SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

Electric Power Systems Project:
Power Flow Analysis on Medium Sized Systems

	Family name	Given name	Student ID
1	Ferrari	Gianluca	873201
2	Ferri	Edoardo	940112
3	Pessina	Manuel	941667
4	Pisani	Matteo	944056
5	Pivari	Simone	946762
6	Secchi	Alessandro	944668

E-mail given in the registration form: alessandro2.secchi@mail.polimi.it

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SUMMARY

1. INTRODUCTION

The purpose of this project is to analyze a given system, presenting an Emergency State, in order to find the optimal solution to mitigate the contingencies (Correctable Emergency State). The system considered, which is shown in figure 1.1, is a 37-bus system operating at 345/138/69 kV. The critical event that led to the emergency condition is a failure at the SPIRIT69 generator, resulting in a loss of injected power equal to 110 MW and causing important overloads at:

- TEXAS345-TEXAS138 transformer
- HOWDY138-HOWDY69 transformer
- TEXAS69-MAROON69 line.

The step-by-step plan to follow in order to bring back the system to a secure condition is described in the following document. Moreover, a further procedure to minimize system's total losses is also presented, as requested.

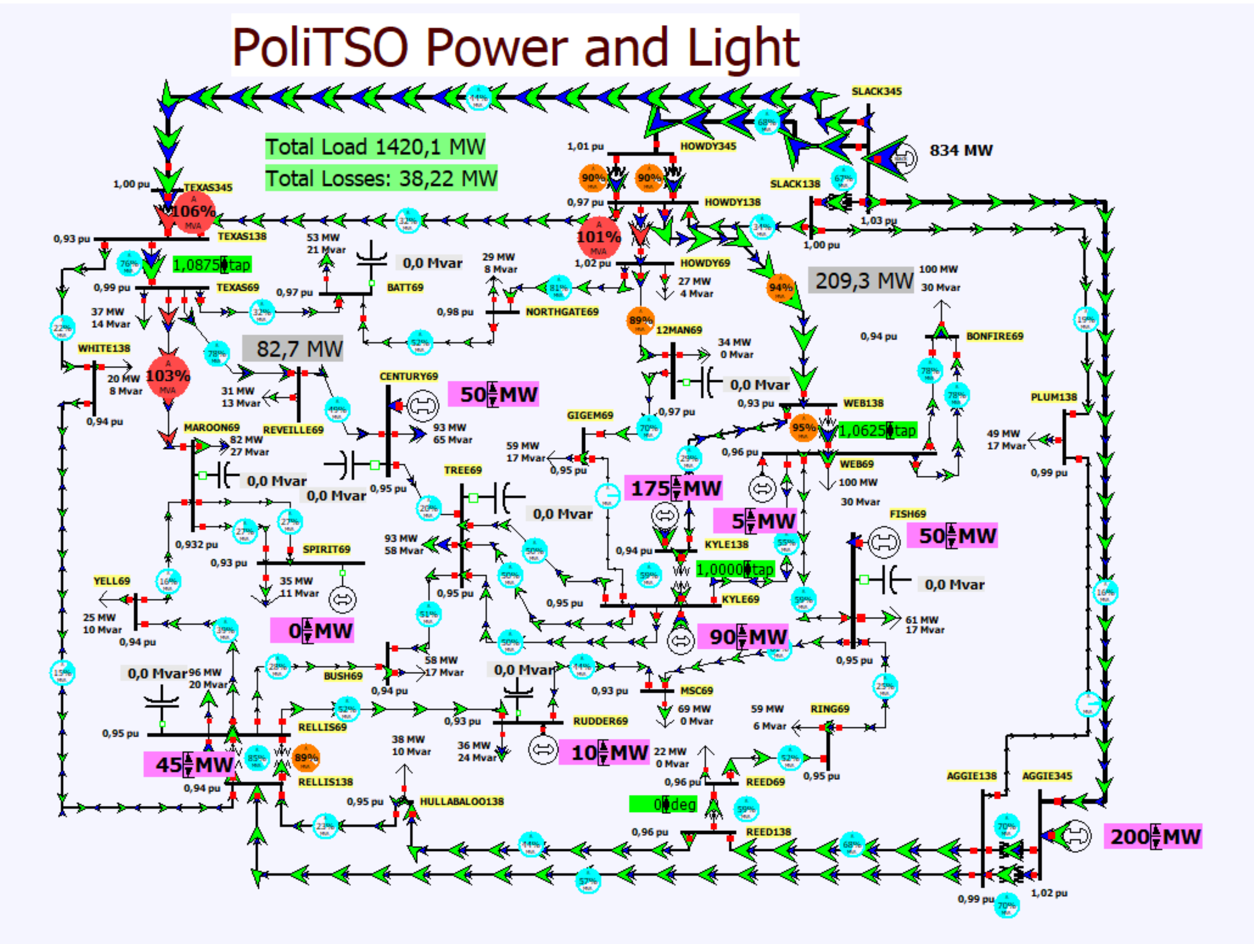

Figure 0.1 37-bus system in Emergency State

2. GENERATORS SELECTION AND SENSITIVITIES

• Selection of Generators

The first step on which the team has focused is the choice of two generators to fix the power flow violations. The most efficient way to select them is to look at the Generation Shift Factors of the overloaded elements with respect to each generator, in order to have a complete vision of the sensitivities (how a unitary change in power injected at each generator influences the overloaded components) so that it is possible to determine the most influent generators on the critical line/transformers. The results achieved, by using the PowerWorld's tool "Sensitivities - Generation Shift Factors", are reported in figures below.

	Number of Bus	Name of Bus	ID	Area Name of Gen	AGC	P Sensitivity ▲
1	37	SPIRIT69	1	1	NO	-0,307692
2	44	RELLIS69	1	1	NO	-0,252505
3	16	CENTURY69	2	1	YES	-0,248851
4	14	RUDDER69	1	1	YES	-0,240157
5	54	KYLE69	1	1	NO	-0,239831
6	48	WEB69	1	1	NO	-0,222930
7	20	FISH69	2	1	NO	-0,221386
8	53	KYLE138	1	1	NO	-0,209830
9	28	AGGIE345	1	1	NO	-0,063237
10	31	SLACK345	1	1	YES	0,000000

Figure 1.1 TEXAS345-TEXAS138, Generation Shift Factors

	Number of Bus	Name of Bus	ID	Area Name of Gen	AGC	P Sensitivity ▲
1	54	KYLE69	1	1	NO	-0,137656
2	16	CENTURY69	2	1	YES	-0,137075
3	37	SPIRIT69	1	1	NO	-0,116368
4	48	WEB69	1	1	NO	-0,100087
5	44	RELLIS69	1	1	NO	-0,093162
6	14	RUDDER69	1	1	YES	-0,092730
7	20	FISH69	2	1	NO	-0,092073
8	53	KYLE138	1	1	NO	-0,073996
9	28	AGGIE345	1	1	NO	-0,016612
10	31	SLACK345	1	1	YES	0,000000

Figure 1.2 HOWDY138-HOWDY69, Generation Shift Factors

	Number of Bus	Name of Bus	ID	Area Name of Gen	AGC	P Sensitivity ▲
1	37	SPIRIT69	1	1	NO	-0,563350
2	44	RELLIS69	1	1	NO	-0,164470
3	14	RUDDER69	1	1	YES	-0,120781
4	20	FISH69	2	1	NO	-0,054360
5	48	WEB69	1	1	NO	-0,026428
6	28	AGGIE345	1	1	NO	-0,019852
7	54	KYLE69	1	1	NO	-0,018303
8	53	KYLE138	1	1	NO	-0,014739
9	16	CENTURY69	2	1	YES	-0,011622
10	31	SLACK345	1	1	YES	0,000000

Figure 1.3 TEXAS69-MAROON69, Generation Shift Factors

Through a critical analysis on the sensitivity values the number of selectable generators has been reduced to four. More precisely, KYLE69, RUDDER69, FISH69 and CENTURY69 represent the best compromise for each overloaded element while RELLIS69, even though it has a quite big influence on each considered element, has been excluded due to its limited capacity (only 5MW more available: low reliability margin).

KYLE69 has been selected first and set to 110 MW because of its wide margin (70 MW more available) so that, in case of necessity, it would be possible to increase again the injected power. Moreover, since FISH69 has a limited influence on the two overloaded transformers and CENTURY69 does not affect too much TEXAS69-MAROON69 branch, they have not been considered. Therefore, RUDDER69 represents a good choice (also due to its mitigation effect on the overloaded line TEXAS69-MAROON69) and it has been selected as second generator and set to 35 MW.

The obtained system's state is shown in Figure 2.4.

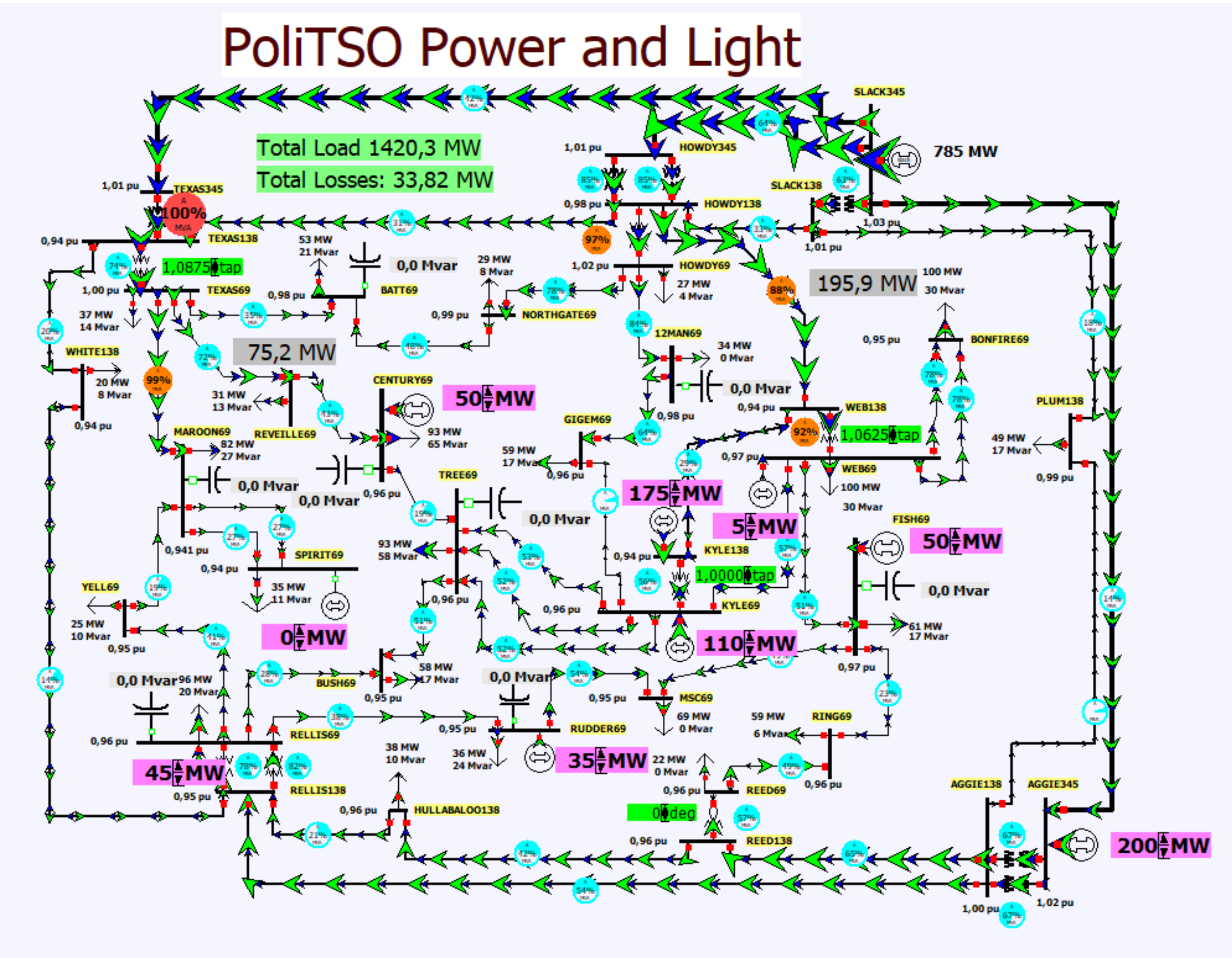

Figure 1.4 System's state after changing injections

It's also important to notice that the power injected (45 MW) to fix the power flow violations is lower than the power lost due to the fault at SPIRIT69 bus (110 MW). This is because the actual goal of the procedure is to bring back the system to a stable secure state in which operational constraints and limits of lines and transformers are not violated (therefore, it's not a problem if a line is at 100% of its transmitted power) so that, in a reasonable amount of time, SPIRIT69 generator can be restored.

