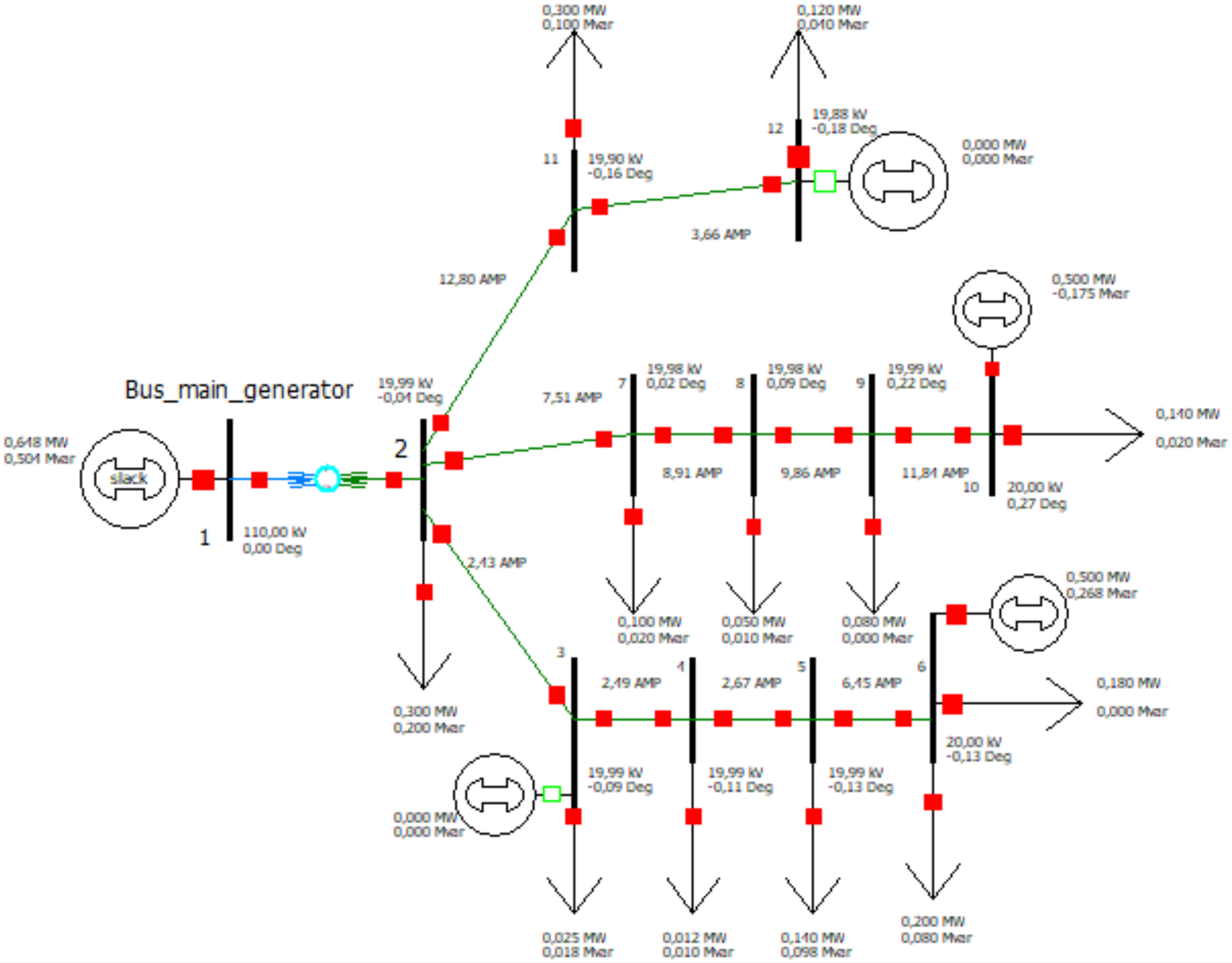


Figure 9.5. Simulation case e)

The power consumed by the generators is:

Table 9.5.1. Power consumed case e)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	0,648	0,504
RES 1	0	0
RES 2	0,500	-0,175
RES 3	0,500	0,268
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 9.5.2. Voltage and offset case e)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,99	-0,04
3	19,99	-0,09
4	19,99	-0,11
5	19,99	-0,13
6 (end of bottom line)	20,00	-0,13
7	19,98	0,02
8	19,98	0,09
9	19,99	0,22
10 (end of middle line)	20,00	0,27
11	19,90	-0,16
12 (end of top line)	19,88	-0,18

The current flowing through the distribution lines is:

Table 9.5.3. Current case e)

	Length (km)	Current (A)
2-3	18	2,43
3-4	6	2,49
4-5	8	2,67
5-6	3	6,45
2-7	7	7,51
7-8	8	8,91
8-9	12	9,86
9-10	4	11,84
2-11	20	12,80
11-12	10	3,66

The following simulation shows the main generator connected and all the RES switch on, too.

