IMPACT OF UCTE RECONNECTION TO ACTIVE POWER LOSSES IN TRANSMISSION NETWORK OF CROATIA

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ABSTRACT

The reconnection of the 2nd synchronous zone to the main UCTE (Union for the Co-ordination of Transmission of Electricity) grid opens new market possibilities in the region of South-East Europe. Due to specific geographical position of Croatia, realisation of significant power transactions is expected over Croatian transmission network. Croatian specifics are recognized in changed position of the power system (from an end part to a middle one) in states before and after the UCTE reconnection. Power exchanges will certainly influence power flows, loading levels, voltage levels, congestions and power losses in Croatian power system. This paper treats comparison of power losses that are computed for two system states. It is numerically related to active power losses at 400 kV, 220 kV and 110 kV voltage level.

KEYWORDS

Transmission network, active power losses, UCTE reconnection

1. Introduction

Since 1991 all electric ties between western and eastern parts of former Yugoslavian power system were broken as a result of war. The last interrupted interconnection was 400 kV line Ernestinovo – Tumbri in Croatia. Besides other tragic war consequences, afterwards it was not possible to control and operate Croatian power system normally. Accordingly, power systems of Serbia, Montenegro, eastern part of Bosnia and Herzegovina, Macedonia, Albania and Greece remained in islanded operation as the 2nd UCTE synchronous zone. In 1994 Romanian power system was synchronized to the 2nd UCTE zone, as well as Bulgarian one two years later. Isolated operation of two UCTE synchronous zones remains unchanged till today.

Eleven years after its destruction, Croatian Power Company (HEP) started reconstruction process of SS 400 kV/110 kV Ernestinovo as the most important point for power supply of eastern Croatia as well as for the UCTE reconnection. Role of Croatian power system in the UCTE reconnection is considered to be very important since the reconnection is supposed to be realized by two 400 kV and five 220 kV transmission lines over Croatian border. The UCTE resynchronization will enable parallel operation of the 2nd synchronous zone with 30000 MW load and the main UCTE grid with 300000 MW load.

After reconnection of the 2nd UCTE synchronous zone to the main UCTE grid, position of Croatian transmission network is expected to change considerably. Before UCTE reconnection, Croatian transmission network is being at the border between two non-synchronized zones without any East↔West power transit possibilities. Upon reconnection, it will become a central part of South-Eastern European network with enormous expectations to satisfy various demands for power transits in these newly liberalized market conditions. Obviously, new circumstances will change operation and control activities in Croatian system. One of the tasks that will be considerably changed after reconnection is accounting for the active power losses. Therefore, this paper presents expected impact of the UCTE reconnection to the active power losses in Croatian transmission network.

2. Mathematical Background

Due to different models, branch participation factors in the active power losses are defined for transmission lines and transformers separately.

Transmission line is represented by π model (Fig. 1). It has a series admittance g_l+jb_l, and two shunt ones $jb_c/2$.

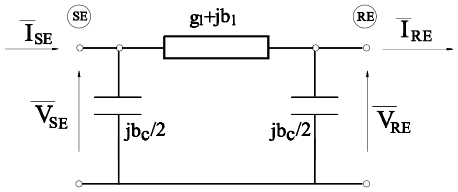

Fig. 1 Transmission line π model

Apparent power at the sending end of the line model $\overline{S}_{SE}$ is given as

$$\begin{aligned}&\overline{S}_{SE}=P_{SE}+jQ_{SE}=\overline{V}_{SE}\overline{I}_{SE}^{*}=\\&=\overline{V}_{SE}\left[(g_l+jb_l)\left(\overline{V}_{SE}-\overline{V}_{RE}\right)+j\frac{b_c}{2}\overline{V}_{SE}\right]^{*}=\\&=\left[V_{SE}^2g_l-V_{SE}V_{RE}(g_l\cos\Theta_{SR}+b_l\sin\Theta_{SR})\right]+\\&+j\left[-V_{SE}^2\left(b_l+\frac{b_c}{2}\right)+V_{SE}V_{RE}(b_l\cos\Theta_{SR}-g_l\sin\Theta_{SR})\right]\end{aligned}\tag{1}$$

where Θ_{SR} denotes angle difference (Θ_{SE} - Θ_{RE}).