- ## Sensitivities Computation

The second step on which the team has focused was the experimental computation of the sensitivities of each overloaded element of the grid with respect to the two generators selected in the previous paragraph, in order to understand whether they are linear or not. For the sake of clearness, it is recalled that the sensitivities mentioned are called Generation Shift Factors and are defined as:

$$L_{ij,m} = \frac{\Delta P_{ij}}{\Delta P_m}$$

where ΔP_{ij} represents the changing in power transmitted through a line ij and ΔP_m represent a variation in power injected at bus m.

There are several techniques that can be used to estimate $L_{ij,m}$ values:

- Compute with the DC Power Flow method $\Delta\delta$ (variations of voltage angles at every busses) after a unitary change in power injected at bus m ($\Delta P_m = 1$) so that it is possible to compute ΔP_{ij} as $\Delta P_{ij} \approx \frac{\Delta\delta_i - \Delta\delta_j}{x_{ij}}$
- Select a control variable u and compute with the Jacobian matrixes $J_x = \begin{matrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{matrix}$ and $J_u = \begin{matrix} \frac{\partial (P_{rated} - P)}{\partial u} \\ \frac{\partial (Q_{rated} - Q)}{\partial u} \end{matrix}$. Then, compute the sensitivities of the state variables (voltage's magnitude and angle at each bus) as $\begin{matrix} \Delta\delta \\ \Delta V \end{matrix} = -{J_x}^{-1} J_u \, \Delta u$ so that is possible to compute ΔP_{ij} as $\Delta P_{ij} \approx \frac{\Delta\delta_i - \Delta\delta_j}{x_{ij}}$ (in this case $u = P_{rated,m}$).
- Run different Power Flows changing the power injected at bus m and record the power transmitted over line ij: find S as $S = \frac{\Delta P_{ij}}{\Delta P_m}$ for each recorded value and interpolate the data obtained in order to find a constant sensitivity value (that means it's linear).

The team worked on the third method since it is the most accurate and precise; the result achieved are presented and analyzed in the next page.

$\Delta P_{inje\ cted}$ $[MW]$	0	5	10	15	20	25
Rudder69	232.8	231.52	230.24	228.97	227.7	226.43
Kyle69	232.8	231.57	230.33	229.1	227.87	226.64
S(Rudder) btw 2		-0.256	-0.256	-0.254	-0.254	-0.254
S(Kyle) btw 2		-0.246	-0.248	-0.246	-0.246	-0.246

Table 2. 1 TEXAS345-TEXAS138 line's power values changing the power injected by Rudder69 and Kyle69 generators

$\Delta P_{injected}$ [MW]	0	5	10	15	20	25
Rudder69	102.69	102.02	101.35	100.68	100.01	99.35
Kyle69	102.69	102.6	102.52	102.43	102.34	102.25

Table 2.2 TEXAS69-MAROON69 line's power values changing the power injected by Rudder69 and Kyle69 generators

$\Delta P_{injected}$ $[MW]$	0	5	10	15	20	25
R69	179.03	178.45	177.87	177.3	176.63	176.17
K69	179.03	178.27	177.51	176.75	175.99	175.23

Table 2.3 HOWDIE138-HOWDIE69 line's power values changing the power injected by Rudder69 and Kyle69

It is possible to observe, from the table 2.1, that the sensitivities with respect to the two generators are relatively constant. For instance, consider the "S(Rudder) btw 2" and "S(Kyle) btw 2" parameters: they represent the sensitivity values computed as $S_i = \frac{\Delta P_i - \Delta P_{i-1}}{5}$, where ΔP_i is the recorded variation in power transmitted over the TEXAS345-TEXAS138 line and ΔP_{i-1} is the recorded variation in power transmitted over the TEXAS345-TEXAS138 line at the previous Power Flow run (so that, for every value S_i computed between two records, the variation of injected power is always equal to 5 MW). Since the results achieved are relatively constant, the team has chosen to compute the Generation Shift Factors by calculating the mean between the S_i values obtained. A faster way to do it is to predict (by interpolating the power values recorded in the tables) the power transferred over the lines corresponding to a $\Delta P_{injected} = 30\ MW$ so that, in case of a clear degree of linearity, it is possible to compute the Sensitivity as the angular coefficient of the interpolating line that relates the variation of power over the considered lines to the different variations of injections at each of the two generators selected in the previous paragraph. More precisely, $S = \frac{\Delta P_{line,30\ predicted} - \Delta P_{line,0}}{30}$ where $\Delta P_{line,30\ predicted}$ is the predicted value of power transferred over the considered line (injecting a $\Delta P_{injected} = 30\ MW$) and $\Delta P_{line,0}$ is the initial value of the power transferred over that line.

LINE	30 predicted [MW]	30 real [MW]	Sensitivity=m
T345-T138	225.152	225.18	-0.25493
T69-M69	98.67666	98.64	-0.13378
H138-H69	175.542	174.61	-0.11627

Table 2.4 Lines Sensitivities with respect to RUDDER69 generator

LINE	30 predicted [MW]	30 real [MW]	Sensitivity=m
T345-T138	225.4053	224.13	-0.24649
T69-M69	102.16467	101.44	-0.01751
H138-H69	174.47	172.9	-0.152

Table 2.5 Lines Sensitivities with respect to KYLE69 generator

It is also possible to represent in a graph the variation of power transferred over the considered lines with respect to the variation of power injected to the grid by the two generators selected. The results are shown in the following pictures:

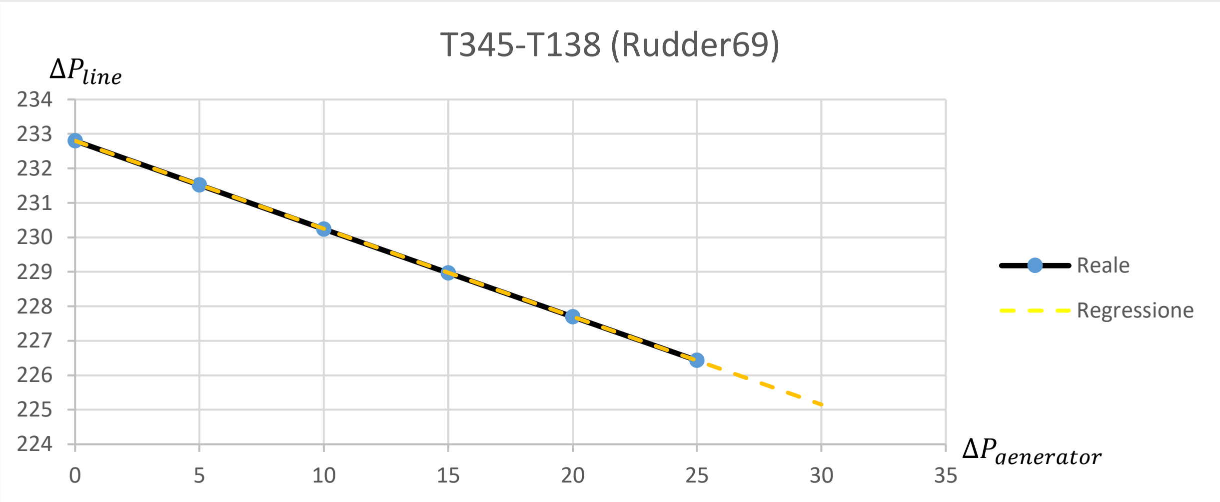

Figure 2.5 Graph of the relation between the variation of power over the TEXAS345-TEXAS138 line and the variation of power injected by RUDDER69 generator

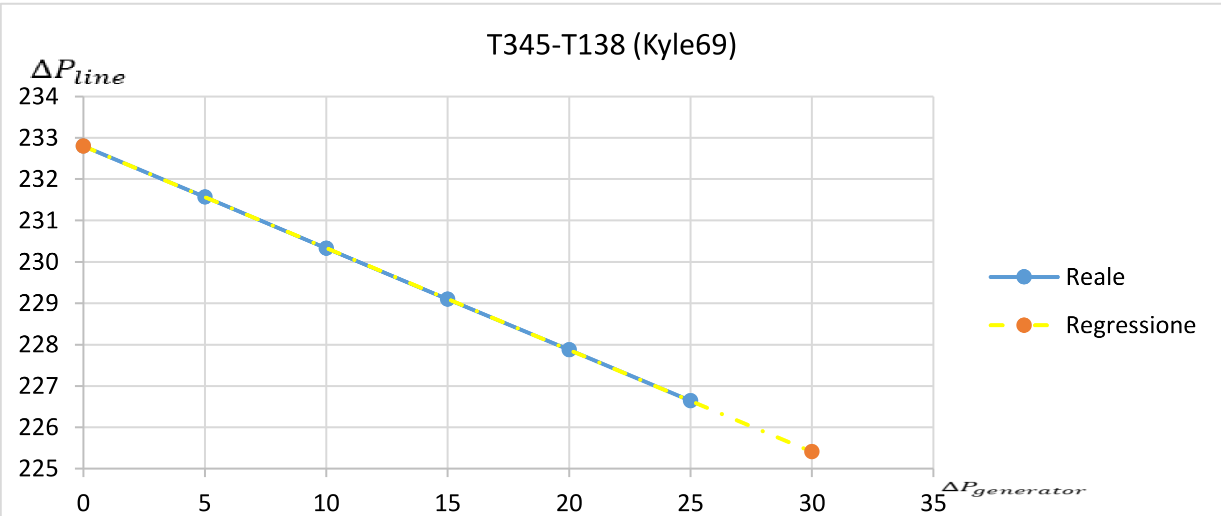

Figure 2.6 Graph of the relation between the variation of power over the TEXAS345-TEXAS138 line and the variation of power injected by KYLE69 generator