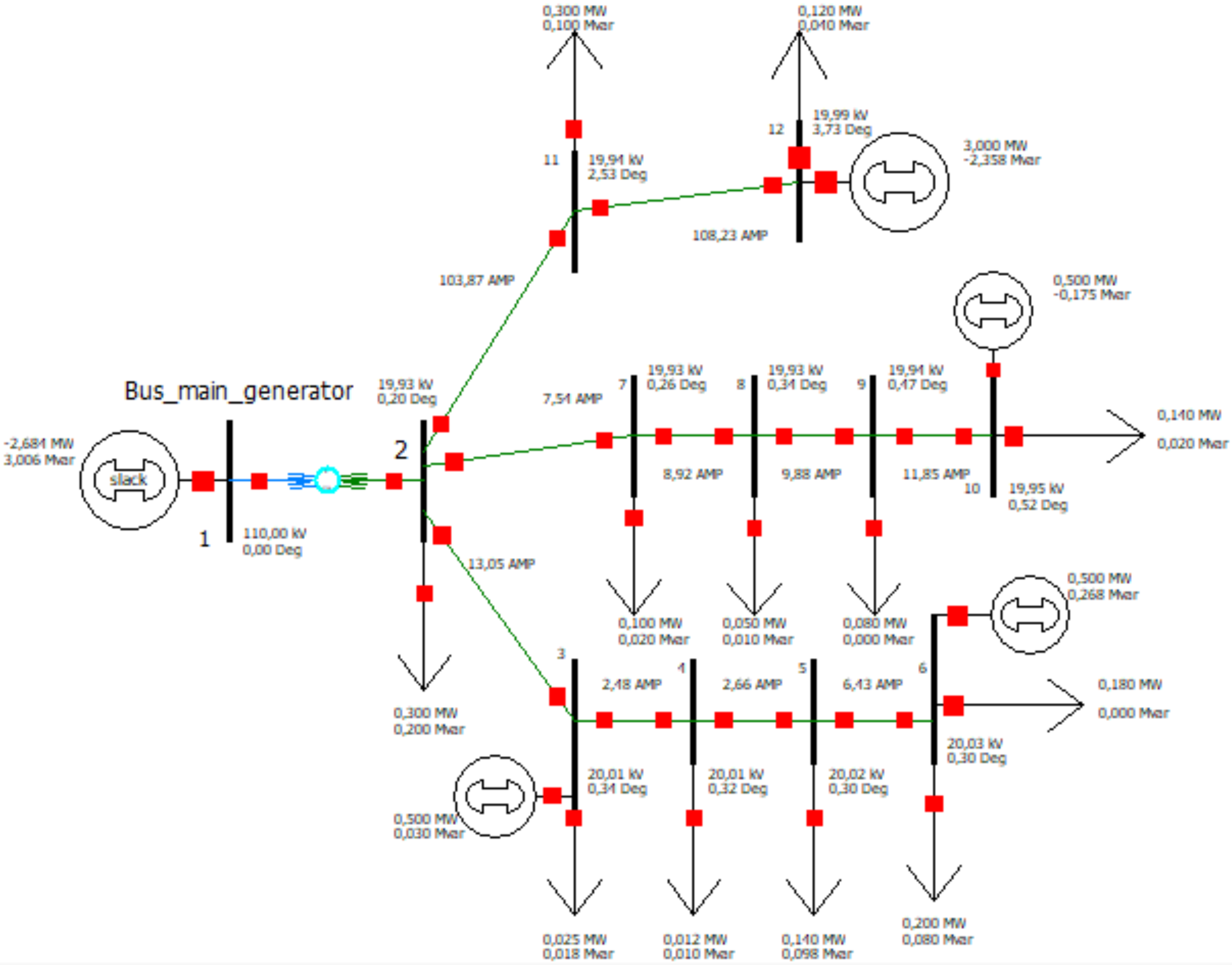


Figure 9.6. Simulation case f)

The power consumed by the generators is:

Table 9.6.1. Power consumed case f)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-2,684	3,006
RES 1	3,000	-2,358
RES 2	0,500	-0,175
RES 3	0,500	0,268
RES 4	0,500	0,030

The voltage and its offset in the bus-bars is:

Table 9.6.2. Voltage and offset case f)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0
2 (transformer output)	19,93	0,20
3	20,01	0,34
4	20,01	0,32
5	20,02	0,30
6 (end of bottom line)	20,03	0,30
7	19,93	0,26
8	19,93	0,34
9	19,94	0,47
10 (end of middle line)	19,95	0,52
11	19,94	2,53
12 (end of top line)	19,99	3,73

The current flowing through the distribution lines is:

Table 9.6.3. Current case f)

	Length (km)	Current (A)
2-3	18	13,05
3-4	6	2,48
4-5	8	2,66
5-6	3	6,43
2-7	7	7,54
7-8	8	8,92
8-9	12	9,88
9-10	4	11,85
2-11	20	103,87
11-12	10	108,23

The following simulation shows the case where the main generator breaks down or there is a problem in its supply line, so only the RES are connected.

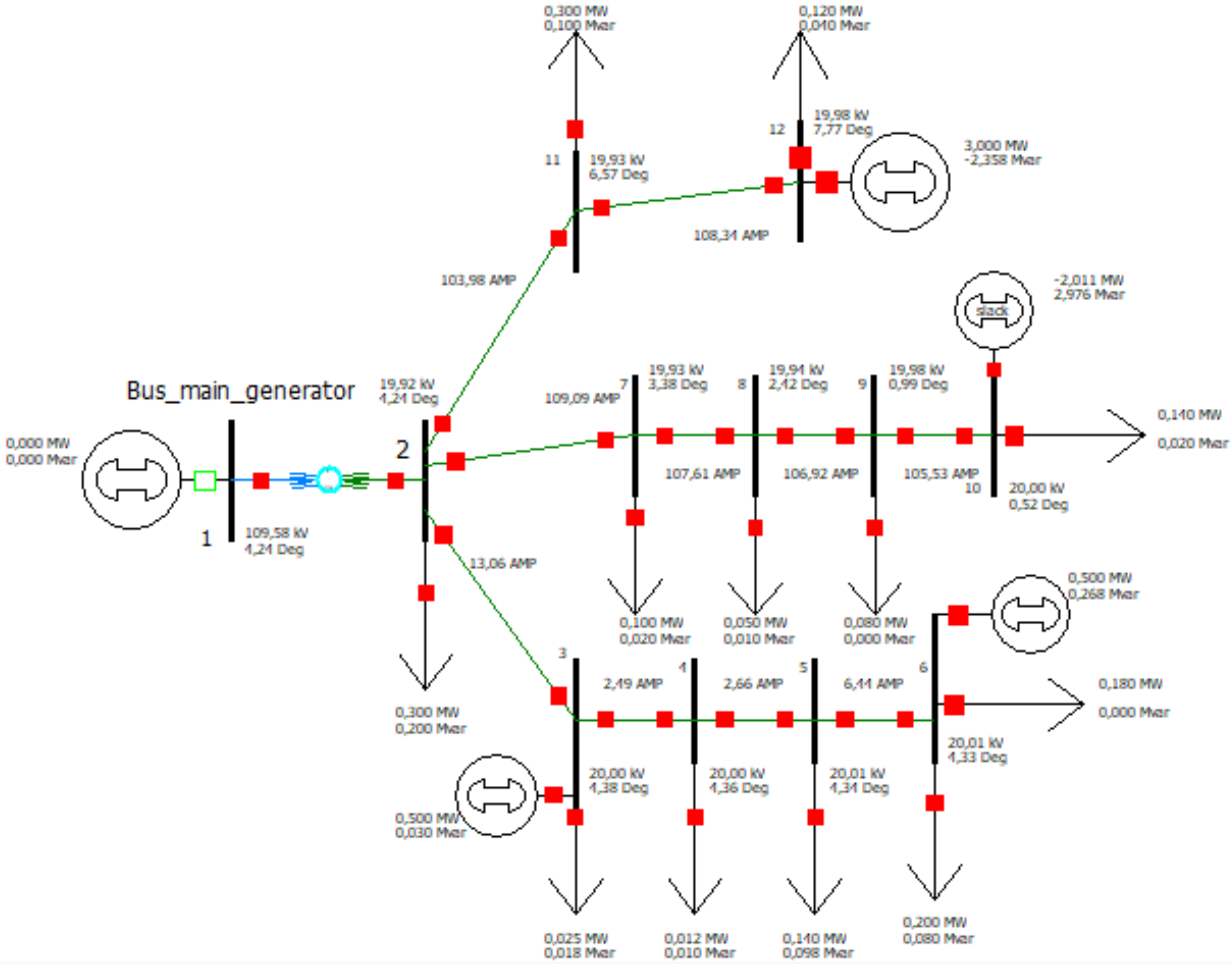


Figure 9.7. Simulation case g)

The power consumed by the generators is:

Table 9.7.1. Power consumed case g)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	0	0
RES 1	3,000	-2,358
RES 2	-2,011	2,976
RES 3	0,500	0,268
RES 4	0,500	0,030

The voltage and its offset in the bus-bars is:

Table 9.7.2. Voltage and offset case g)

	Voltage (kV)	Offset (deg)
1 (transformer input)	109,58	4,24
2 (transformer output)	19,92	4,24
3	20,00	4,38
4	20,00	4,36
5	20,01	4,34
6 (end of bottom line)	20,01	4,33
7	19,93	3,38
8	19,94	2,42
9	19,98	0,99
10 (end of middle line)	20,00	0,52
11	19,93	6,57
12 (end of top line)	19,98	7,77

The current flowing through the distribution lines is:

Table 9.7.3. Current case g)

	Length (km)	Current (A)
2-3	18	13,06
3-4	6	2,49
4-5	8	2,66
5-6	3	6,44
2-7	7	109,09
7-8	8	107,61
8-9	12	106,92
9-10	4	105,33
2-11	20	103,98
11-12	10	108,34

10. Simulations without reactive power generation of the RES

The first simulation below shows the main generator connected and the rest of the generators deactivated.

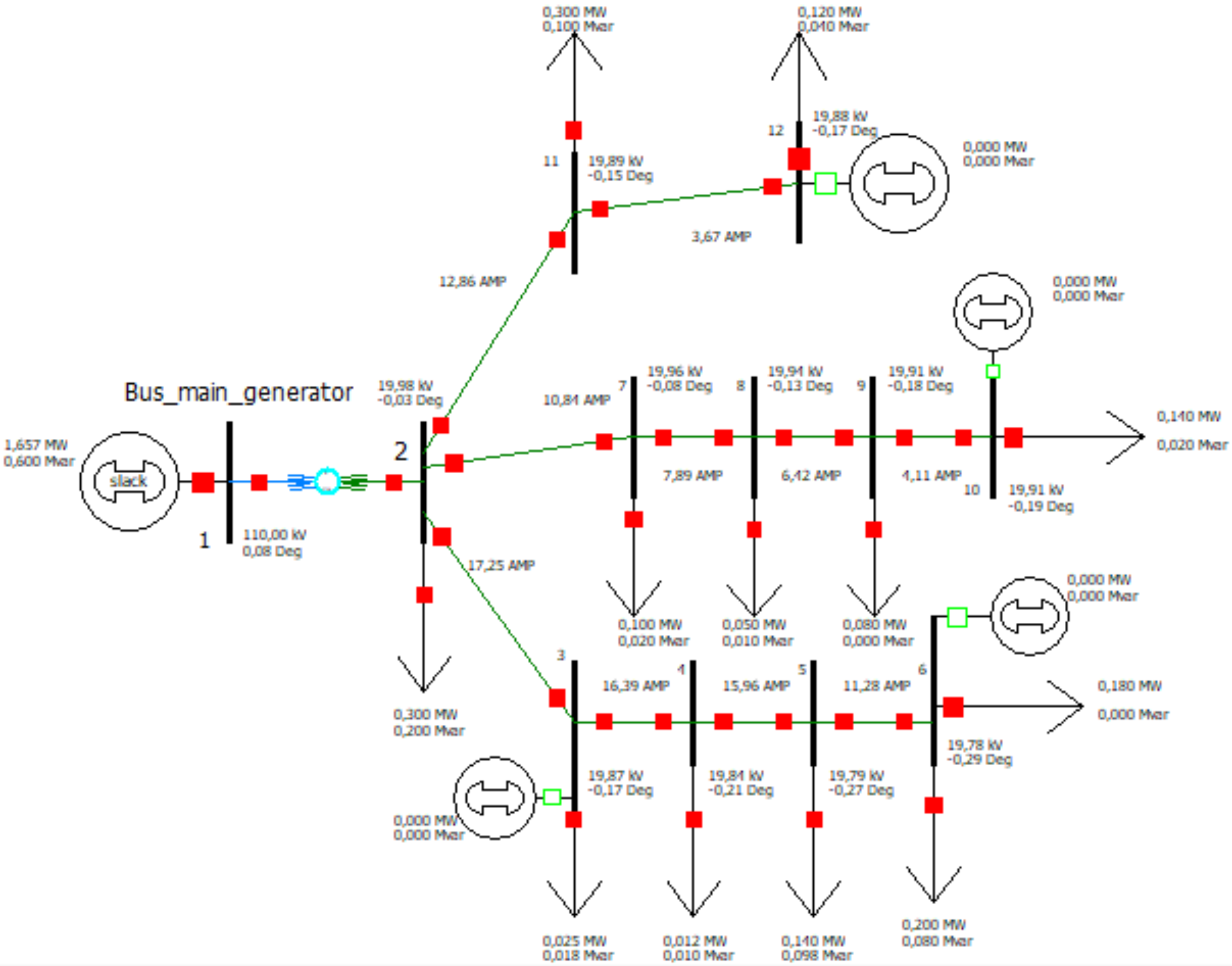


Figure 10.1. Simulation case a)

The power consumed by the generators is:

Table 10.1.1. Power consumed case a)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	1,657	0,600
RES 1	0	0
RES 2	0	0
RES 3	0	0
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 10.1.2. Voltage and offfset case a)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0,08
2 (transformer output)	19,98	-0,03
3	19,87	-0,17
4	19,84	-0,21
5	19,79	-0,27
6 (end of bottom line)	19,78	-0,29
7	19,96	-0,08
8	19,94	-0,13
9	19,91	-0,18
10 (end of middle line)	19,91	-0,19
11	19,89	-0,15
12 (end of top line)	19,88	-0,17

The current flowing through the distribution lines is:

Table 10.1.3. Current case a)

	Length (km)	Current (A)
2-3	18	17,25
3-4	6	16,39
4-5	8	15,96
5-6	3	11,28
2-7	7	10,84
7-8	8	7,89
8-9	12	6,42
9-10	4	4,11
2-11	20	12,86
11-12	10	3,67

The following simulation shows the main generator connected and the main renewable energy source switched on, which is the generetaor situated in the end of the top line.