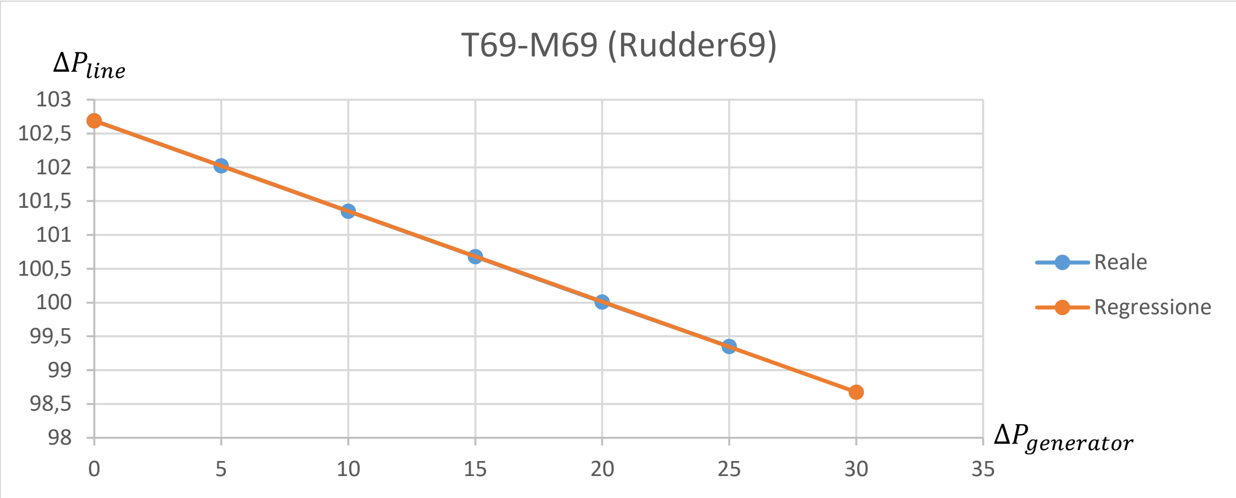

Figure 2.7 Graph of the relation between the variation of power over the TEXAS69-MAROON69 line and the variation of power injected by RUDDER69 generator

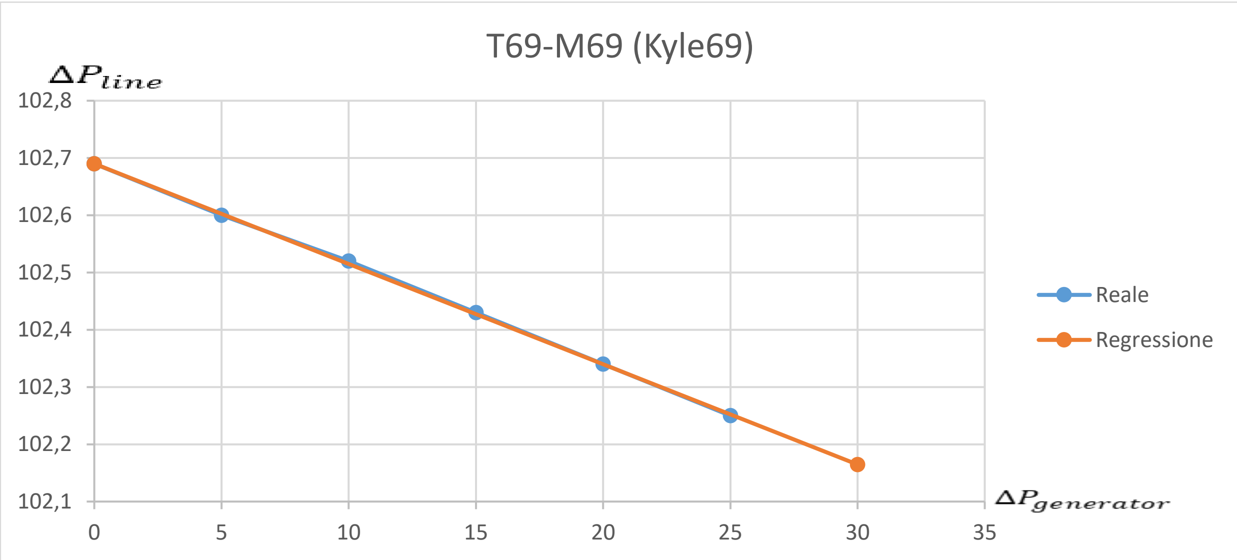

Figure 2.8 Graph of the relation between the variation of power over the TEXAS69-MAROON69 line and the variation of power injected by KYLE69 generator

Figure 2.9 Graph of the relation between the variation of power over the HODIE138-HOWDIE69 line and the variation of power injected by RUDDER69 generator

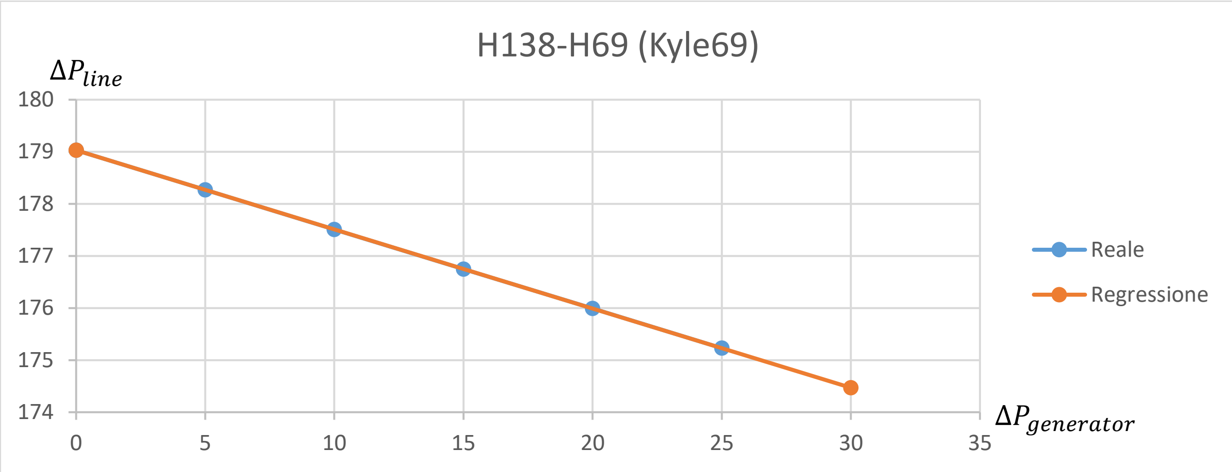

Figure 2.10 Graph of the relation between the variation of power over the HODIE138-HOWDIE69 line and the variation of power injected by KYLE69 generator

It's worth to notice that there are two main elements in the previous graphs: the set of records (blue dots) and the interpolating line (orange line). Since the mismatches between the two elements considered are very small, the relationship between the variation of power over a line and the variation of injected power at a bus can be considered linear and, therefore, sensitivity, interpreted as the angular coefficient of the interpolating line, is a constant parameter.

3. SENSITIVITIES COMPARISON AND SLACK BUS CHANGE

It is possible to compare the values computed in the previous section with the ones that can be obtained by running PowerWorld simulator tool "Sensitivities".

The results are presented in the next table:

Branch	Generator	Sensitivity	Mismatch
T345-T138	Rudder69	-0.240157	0.014776
	Kyle69	-0.239831	0.006658
T69-M69	Rudder69	-0.120781	0.012997
	Kyle69	-0.018303	-0.000792
H138-H69	Rudder69	-0.092730	0.023537
	Kyle69	-0.137656	0.014344

Table 3.1 Sensitivity values computed with PowerWorld tool "Sensitivities" and the respective mismatch with the value computed in the previous paragraph

Through a critical analysis of the mismatches obtained, since their values are very small (always lower than 0.025), the sensitivities previously computed are correct. It is worth observing that almost every mismatch value is positive; that means that the sensitivities estimated by running different power flows are lower (more negative) than the ones estimated by the PowerWorld simulator. It is also interesting to notice that the technique used by the tool to compute the sensitivity is based on the lossless DC power flow (first method recalled in paragraph 2.2) so that its results are less accurate than comparing different power flows solutions. Eventually, it is important to recall that the assumption that has been implicitly made in these computations is the fact that the change in the output of each generator is absorbed at the slack bus SLACK345 (already defined in the starting system in Emergency State). For the sake of clearness, it is possible to change the slack bus and record the new results obtained in order to make a comparison. In this case, as requested, bus AGGIE345 has been considered as the new slack bus.

Following the same procedure of the previous paragraph it is possible to compute again the sensitivity values for the three considered lines. The results obtained are shown in the following tables and graphs:

T345-T138	0	5	10	15	20	25	30	Reale 30	m=SENSITIVITA
Rudder 69	229.7	228.84	227.97	227.12	226.26	225.4	224.53933	224.54	-0.172022222
Kyle69	229.7	228.86	228.01	227.16	226.32	225.47	224.62467	224.62	-0.169177778

T69-M69	0	5	10	15	20	25			
R69	101.11	100.6	100.08	99.56	99.05	98.54	98.021333	98.03	-0.102955556
K69	101.11	101.17	101.23	101.28	101.34	101.39	101.44933	101.45	0.011311111

H138-H69	0	5	10	15	20	25			
R69	180.57	180.13	179.7	179.26	178.84	178.41	177.974	177.99	-0.086533333
K69	180.57	179.94	179.31	178.68	178.05	177.43	176.79667	176.8	-0.125777778

Table 3.2 Values of power transmitted over the overloaded lines for each considered variation in power injection of the two selected generators and corresponding sensitivity values computed with the method explained before

OLD SLACK

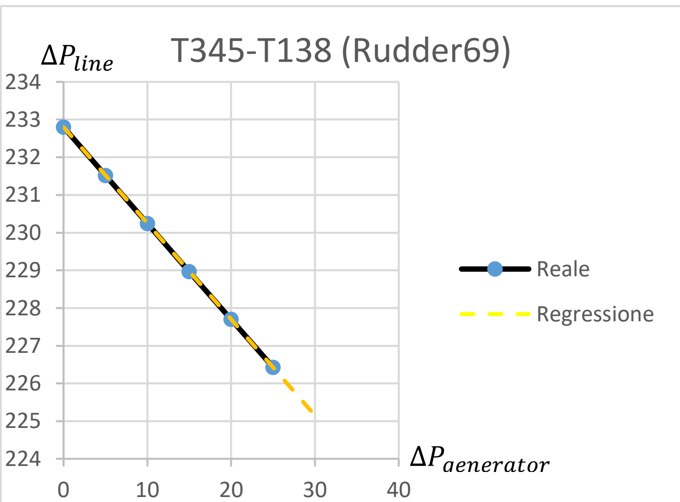

Figure 3.1 Graph of the relation between the variation of power over the TEXAS345-TEXAS138 line and the variation of power injected by RUDDER 69 generator with old slack bus

NEW SLACK

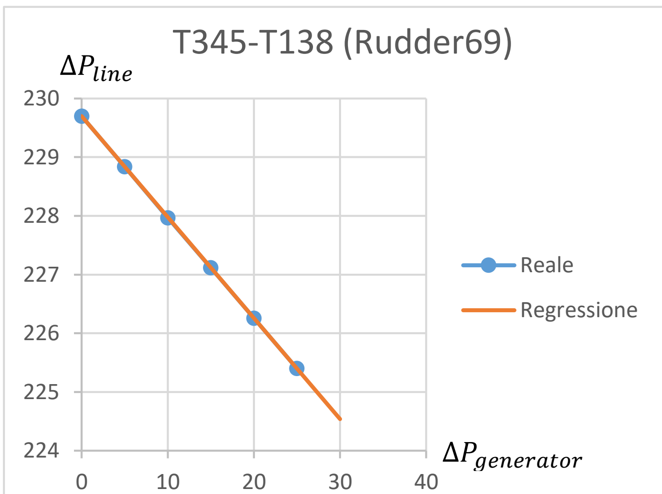

Figure 3.2 Graph of the relation between the variation of power over the TEXAS345-TEXAS138 line and the variation of power injected by RUDDER69 generator with new slack bus