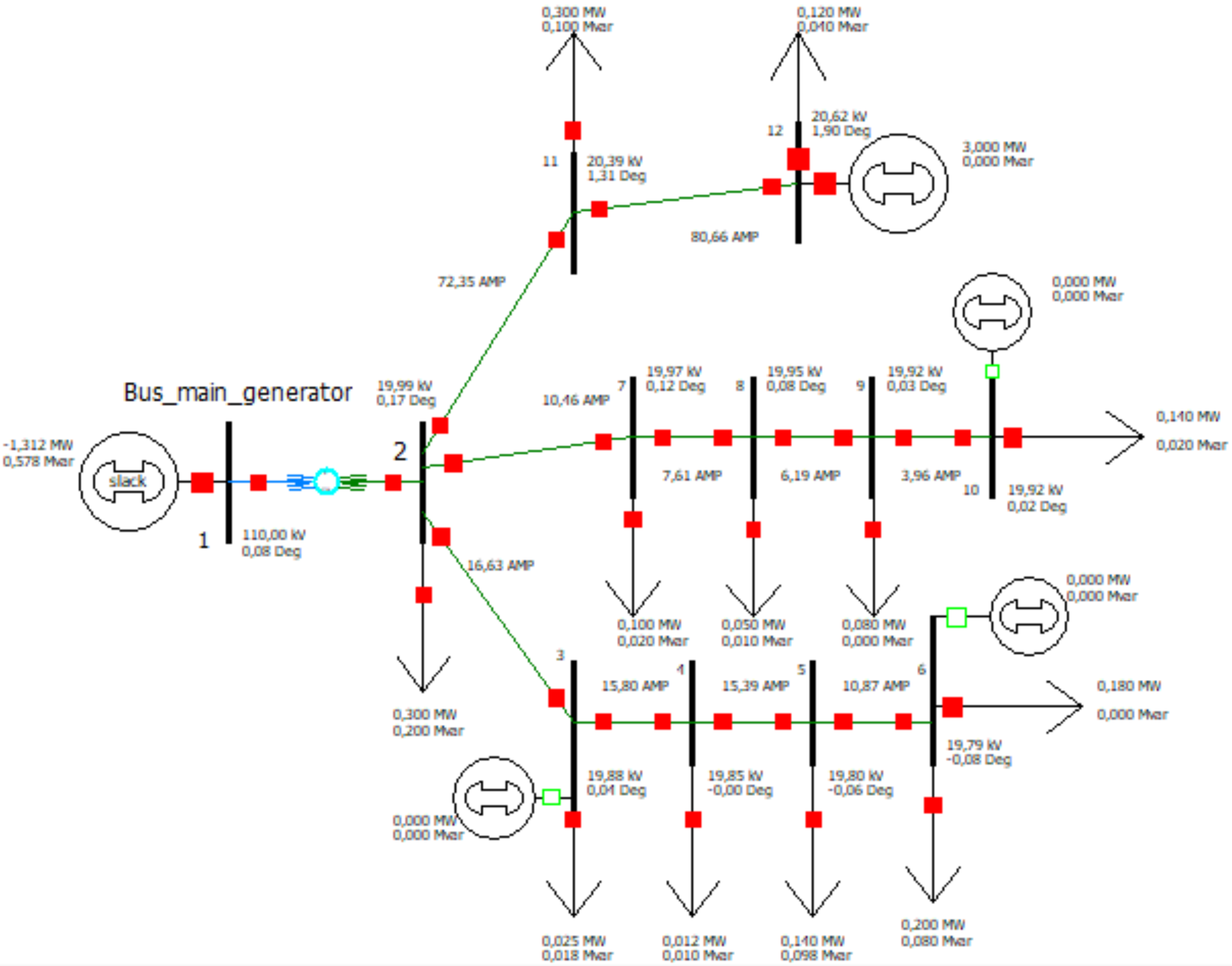


Figure 10.2. Simulation case b)

The power consumed by the generators is:

Table 10.2.1. Power consumed case b)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-1,312	0,578
RES 1	3,000	0
RES 2	0	0
RES 3	0	0
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 10.2.2. Voltage and offfset case b)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0,08
2 (transformer output)	19,99	0,17
3	19,88	0,04
4	19,85	-0,00
5	19,80	-0,06
6 (end of bottom line)	19,79	-0,08
7	19,97	0,12
8	19,95	0,08
9	19,92	0,03
10 (end of middle line)	19,92	0,02
11	20,39	1,31
12 (end of top line)	20,62	1,90

The current flowing through the distribution lines is:

Table 10.2.3. Current case b)

	Length (km)	Current (A)
2-3	18	16,63
3-4	6	15,80
4-5	8	15,39
5-6	3	10,87
2-7	7	10,46
7-8	8	7,61
8-9	12	6,19
9-10	4	3,96
2-11	20	72,35
11-12	10	80,66

The following simulation shows the main generator connected, the main renewable energy source switched on, which is the generetaor situated in the end of the top line and the RES 4 switched on too, which is the only generator is not connected in the final of one if the lines.