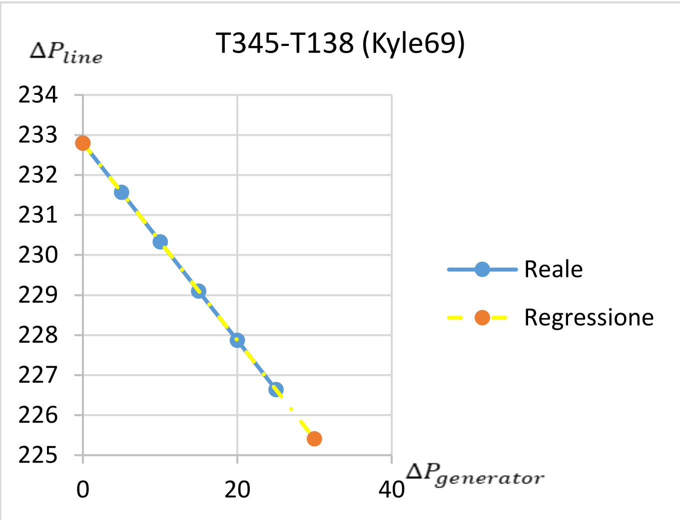

Figure 3.3 Graph of the relation between the variation of power over the TEXAS345-TEXAS138 line and the variation of power injected by KYLE69 generator with old slack bus

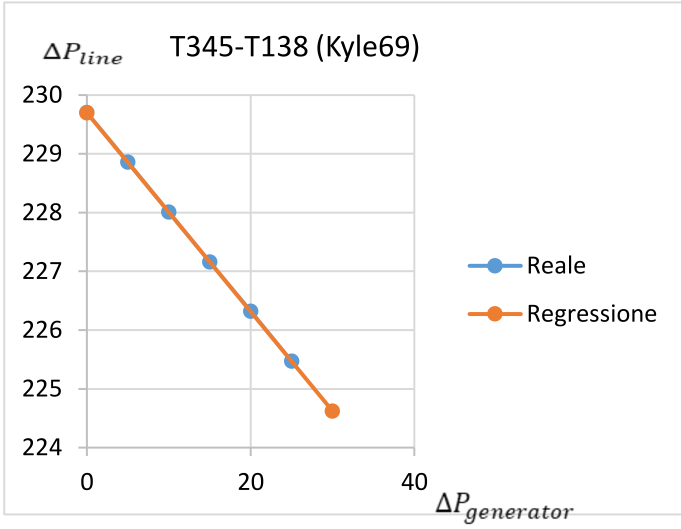

Figure 3.4 Graph of the relation between the variation of power over the TEXAS345-TEXAS138 line and the variation of power injected by KYLE69 generator with new slack bus

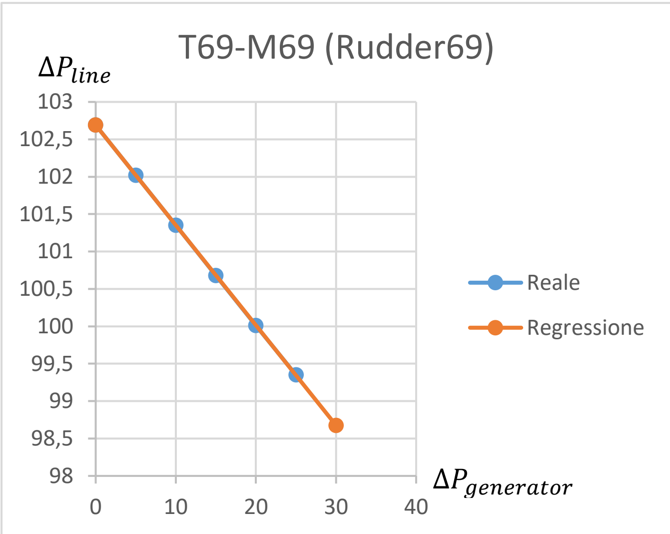

Figure 3.5 Graph of the relation between the variation of power over the TEXAS69-MAROON69 line and the variation of power injected by RUDDER69 generator with old slack bus

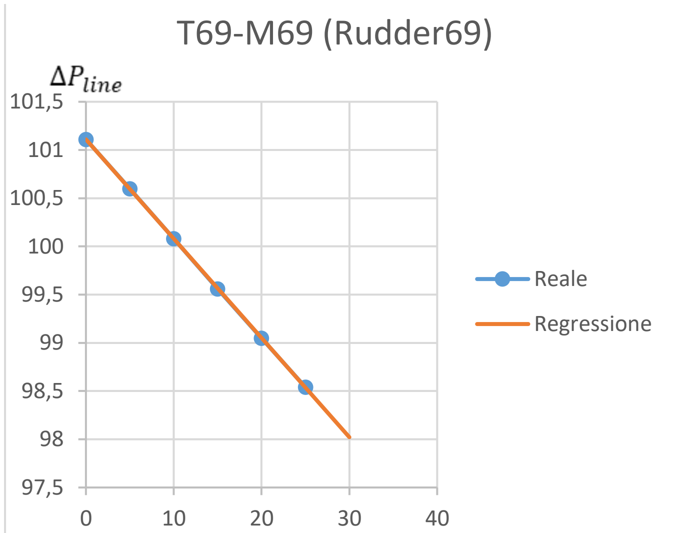

Figure 3.6 Graph of the relation between the variation of power over the TEXAS69-MAROON69 line and the variation of power injected by RUDDER69 generator with new slack bus

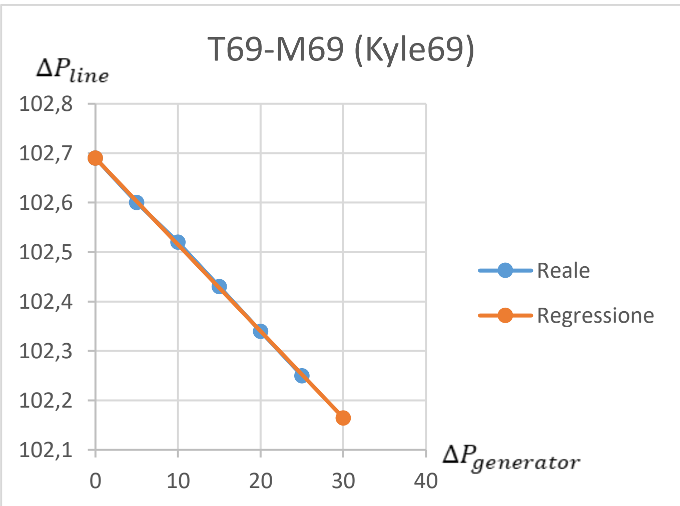

Figure 3.5 Graph of the relation between the variation of power over the TEXAS69-MAROON69 line and the variation of power injected by KYLE69 generator with old slack bus

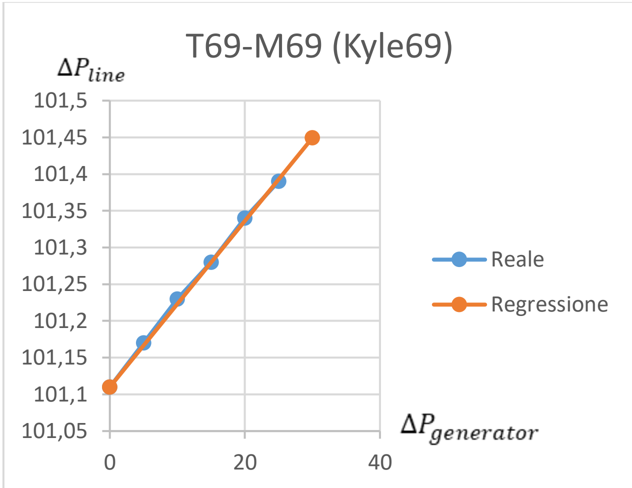

Figure 3.6 Graph of the relation between the variation of power over the TEXAS69-MAROON69 line and the variation of power injected by KYLE69 generator with new slack bus

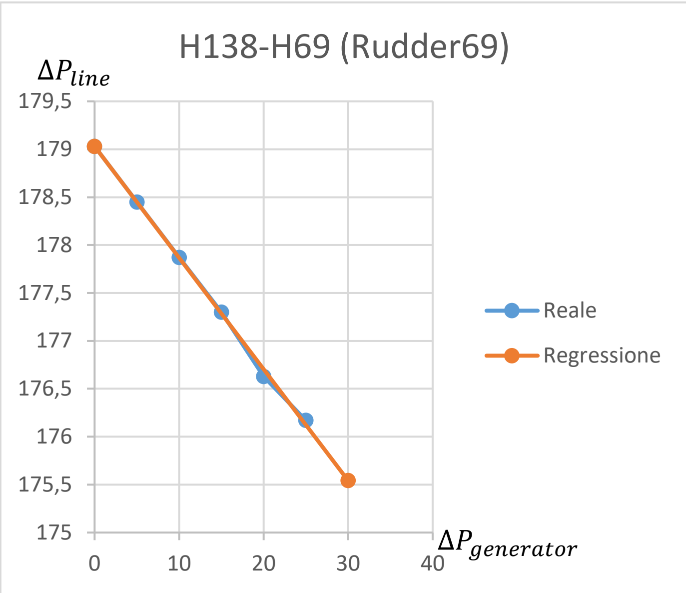

Figure 3.7 Graph of the relation between the variation of power over the HOWDY138-HOWDY69 line and the variation of power injected by RUDDER69 generator with old slack bus

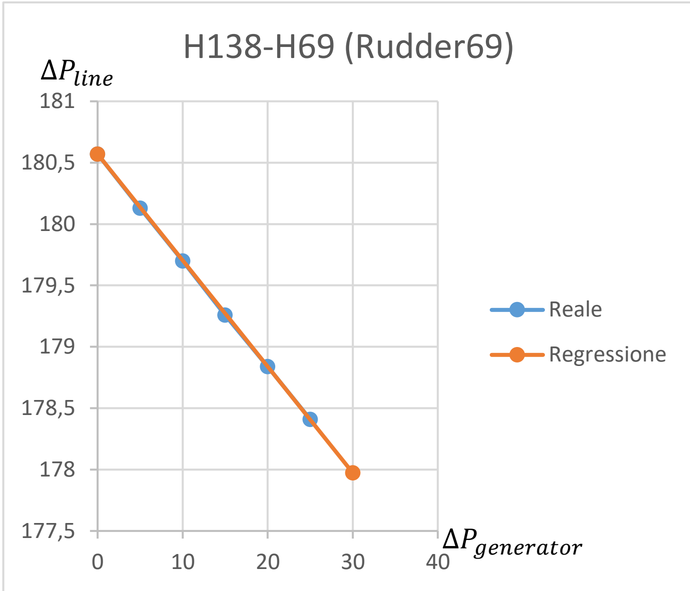

Figure 3.8 Graph of the relation between the variation of power over the HOWDY138-HOWDY69 line and the variation of power injected by RUDDER69 generator with new slack bus

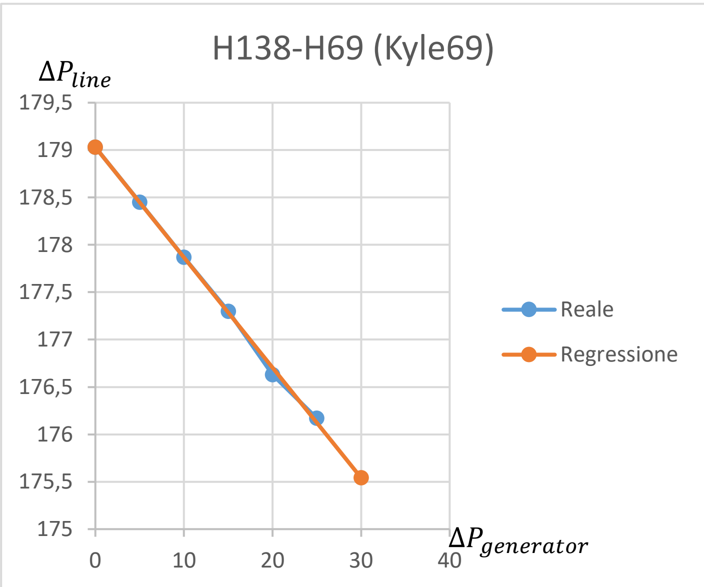

Figure 3.9 Graph of the relation between the variation of power over the HOWDY138-HOWDY69 line and the variation of power injected by KYLE69 generator with old slack bus

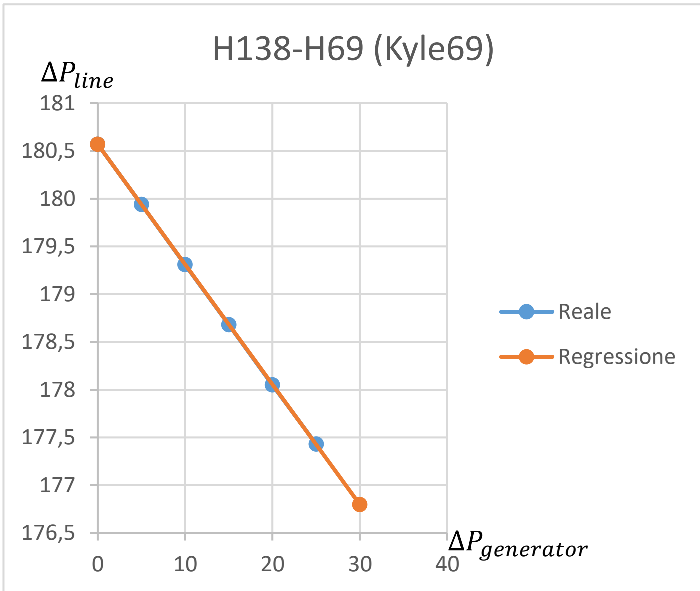

Figure 3.10 Graph of the relation between the variation of power over the HOWDY138-HOWDY69 line and the variation of power injected by KYLE69 generator with new slack bus

Since the change in the output of each generator is absorbed at the slack bus, changing the slack itself will reflect on the computations made and, therefore, on the sensitivity values. For instance, it is interesting to notice that the sensitivity of line TEXAS69-MAROON69 with respect to KYLE69 generator changes its sign (this can be seen looking at the table 3.2 or at the slopes of the graphs 3.5 and 3.6): taking AGGIE345 as the new slack bus means modifying the power flows through the grid, even reversing the influence of several generators.

4. PHASE-SHIFTING TRANSFORMER INFLUENCE

The next step that has been treated is the computation of the overloaded lines' sensitivities with respect to a change in the phase shift provided by the Phase Shifter Transformer at REED substation. To understand whether they are linear or not, the team has decided to follow the same approach described in the second paragraph. Therefore, by incrementing the phase shift of 2° for each step, in a range from -30° to 30°, the loading value of each overloaded line has been recorded and reported in the following table (Power values in MW).

Phase Shift	TEXAS345-TEXAS138	HOWDY138-HOWDY69	TEXAS69-MAROON69
-30°	245,31	193,01	103,21
-28°	244,17	192,17	103,05
-26°	243,16	191,35	102,91
-24°	242,16	190,55	102,79
-22°	241,16	188,79	102,64
-20°	240,23	188,03	102,56
-18°	239,3	186,31	102,45
-16°	238,43	185,6	102,4
-14°	237,59	184,92	102,38
-12°	236,79	184,27	102,38
-10°	236,01	182,65	102,35
-8°	235,29	182,06	102,39
-6°	234,6	181,5	102,45
-4°	233,96	180,97	102,53
-2°	233,36	180,48	102,63
0°	232,8	179,03	102,69
2°	232,29	178,62	102,83
4°	231,83	178,23	102,98
6°	231,41	177,89	103,15
8°	231,04	177,59	103,34
10°	230,72	177,32	103,54
12°	230,44	177,09	103,76

14°	230,22	177,89	104
16°	230,04	177,74	104,31
18°	229,92	177,64	104,57
20°	229,84	177,57	104,85
22°	229,82	178,51	105,19
24°	229,84	178,52	105,5
26°	229,92	179,53	105,87
28°	230,04	179,63	106,19
30°	230,22	180,7	106,58

Table 4.1 Power values at each overloaded branch with respect to the phase shift

After the recording of power values, sensitivities have been computed by the following relation:

$$S_i = \frac{P_{branch,i}(\vartheta) - P_{branch,i}(\vartheta - 2°)}{\Delta\vartheta}$$

where $P_{branch}(\vartheta)$ represent the power of the considered branch at a specific value of the phase shift and $\Delta\vartheta$ is the variation of the phase shift angle at each step (always equal to 2°). The results are reported in the table below.

$\Delta\vartheta$	TEXAS345-TEXAS138	HOWDY138-HOWDY69	TEXAS69-MAROON69
From -30° to -28°	-0,57	-0,42	-0,08
From -28° to -26°	-0,505	-0,41	-0,07
From -26° to -24°	-0,5	-0,4	-0,06
From -24° to -22°	-0,5	-0,88	-0,075
From -22° to -20°	-0,465	-0,38	-0,04
From -20° to -18°	-0,465	-0,86	-0,055
From -18° to -16°	-0,435	-0,355	-0,025
From -16° to -14°	-0,42	-0,34	-0,01
From -14° to -12°	-0,4	-0,325	0
From -12° to -10°	-0,39	-0,81	-0,015

From -10° to -8°	-0,36	-0,295	0,02
From -8° to -6°	-0,345	-0,28	0,03
From -6° to -4°	-0,32	-0,265	0,04
From -4° to -2°	-0,3	-0,245	0,05
From -2° to 0°	-0,28	-0,725	0,03
From 0° to 2°	-0,255	-0,205	0,07
From 2° to 4°	-0,23	-0,195	0,075
From 4° to 6°	-0,21	-0,17	0,085
From 6° to 8°	-0,185	-0,15	0,095
From 8° to 10°	-0,16	-0,135	0,1
From 10° to 12°	-0,14	-0,115	0,11
From 12° to 14°	-0,11	0,4	0,12
From 14° to 16°	-0,09	-0,075	0,155
From 16° to 18°	-0,06	-0,05	0,13
From 18° to 20°	-0,04	-0,035	0,14
From 20° to 22°	-0,01	0,47	0,17
From 22° to 24°	0,01	0,005	0,155
From 24° to 26°	0,04	0,505	0,185
From 26° to 28°	0,06	0,05	0,16
From 28° to 30°	0,09	0,535	0,195

Table 4.2 Sensitivities of the overloaded branches with respect to the phase shift

Looking at the results obtained it is clear that the sensitivities for the three considered lines are not constant at all; therefore, the relationship between the power transmitted through those lines and the phase-shift angle must not be linear. This result should not impress since it is well known the power is a related to the voltage angle as a sine function, as shown in Fig. 4.1, 4.2 and 4.3 in the next page.

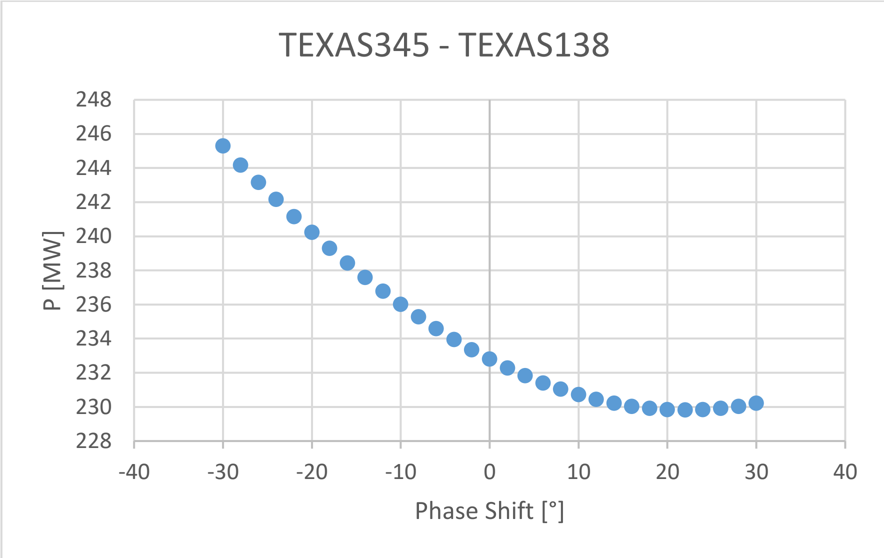

Figure 4.1 Power trend vs PST angle in TEXAS345-TEXAS138 branch

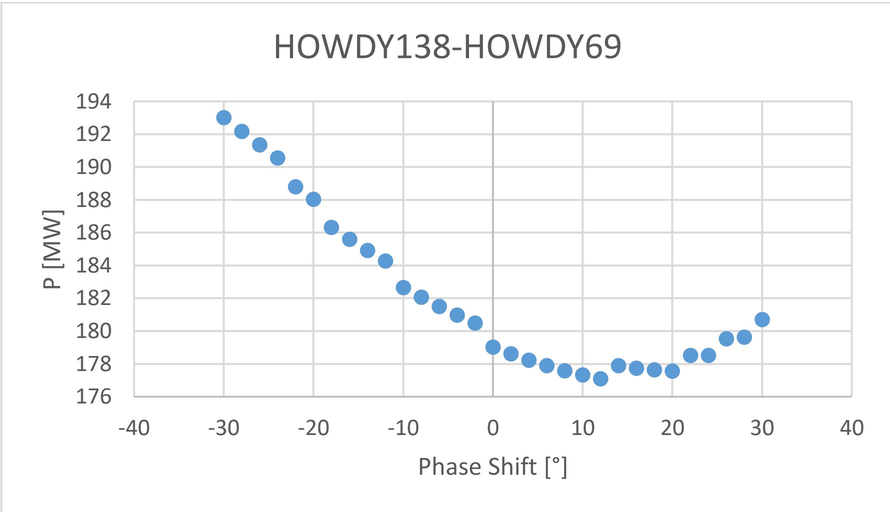

Figure 4.2 Power trend vs PST angle in HOWDY138-HOWDY69 branch

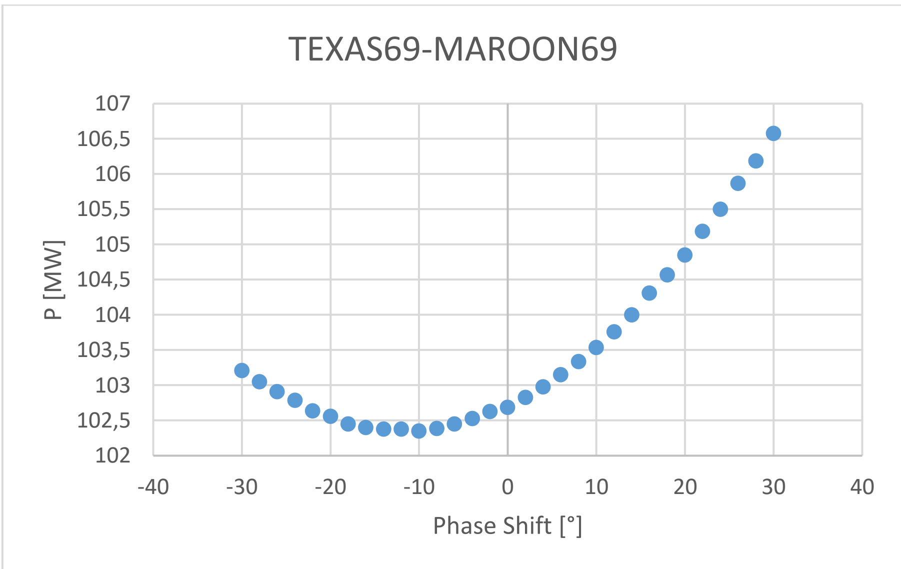

Figure 4.3 Power trend vs PST angle in TEXAS69-MAROON69 branch

It is also possible to make a graph of the computed sensitivity value to understand how they vary in time (that means, to say, what is the grade of non-linearity in the relationship between powers and angles). The results obtained are shown below.