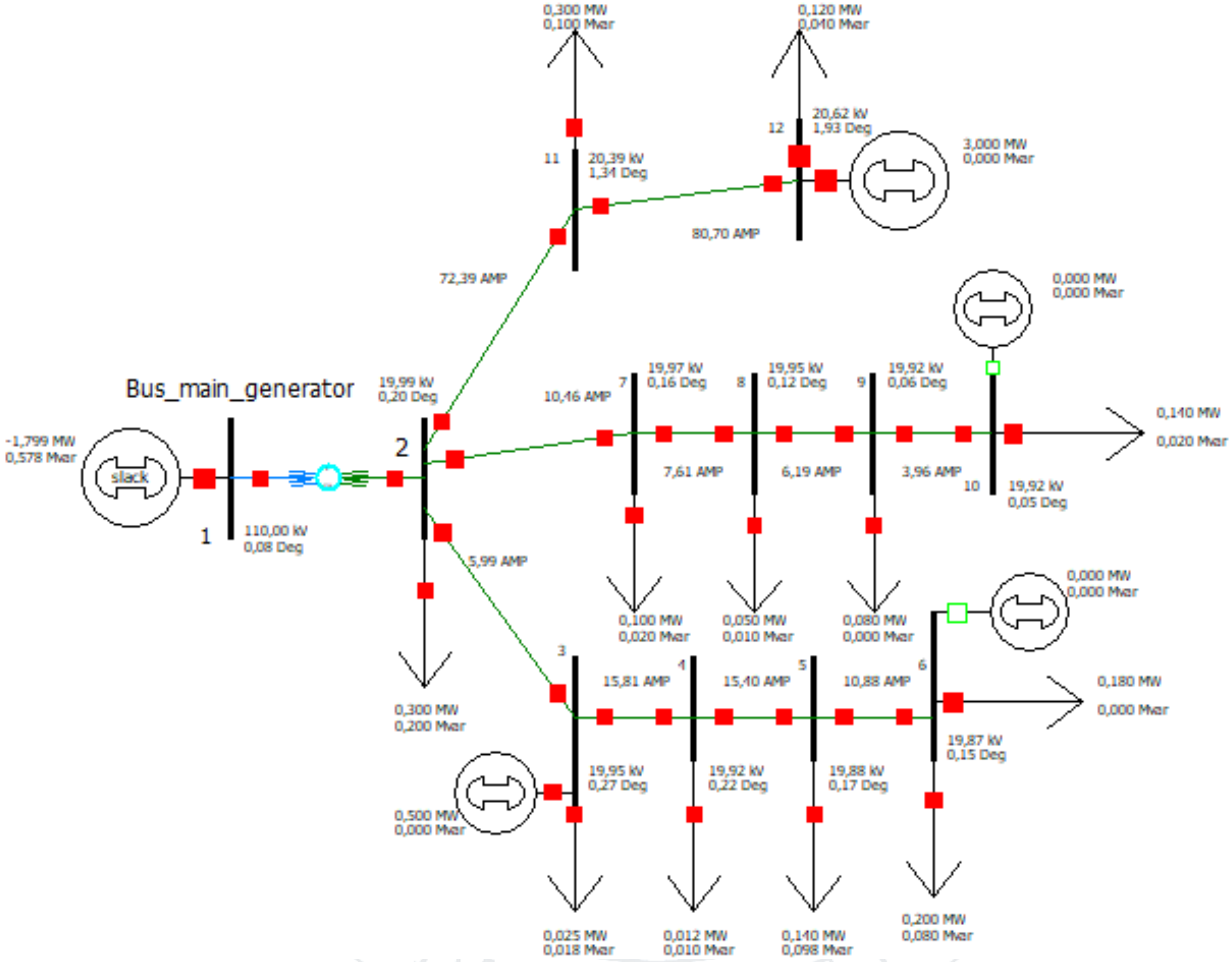


Figure 10.3. Simulation case c)

The power consumed by the generators is:

Table 10.3.1. Power consumed case c)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-1,799	0,578
RES 1	3,000	0
RES 2	0	0
RES 3	0	0
RES 4	0,500	0

The voltage and its offset in the bus-bars is:

Table 10.3.2. Voltage and offfset case c)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0,08
2 (transformer output)	19,99	0,20
3	19,95	0,27
4	19,92	0,22
5	19,88	0,17
6 (end of bottom line)	19,87	0,15
7	19,97	0,16
8	19,95	0,12
9	19,92	0,06
10 (end of middle line)	19,92	0,05
11	20,39	1,34
12 (end of top line)	20,62	1,93

The current flowing through the distribution lines is:

Table 10.3.3. Current case c)

	Length (km)	Current (A)
2-3	18	5,99
3-4	6	15,81
4-5	8	15,40
5-6	3	10,88
2-7	7	10,46
7-8	8	7,61
8-9	12	6,19
9-10	4	3,96
2-11	20	72,39
11-12	10	80,70

The following simulation shows the main generator connected and all the RES, which are in the end of the line, are switched on. The only RES is switched off is the RES 4, which is the only generator is not connected in the final of the line.

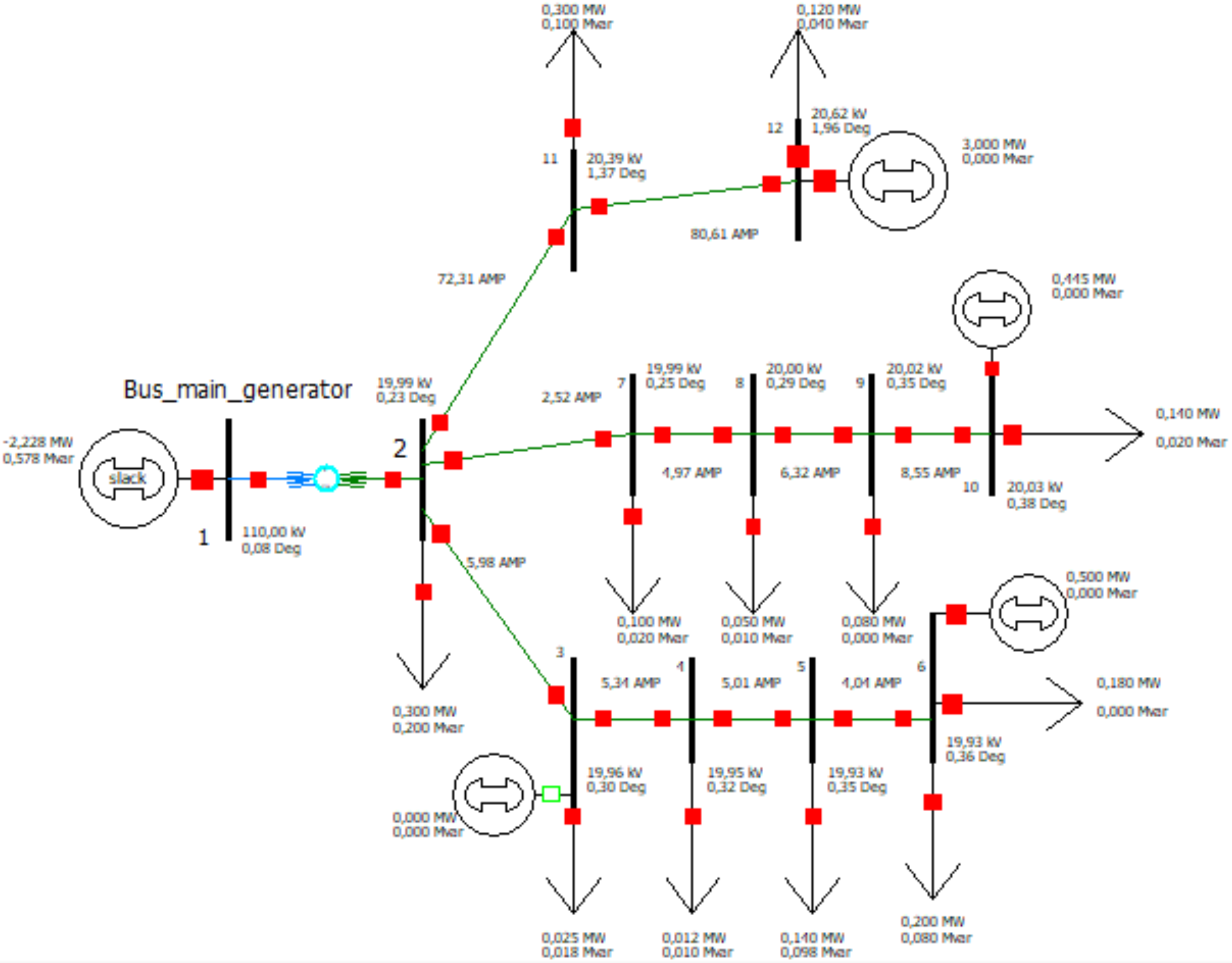


Figure 10.4. Simulation case d)