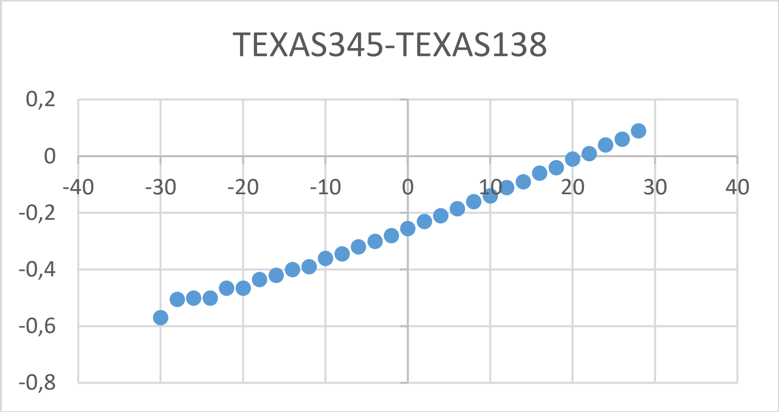

Figure 4.4   Phase-Shift Sensitivity of TEXAS345-TEXAS138 branch

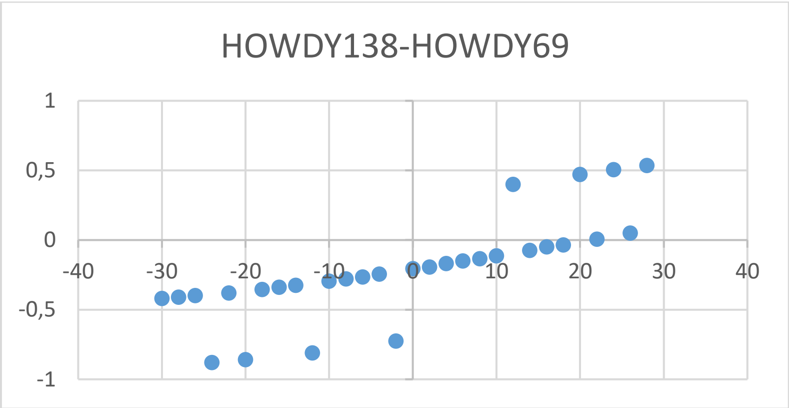

Figure 4.5   Phase-Shift Sensitivity of HOWDY138-HOWDY69 branch

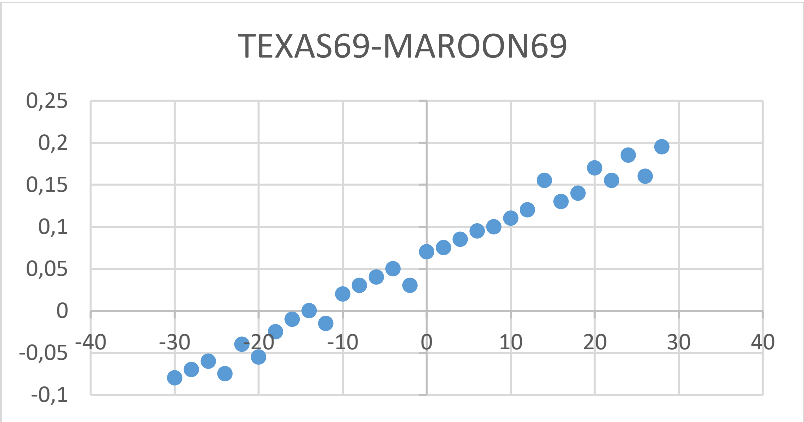

Figure 4.6   Phase-Shift Sensitivity of TEXAS69-MAROON69 branch

Since the shape of the graphs obtained is not a horizontal line (that means a constant sensitivity), it is clear that the relationship between tap-change and power over the overloaded line is not linear at all.

5. ACTION PLAN

As shown in Chapter 2, the chosen generators to ease the overloaded branches are KYLE69 and RUDDER69. Through a critical analysis of data obtained in the previous paragraphs and data obtained by running different Power Flows, the team has determined four main corrective actions:

- Kyle69=110 MW, Rudder69=40 MW, Phase Shift=6°;
- Kyle69=105 MW, Rudder69=40 MW, Phase Shift=6°;
- Kyle69=110 MW, Rudder69=35 MW, Phase Shift=4°;
- Kyle69=110 MW, Rudder69=35 MW, Phase Shift=2°.

Since the best plans are the ones that requires less change in total generation, the team has focused on the last three plans. Eventually, the fourth solution proposed has been selected since the total system losses are lower than in the other cases. Hence, the total generation power used to bring back the branches at a maximum of 100% of loading is equal to 45 MW (see Fig. 2.1). Moreover, a slight improvement is reached by set the phase shifting at 2°; this action has the effect of alleviating a bit the transformer between TEXAS345 and TEXAS138.

As requested, the step by step procedure to be provided to the system operator is reported next:

1. Increase RUDDER69's generation of 25 MW (final value 35 MW);
2. Increase KYLE69's generation of 20 MW (final value 110 MW);
3. Select 2° as phase shifting on REED PST.

The final status of the system is shown in Figure 5.1.

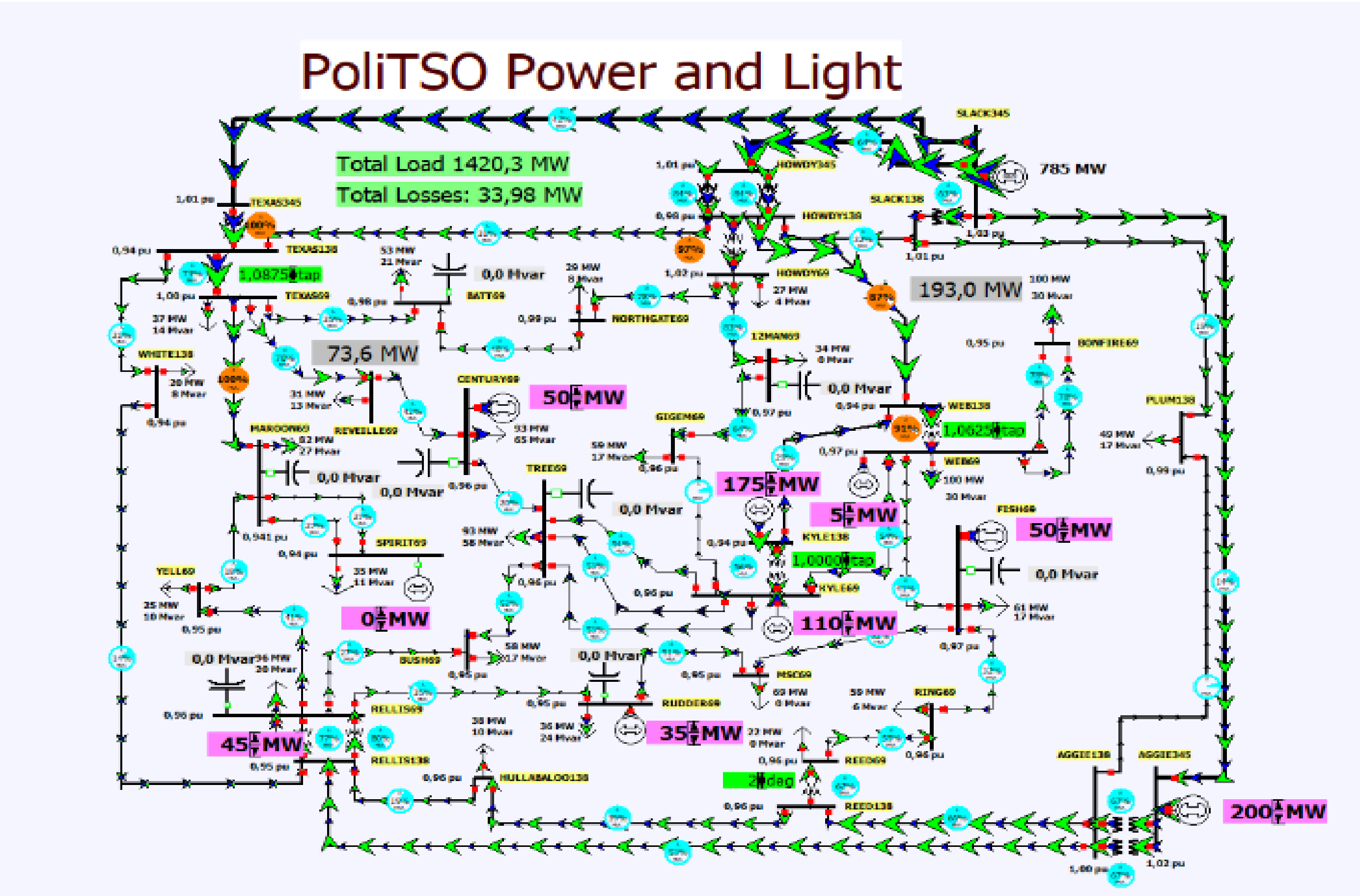

Figure 5.1 System's status after the relieving procedure

6. TAP CHANGER INFLUENCE

Since the overloading on lines and transformers has been mitigated, the team has then focused on reducing total system' losses as much as possible. In order to properly achieve this objective, it is necessary to understand the tap changer and the capacitors switching-in/out influence on the total losses.

To experimentally determine the first one considered (tap changer influence) it is convenient to move the tap between 0.9 and 1.1 off-nominal turns ratios through 0.00625 steps (hence a total of 33 steps). For this system, as requested, the team has considered the transformer at WEB busses (between WEB138 and WEB69 busses): moving the tap as explained previously and, more precisely, going on with two-tap increments (to reduce the number of considered values and, therefore, to reduce the number of points in the graph), total losses has been recorded. The results obtained are shown in the following table:

Tap	Losses [MW]
0.9	37.13
0.9125	36.46
0.925	35.87
0.9375	35.37
0.95	34.95
0.9625	34.60
0.975	34.33
0.9875	34.11
1	33.96
1.0125	33.86
1.025	33.82
1.0375	33.83
1.05	33.88
1.0625	33.98
1.075	34.12
1.0875	34.29
1.1	34.51

Table 6.1 Total System Losses corresponding to a change of the tap on the transformer at busses WEB

Increasing the tap, as it is possible to understand looking at the numbers in the table 6.1, total system' losses decrease until a minimum (corresponding to tap=1.025), then they increase again; therefore, the relationship between losses and tap-change is clearly non-linear. It is possible to assume that there is a quadratic dependence between the two considered variables, as it is well known that $P = P(V^2)$. In order to understand whether this assumption is correct or not, a graph relating the tap change (x-axis) to the total losses (y-axis) can be made. The result is shown in the next page.

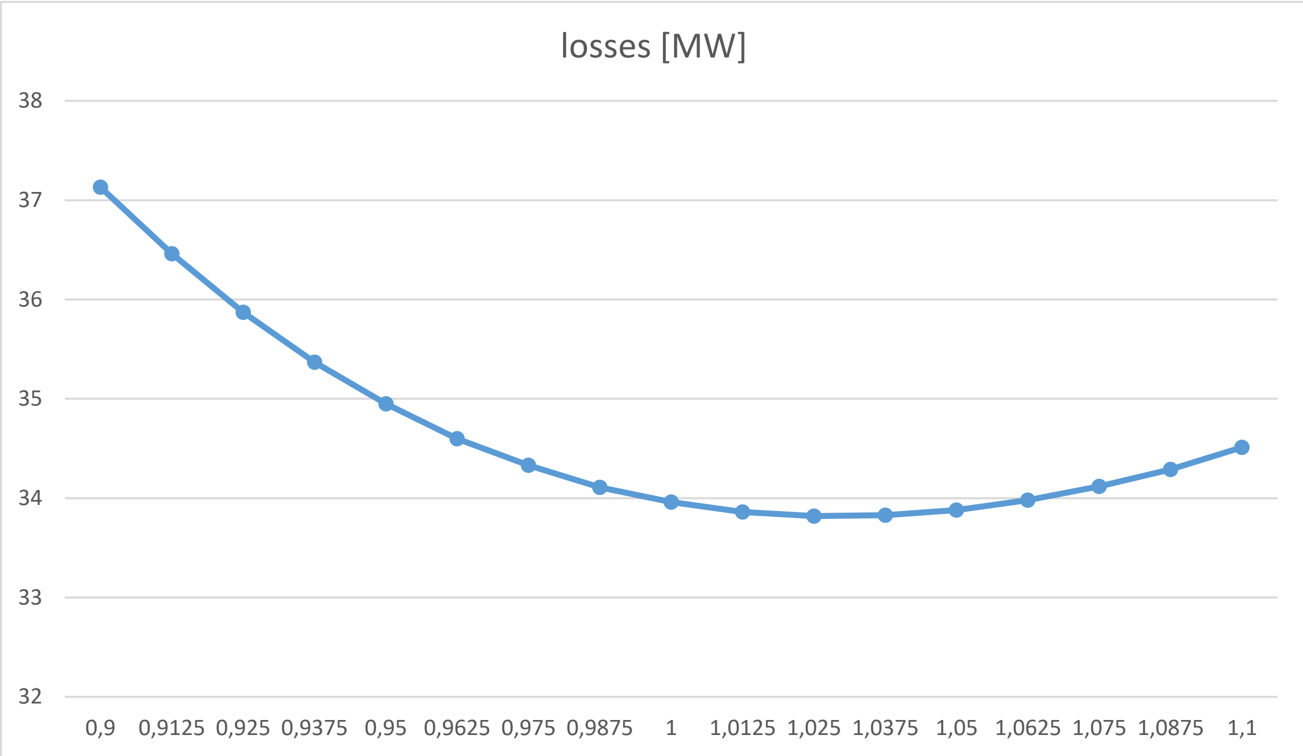

Figure 6.1 Graph of the relationship between tap-change on transformer at busses WEB and total system losses

Observing the shape of the graph obtained, the assumption made seems correct (the graph resembles a parabola and, therefore, the relationship is quadratic).

It is possible to compute the optimal tap for the transformer at WEB busses as the minimum (that is the vertex) of the parabola obtained; in particular $tap_{optimal} = 1.025$ corresponding to $Losses = 33.82\ MW$. The achieved reduction in total losses of the system corresponds to $\Delta P_{tot} = P_{tot,tap=1.025} - P_{tot,initial}$.

For the case considered $\Delta P_{tot} = 33.82\ MW - 33.98\ MW = -0.16\ MW$.

It is worth to notice that, since it is necessary to have negative ΔP_{tot} in order to decrease system losses, there are maximum limit values of the tap that can be reached. More precisely, in this case, the tap selected must be within 1 and 1.0625, otherwise losses will increase with respect to the initial condition and some lines will be overloaded.

7. CAPACITORS SWITCH-IN/OUT INFLUENCE

Since even the capacitors have influence on the total losses of the system, it is possible to furtherly reduce the value obtained in the previous paragraph by switching-in or switching-out several of them. In order to understand the optimal solution to this, as requested, the team has closed each one capacitor sequentially and has recorded how the losses change if the considered capacitor (and only that capacitor) is energized. The result is shown in the following table.

Closed capacitor	Losses [MW]	ΔLosses [MW]
BATT69	33.52	-0.46
MAROON69	33.32	-0.66
CENTURY69	33.09	-0.89
TREE69	33.49	-0.49
12MAN69	33.49	-0.49
FISH69	33.54	-0.44
RUDDER69	33.7	-0.28
RELLIS69	33.31	-0.67

Table 7.1 Change in losses after closing one capacitor at a time

Looking at the values of $\Delta Losses$ it is possible to make some observations. Firstly, each capacitor reduces total losses of the system (negative $\Delta Losses$) by influencing the reactive power flows. This is the key difference between tap changer and capacitors-switching effect on the system: even if both reduces the losses, moving the tap changer means changing the voltage and therefore, it affects both active and reactive power; switching-in/out some capacitors, instead, affects only the reactive power flow. These considerations can also be applied to bus voltages: moving the tap changer influences both voltages magnitude and angle while switching-in/out some capacitors affects particularly voltages magnitude, not having a great influence on voltages angle (since the $[\frac{\partial Q}{\partial \delta}]$ submatrix of the Jacobina matrix of the system has very small values compared to the $[\frac{\partial P}{\partial \delta}]$ submatrix). It is also possible to consider $[\frac{\partial Q}{\partial \delta}]$ as a matrix of zeros and, therefore, neglecting the influence on voltages angle of variations of the reactive power injected in the grid.

Secondly, CENTURY69 appears to be the most influent capacitor on the total losses of the system (it has the greatest negative $\Delta Losses$ value). Due to this, the team has selected this capacitor to be permanently closed. This consideration has been useful to obtain the optimal values for the three LTC transformer tap ratios, and the eight capacitor switch positions, as it is reported in the 9^{th} chapter.

8. DEGREE OF LINEARITY OF CAPACITORS

The next step on which the team has focused has been understanding whether there is a linear relationship between capacitors switching-in and total losses of the system (that means understanding if superposition principle works or not).

The first decision of the team has been to take into account couples of capacitors, in order to understand whether the superposition occurs. Operatively, each possible couple of capacitors has been closed and the value of the losses registered and reported in the next table.

Capacitor	Bat	Maroon	Century	Tree	Man	Fish	Rudder	Rellis
Bat	-	32,71	32,48	32,87	32,85	32,92	33,08	32,66
Maroon	32,71	-	32,3	32,76	32,67	32,74	32,92	32,52
Century	32,48	32,3	-	32,56	32,46	32,64	32,66	32,33
Tree	32,87	32,76	32,56	-	32,85	32,93	33,13	32,72
Man	32,85	32,67	32,46	32,85	-	32,83	33,05	32,63
Fish	32,92	32,74	32,64	32,93	32,83	-	33,15	32,73
Rudder	33,08	32,92	32,66	33,13	33,05	33,15	-	32,93
Rellis	32,66	32,52	32,33	32,71	32,63	32,73	32,93	-

Table 8.1 Losses results [MW] obtained by the simulation.

For each ij element, the value represents total losses obtained with PowerWorld by closing both i and j capacitors (the darker the green, the less the losses).

The same matrix has been built by summing the losses value obtained with only capacitor i closed with the ΔLosses value of each other j capacitor (reported in the previous chapter); then, mismatches between simulation and superimposition results have been computed (the darkest the red, the less the mismatch). The following tables show the obtained results.

Capacitor	Bat	Maroon	Century	Tree	Man	Fish	Rudder	Rellis
Bat	-	32,86	32,63	33,03	33,03	33,08	33,24	32,85
Maroon	32,86	-	32,43	32,83	32,83	32,88	33,04	32,65
Century	32,63	32,43	-	32,6	32,6	32,65	32,81	32,42
Tree	33,03	32,83	32,6	-	33	33,05	33,21	32,82
Man	33,03	32,83	32,6	33	-	33,05	33,21	32,82
Fish	33,08	32,88	32,65	33,05	33,05	-	33,26	32,87
Rudder	33,24	33,04	32,81	33,21	33,21	33,26	-	33,03
Rellis	32,85	32,65	32,42	32,82	32,82	32,87	33,03	-

Table 8.2 Losses results [MW] obtained by superimposition.

Capacitor	Bat	Maroon	Century	Tree	Man	Fish	Rudder	Rellis
Bat	-	-0,15	-0,15	-0,16	-0,18	-0,16	-0,16	-0,19
Maroon	-0,15	-	-0,13	-0,07	-0,16	-0,14	-0,12	-0,13
Century	-0,15	-0,13	-	-0,04	-0,14	-0,01	-0,15	-0,09
Tree	-0,16	-0,07	-0,04	-	-0,15	-0,12	-0,08	-0,1
Man	-0,18	-0,16	-0,14	-0,15	-	-0,22	-0,16	-0,19
Fish	-0,16	-0,14	-0,01	-0,12	-0,22	-	-0,11	-0,14
Rudder	-0,16	-0,12	-0,15	-0,08	-0,16	-0,11	-	-0,1
Rellis	-0,19	-0,13	-0,09	-0,11	-0,19	-0,14	-0,1	-

Table 8.3 Mismatches values in [MW].

Since the mismatches are not big (the maximum value is -0,19 MW), superimposition could be considered as valid of each couple of capacitors.

In order to understand if the superimposition is valid in a general case, the losses value with all capacitors closed has been computed by subtracting from initial losses (33,98 MW) the sum of the ΔLosses of each capacitor switching in (see previous chapter). The result has been then compared with the one obtained with the simulation: superimposition approach gives a value of 29,6 MW of total losses, while the simulation gives 31,21 MW. In this case, the mismatch value is not negligible (1,61 MW) and the superimposition is not considered as valid.

The obtained outcome show that the superimposition approach could be considered a good approximation for relatively small reactive power variations (only two capacitors closed), while does not give precise results for a higher number of capacitors due to the non-linearity of the system.

9. OPTIMAL LOSSES SOLUTION

- *Capacitors*

  The optimal configuration for capacitors in order to reduce losses has been found closing them one by one an looking at the losses value given by PowerWorld. The team has noticed that the losses does not follow a monotone trend, in fact the result reached by closing all the capacitors is worse than the one obtained with only seven capacitors and keeping open the one installed at FISH69 (this is due to the non-linearity of the system).

- *Tap-Changers*

  As first step, all the other tap changers' optimal configuration has been found by successive simulation (as shown in Chapter 6). For KYLE tap changer, the optimal ratio is 1.0625, while for TEXAS is 1.0875. Anyway, this procedure has represented only a starting point (since the system is not linear the superimposition does not occur and by setting all the three tap-changers in their optimal position the losses value is not the smallest one).