The power consumed by the generators is:

Table 10.4.1. Power consumed case d)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-2,228	0,578
RES 1	3,000	0
RES 2	0,500	0
RES 3	0,500	0
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 10.4.2. Voltage and offfset case d)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0,08
2 (transformer output)	19,99	0,23
3	19,96	0,30
4	19,95	0,32
5	19,93	0,35
6 (end of bottom line)	19,93	0,36
7	19,99	0,25
8	20,00	0,29
9	20,02	0,35
10 (end of middle line)	20,03	0,38
11	20,39	1,37
12 (end of top line)	20,62	1,96

The current flowing through the distribution lines is:

Table 10.4.3. Current case d)

	Length (km)	Current (A)
2-3	18	5,98
3-4	6	5,34
4-5	8	5,01
5-6	3	4,04
2-7	7	2,52
7-8	8	4,97
8-9	12	6,32
9-10	4	8,55
2-11	20	72,31
11-12	10	80,61

The following simulation shows the main generator connected and only the RES 2 and RES 3 are switched on, which are the generators of the middle and bottom end of lines.

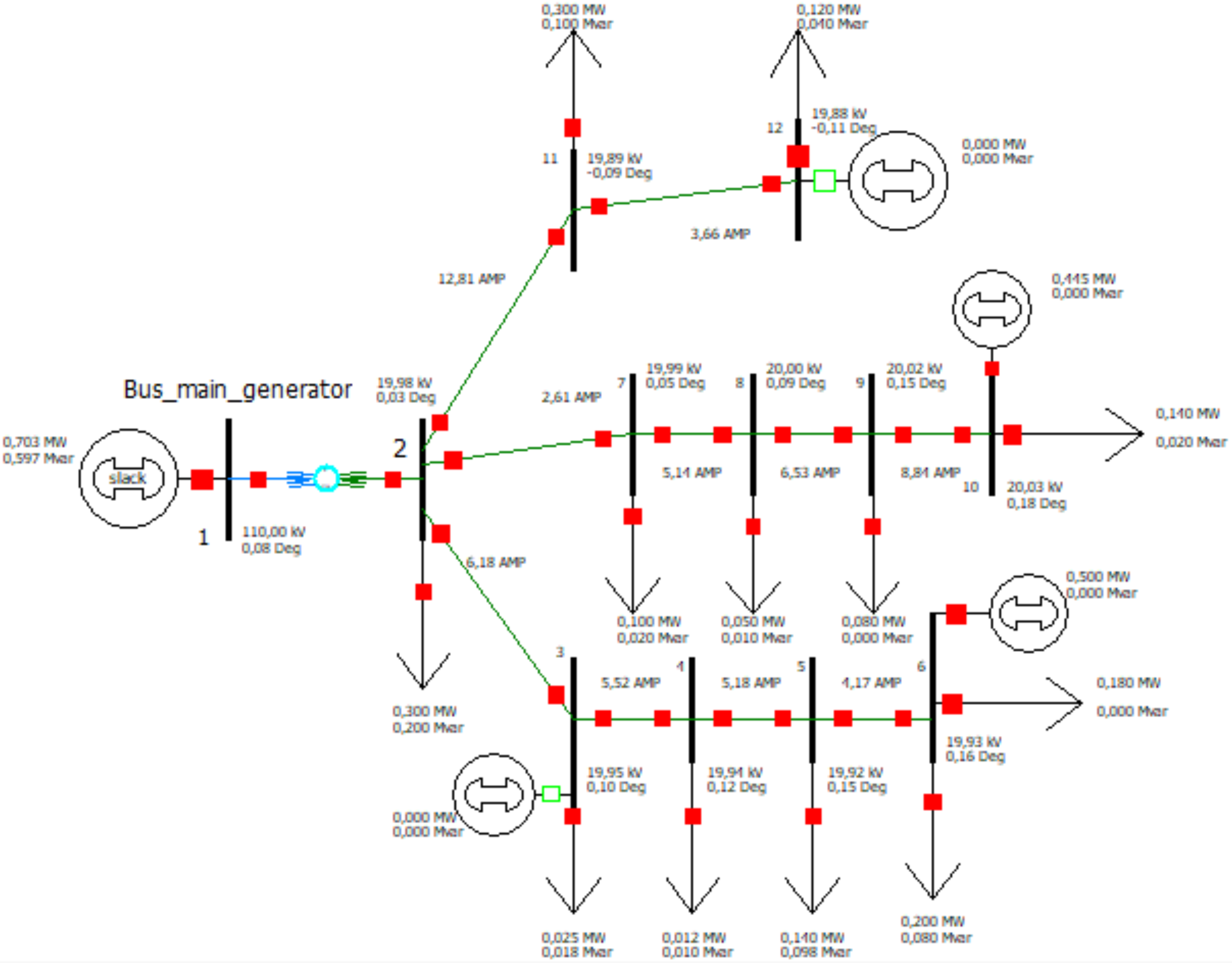


Figure 10.5. Simulation case e)

The power consumed by the generators is:

Table 10.5.1. Power consumed case e)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	0,703	0,597
RES 1	0	0
RES 2	0,445	0
RES 3	0,500	0
RES 4	0	0

The voltage and its offset in the bus-bars is:

Table 10.5.2. Voltage and offfset case e)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0,08
2 (transformer output)	19,98	0,03
3	19,95	0,10
4	19,94	0,12
5	19,92	0,15
6 (end of bottom line)	19,93	0,16
7	19,99	0,05
8	20,00	0,09
9	20,02	0,15
10 (end of middle line)	20,03	0,18
11	19,89	-0,09
12 (end of top line)	19,88	-0,11

The current flowing through the distribution lines is:

Table 10.5.3. Current case e)

	Length (km)	Current (A)
2-3	18	6,18
3-4	6	5,52
4-5	8	5,18
5-6	3	4,17
2-7	7	2,61
7-8	8	5,14
8-9	12	6,53
9-10	4	8,84
2-11	20	12,81
11-12	10	3,66

The following simulation shows the main generator connected and all the RES switch on, too.