The optimal solution has been found by setting initially the capacitor in the configuration reported above as well as the tap-changers and then modifying them, seeing how the losses change. After different attempts, the best configuration obtained has been with all the tap-changers ratio set on 1.0375 and all capacitor switches closed, except for FISH69. The final losses value is 30.31 MW. A step-by-step procedure is reported below:

1. Switch on all capacitors, except for FISH69;
2. Set the Tap-Changer on TEXAS bus to 1.0625 ratio;
3. Set the Tap-Changer on KYLE bus to 1.0250 ratio;
4. Set the Tap-Changer on WEB bus to 1.0375 ratio.

The system's status after the previous procedure is reported in the following picture:

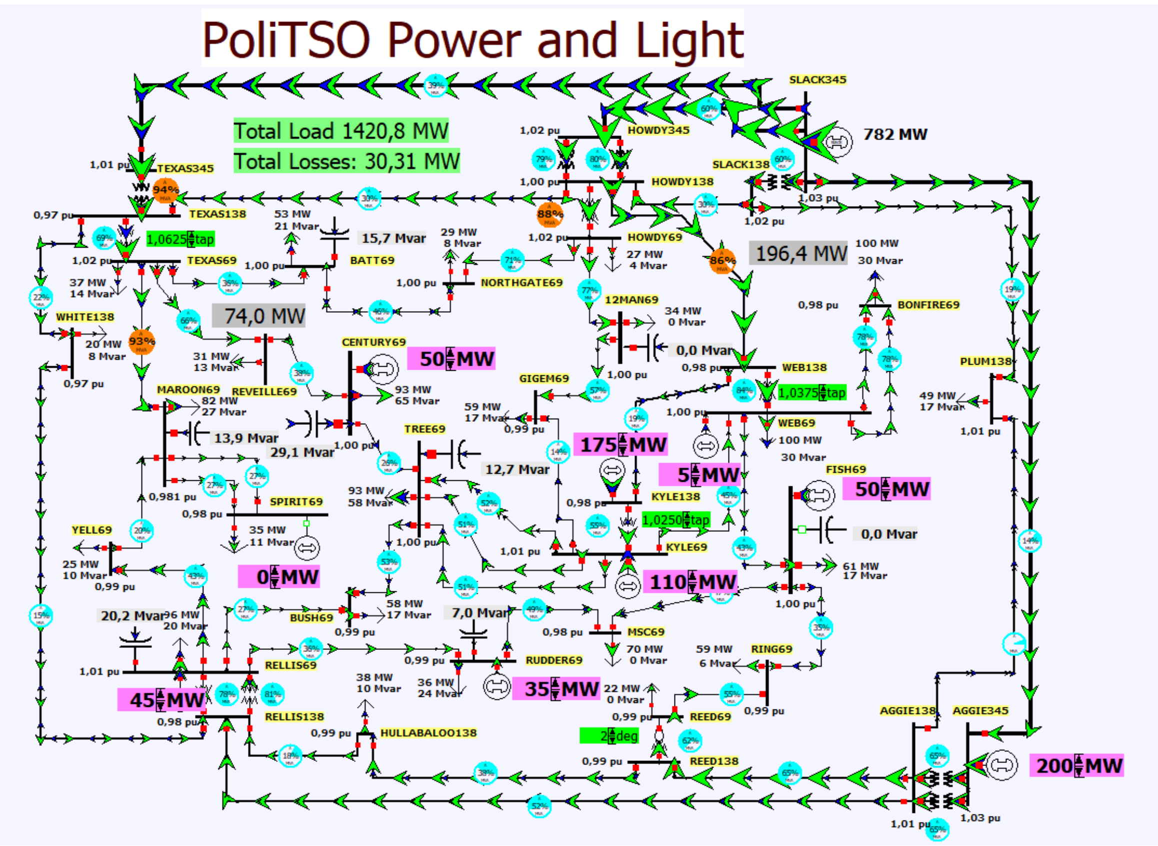

Figure 9.1 Final optimal system status

In general case, the optimal procedure to be follow in order to find the optimal losses is the following one:

1. Switch on all the capacitors one by one and look at the value of the losses; select the one which provides the smallest losses value;
2. By closing groups of capacitors (even all the eight capacitors together) find the best configuration in term of total losses;
3. Find the optimal ratio of all the tap-changers, as shown in chapter 6, then set it;
4. Starting from this optimal position point, adjust tap-changers' ratio in order to have the smallest losses, as possible.

10. CONTINGENCY ANALYSIS (N-1 CRITERION)

Eventually, it is convenient to understand is the system is secure, according to the ENTSO-E N-1 criterion. For the sake of clearness, it is recalled that a system is secure if it is able to survive to low-probable perturbations with a minimum load curtailment. More precisely, the N-1 security criterion establishes that, following a credible contingency on each possible line/element of the grid, no operational constraints must be violated (in terms of maximum branch current [%], maximum and minimum bus voltage), so that the system can function properly. Operatively, each possible contingency must be simulated in order to understand if it brings to violations of technical limits: this iterative operation has been made by means of PowerWorld Tool "Contingency Analysis". The obtained total number of possible contingencies is 1067. In Table 10.1 are reported only the most critical one, because most of them do not require an instant procedure to restore the system before other possible issues. The total number of critical actions is 22 which produces 59 most critical contingencies that require attention from the operator.

Action	Violations	Category	Contingencies	Percent/Value	*Comment*
OPEN Transformer TEXAS 69 - TEXAS 138	43 - 5 MC	Branch Amp	NORTHGATE69 - BATT69	218,15	*Most critical contingencies are current related. They can even reach more than double maximun value.*
	**MC=most critical*	Branch Amp	HOWDY69 - NORTHGATE69	200,18	
		Branch MVA	HOWDY138 - HOWDY69	159,62	
		Bus Low Volts	SPIRIT69	0,7955	
		Bus Low Volts	MAROON69	0,7981	
OPEN Line SLACK345 - HOWDY345	40 - 5 MC	Branch MVA	TEXAS345 - TEXAS138	180,04	*Critical contingencies are power related and very low bus voltages. No very important current contingency.*
		Branch MVA	SLACK345 - SLACK138	158,96	
		Bus Low Volts	WEB138	0,7757	
		Bus Low Volts	BONFIRE69	0,7757	
		Bus Low Volts	KYLE138	0,7789	
OPEN Line HOWDY138 - WEB138	37 - 3 MC	Branch Amp	TEXAS69 - REVEILLE69	148,78	*Critical contingencies due to current and power exceeding their limits*
		Branch MVA	HOWDY138 - HOWDY69	146,68	
		Bus Low Volts	WEB138	0,8407	
OPEN Line TEXAS345 - SLACK345	36 - 7 MC	Branch Amp	HOWDY69 - NORTHGATE69	130,59	*Different contingencies need to be solved, but not very critical.*
		Branch MVA	HOWDY138 - HOWDY69	126,36	
		Branch MVA	HOWDY345 - HOWDY138 c1	125,88	
		Branch MVA	HOWDY345 - HOWDY138 c2	125,65	
		Bus Low Volts	SPIRIT69	0,8315	
		Bus Low Volts	TEXAS138	0,8317	
		Bus Low Volts	TEXAS345	0,8317	
OPEN Transformer HOWDY69 - HOWDY138	36 - 6 MC	Branch Amp	BATT69 - NORTHGATE69	156,00	*Worst contingencies related to current flowing through line BATT69-NORTHGATE69 .*
		Branch Amp	TEXAS69 - BATT69	143,34	
		Branch MVA	TEXAS345 - TEXAS138 c1	121,48	
		Bus Low Volts	12MAN69	0,8243	
		Bus Low Volts	GIGEM69	0,8264	
		Bus Low Volts	HOWDY69	0,8292	

OPEN Line REED138 - AGGIE138	31 - 2 MC	Branch MVA	TEXAS345 - TEXAS138	117,91	*Not many critical contingencies.*
		Branch Amp	TEXAS69 - MAROON69	116,55	
OPEN Transformer TEXAS345 - TEXAS 138	35 - 5 MC	Branch Amp	HOWDY69 - NORTHGATE69	130,59	*Need to keep monitored branch amp contingencies and to bus low volts.*
		Branch MVA	HOWDY138 - HOWDY69	126,36	
		Branch MVA	HOWDY345 - HOWDY138	125,88	
		Bus Low Volts	SPIRIT69	0,8315	
		Bus Low Volts	TEXAS138	0,8317	
OPEN Line HOWDY69 - 12MAN69	31 - 4 MC	Branch Amp	KYLE69 - GIGEM69	112,81	*Most critical contingencies are bus low volts related.*
		Branch Amp	HOWDY138 - WEB138	112,80	
		Bus Low Volts	12MAN69	0,8327	
		Bus Low Volts	GIGEM69	0,8373	
OPEN Transformer REED69 - REED138	30 - 3 MC	Branch Amp	WEB69 - FISH69	160,83	*Most critical is the WEB69-FISH69 line which requires lot of attention.*
		Bus Low Volts	REED69	0,8723	
		Bus Low Volts	RING69	0,8775	
OPEN Line TEXAS69 - MAROON69	29 - 3 MC	Branch Amp	RELLIS69 - YELL69	152,7400	*Very high current flowing through line RELLIS69 - YELL69*
		Bus Low Volts	SPIRIT69	0,8018	
		Bus Low Volts	MAROON69	0,8043	
OPEN Transformer WEB69 - WEB138	29 - 2 MC	Branch Amp	KYLE69 - WEB69	193,80	*Almost double maximun current value in line kyle69-web69.*
		Bus Low Volts	BONFIRE69	0,8722	
OPEN Transformer HOWDY138 - HOWDY345 - c.1	24 - 1 MC	Branch MVA	HOWDY345 - HOWDY138	134,33	*Only 1 most important contingency*
OPEN Transformer HOWDY138 - HOWDY345 - c.2	23 - 1 MC	Branch MVA	HOWDY345 - HOWDY138	134,43	
OPEN Line REED69 - RING69	22 - 1 MC	Branch Amp	WEB69 - FISH69	131,53	*High current flowing*
OPEN Line 12MAN69 - GIGEM69	22 -1 MC	Bus Low Volts	GIGEM69	0,8848	*Volts under limit.*
OPEN Line BONFIRE69 - WEB69 c.1	15 -1 MC	Branch Amp	WEB69 - BONFIRE69	164,79	*Very high current required to be reduced fast.*
OPEN Line BONFIRE69 - WEB69 c.2	15 -1 MC	Branch Amp	WEB69 - BONFIRE69	164,80	

OPEN Transformer RELLIS69 - RELLIS138 c.1	15 - 1 MC	Branch MVA	RELLIS138 - RELLIS69	129,73	*High power.*
OPEN Transformer RELLIS69 - RELLIS138 c.2	15 - 1 MC	Branch MVA	RELLIS138 - RELLIS69	127,67	*High power.*
OPEN Line FISH69 - MSC69	14 -1 MC	Bus Low Volts	MSC69	0,8715	*Volts under limit.*
OPEN Line YELL69 - RELLIS69	12 - 4 MC	Branch Amp	TEXAS69 - MAROON69	158,10	*Attention required to current flowing throught line.*
		Bus Low Volts	YELL69	0,8779	
		Bus Low Volts	SPIRIT69	0,8829	
		Bus Low Volts	MAROON69	0,8852	
OPEN Line YELL69 - MAROON69	11 - 1 MC	Branch Amp	TEXAS69 - MAROON69	125,02	*High current flowing*

Table 10.1 Most critical contingencies per action.