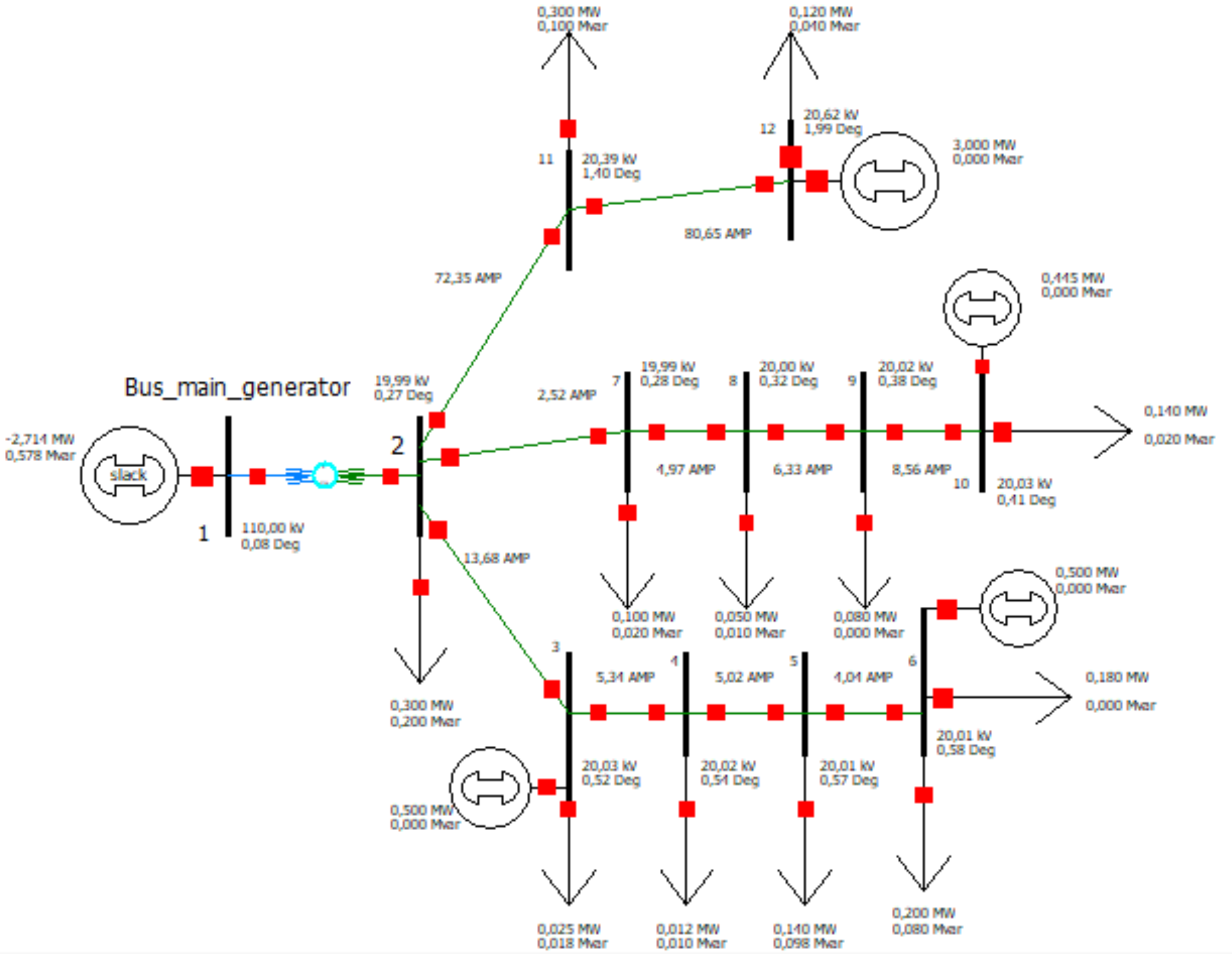


Figure 10.6. Simulation case f)

The power consumed by the generators is:

Table 10.6.1. Power consumed case f)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	-2,714	0,578
RES 1	3,000	0
RES 2	0,445	0
RES 3	0,500	0
RES 4	0,500	0

The voltage and its offset in the bus-bars is:

Table 10.6.2. Voltage and offfset case f)

	Voltage (kV)	Offset (deg)
1 (transformer input)	110	0,08
2 (transformer output)	19,99	0,27
3	20,03	0,52
4	20,02	0,54
5	20,01	0,57
6 (end of bottom line)	20,01	0,58
7	19,99	0,28
8	20,00	0,32
9	20,02	0,38
10 (end of middle line)	20,03	0,41
11	20,39	1,40
12 (end of top line)	20,62	1,99

The current flowing through the distribution lines is:

Table 10.6.3. Current case f)

	Length (km)	Current (A)
2-3	18	13,68
3-4	6	5,34
4-5	8	5,02
5-6	3	4,04
2-7	7	2,52
7-8	8	4,97
8-9	12	6,33
9-10	4	8,56
2-11	20	72,35
11-12	10	80,65

The following simulation shows the case where the main generator breaks down or there is a problem in its supply line, so only the RES are connected.

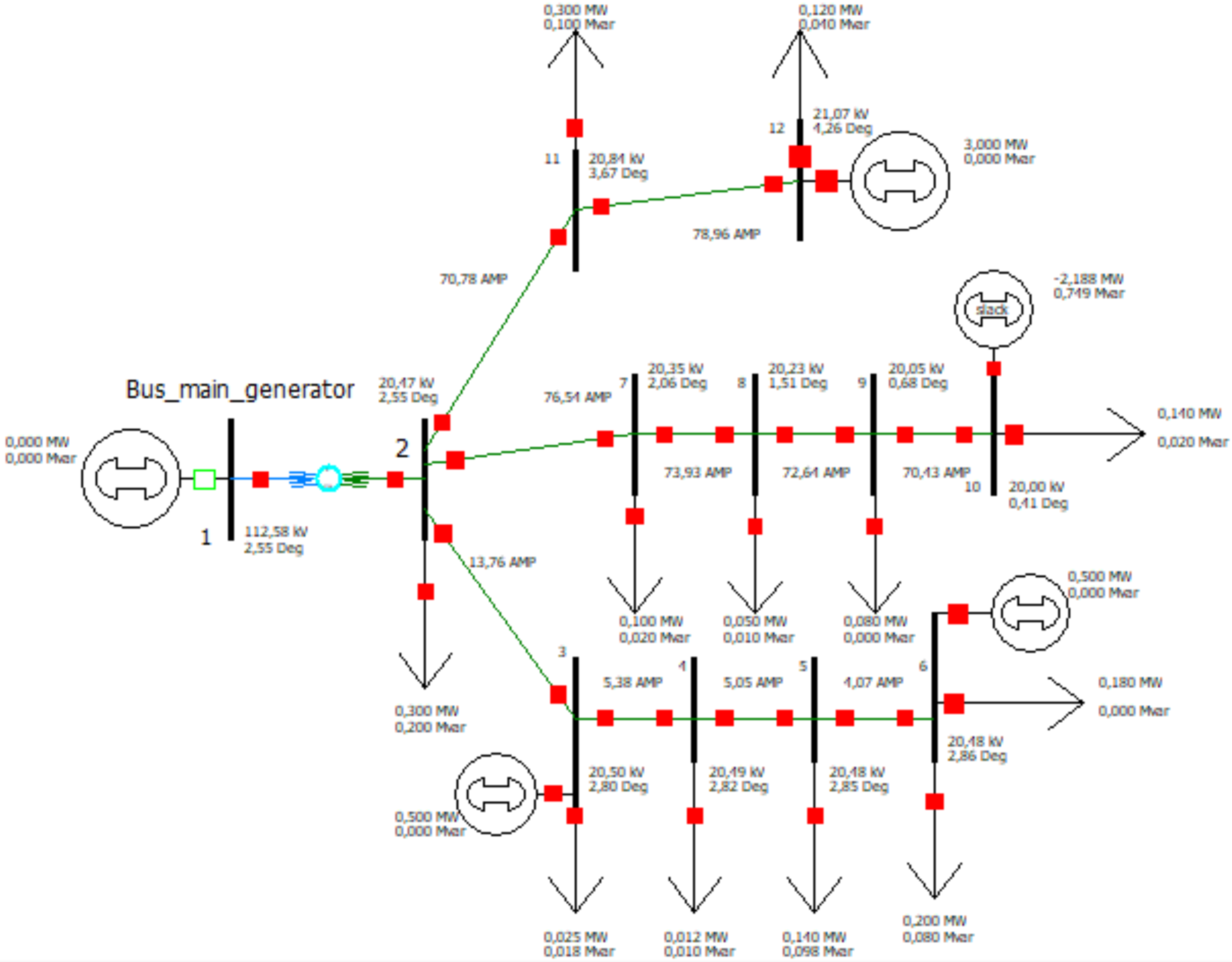


Figure 10.7 Simulation case g)

The power consumed by the generators is:

Table 10.7.1. Power consumed case g)

	Active Power (MW)	Reactive Power (Mvar)
Main generator	0	0
RES 1	3,000	0
RES 2	-2,188	0,749
RES 3	0,500	0
RES 4	0,500	0

The voltage and its offset in the bus-bars is:

Table 10.7.2. Voltage and offfset case g)

	Voltage (kV)	Offset (deg)
1 (transformer input)	112,58	2,55
2 (transformer output)	20,47	2,55
3	20,50	2,80
4	20,49	2,82
5	20,48	2,85
6 (end of bottom line)	20,48	2,86
7	20,35	2,06
8	20,23	1,51
9	20,05	0,68
10 (end of middle line)	20,00	0,41
11	20,84	3,67
12 (end of top line)	21,07	4,26

The current flowing through the distribution lines is:

Table 10.7.3. Current case g)

	Length (km)	Current (A)
2-3	18	13,76
3-4	6	5,38
4-5	8	5,05
5-6	3	4,07
2-7	7	76,54
7-8	8	73,93
8-9	12	72,64
9-10	4	70,43
2-11	20	70,78
11-12	10	78,96

11. Conclusions

Our system being an interconnected network has multiple connections to other supply points. These connection points allow for various configurations of an operational utility by closing and opening switches. Operation of these switches can be by remote control from a control centre or by a line installer. The benefits I can draw from this model is that in the event of a fault or maintenance required a small area of the grid can be isolated and the rest kept in supply, making it perfect for RES as we can no longer always ensure a constant generation of power due to reliance on external factors such as the sun or wind.

Once all the simulations have been carried out and the results have been obtained, we can draw some conclusions from them.

First, let us differentiate between the three types of simulations carried out.
In the first case, we have not changed any options and some generators appear to be consuming energy instead of producing, acting as loads, which means that the system provides more energy than it consumes. In the case of a slack bus, we cannot change these values.

In the second case, to improve the previous results, we set the RES to be unable to regulate the voltage as they did in the first case, so we can better observe the influence of the RES on the system. The RES being unable to regulate the voltage we can see the voltage drop that occurs in each bus-bar and depending on the simulated configuration (e.g. RES 1 and RES 4 activated and RES 3 and 4 deactivated) we can observe the influence of each RES in the system and where the biggest voltage drops are produced by these generators and the loads themselves. The greatest voltage drops, as is logical, are obtained at the end of the line where the RES is deactivated. It can also be observed that the currents tend to be slightly higher in this case, as well as comparing the same case simulated in both types of simulation, which generally consumes more reactive power in the RES in the latter type of simulation.

In the latter case, we will simulate that the renewable energy sources only supply active power so that the reactive power will be equal to zero.
The most remarkable thing in this case is that by reducing the reactive power generated in the RES to zero, the voltage offset is clearly reduced and only altered by the loads. The voltage differences in the different bus-bars are slightly greater, with bus-bars with voltages slightly above the established 20 kV in this last simulation case.

The quality of electrical power depends on several factors such as continuity of service, constant frequency, sinusoidal waveform and to a large extent on the voltage, as we must provide the user with a voltage within a certain range set by the standards. As we have seen in the different simulations, we set a voltage but variations occur when we desactivate or connect RES or if there is a variation in the load. It is very important that there is not a large voltage variation with respect to the service voltage. For example, if the supply voltage is permanently high, this will reduce the lifetime of the electrical equipment. On the other hand, if we supply permanently low voltage, the luminaires will not look as good as they should or the motors will overheat due to overcurrent.

So, to keep the voltages of the distribution system within the admissible limits, i.e. to increase the voltage when it is too low and reduce it when it is too high, we will have to come up with some solutions. The following solutions I can think of to implement in our system are the following: use of voltage regulators in the generators (an option that we have been able to simulate with PowerWorld), installation of capacitors, increasing the cross-section of the conductors or installing new intermediate substations and primary feeders.

12. Bibliography

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13. List of figures

14. List of tables