At the receiving end of the line model, apparent power $\overline{S}_{RE}$ is given as

$$\begin{aligned}&\overline{S}_{RE}=P_{RE}+jQ_{RE}=\overline{V}_{RE}\overline{I}_{RE}^{*}=\\&=\overline{V}_{RE}\left[(g_l+jb_l)\left(\overline{V}_{SE}-\overline{V}_{RE}\right)-j\frac{b_c}{2}\overline{V}_{RE}\right]^{*}=\\&=\left[-V_{RE}^2g_l+V_{SE}V_{RE}(g_l\cos\Theta_{SR}-b_l\sin\Theta_{SR})\right]+\\&+j\left[V_{RE}^2\left(b_l+\frac{b_c}{2}\right)-V_{SE}V_{RE}(b_l\cos\Theta_{SR}+g_l\sin\Theta_{SR})\right]\end{aligned}\tag{2}$$

Active and reactive power losses on a transmission line are defined using (1-2) as it follows

$$\begin{aligned}P_{loss}^{line}&=P_{SE}-P_{RE}=\\&=g_l\left(V_{SE}^2+V_{RE}^2\right)-2g_lV_{SE}V_{RE}\cos\Theta_{SR}\end{aligned},\tag{3}$$

$$\begin{aligned}Q_{loss}^{line}&=Q_{SE}-Q_{RE}=\\&=-\left(b_l+\frac{b_c}{2}\right)\left(V_{SE}^2+V_{RE}^2\right)+2b_lV_{SE}V_{RE}\cos\Theta_{SR}\end{aligned}.\tag{4}$$

By linearising (3) with respect to the set of variables (Θ_{SE}, Θ_{RE}, V_{SE}, V_{RE}), which is given as

$$\begin{aligned}\Delta P_{loss}^{line}=&\frac{\partial P_{loss}^{line}}{\partial\Theta_{SE}}\Delta\Theta_{SE}+\frac{\partial P_{loss}^{line}}{\partial\Theta_{RE}}\Delta\Theta_{RE}+\\&+\frac{\partial P_{loss}^{line}}{\partial V_{SE}}\Delta V_{SE}+\frac{\partial P_{loss}^{line}}{\partial V_{RE}}\Delta V_{RE}\end{aligned},\tag{5}$$

differential change of active power loss appears as

$$\begin{aligned}\Delta P_{loss}^{line}=2g_l\{&[V_{SE}V_{RE}\sin(\Theta_{SE}-\Theta_{RE})](\Delta\Theta_{SE}-\Delta\Theta_{RE})+\\&+[V_{SE}-V_{RE}\cos(\Theta_{SE}-\Theta_{RE})]\Delta V_{SE}+\\&+[V_{RE}-V_{SE}\cos(\Theta_{SE}-\Theta_{RE})]\Delta V_{RE}\}\end{aligned}.\tag{6}$$

By similar reasoning, differential change of reactive power loss from (4) is given as

$$\begin{aligned}\Delta Q_{loss}^{line}=&-\{[2V_{SE}V_{RE}b_l\sin(\Theta_{SE}-\Theta_{RE})](\Delta\Theta_{SE}-\Delta\Theta_{RE})\}+\\&+\left\{\left[-2V_{SE}\left(b_l+\frac{b_c}{2}\right)+2V_{RE}b_l\cos(\Theta_{SE}-\Theta_{RE})\right]\Delta V_{SE}\right\}+\\&+\left\{\left[-2V_{RE}\left(b_l+\frac{b_c}{2}\right)+2V_{SE}b_l\cos(\Theta_{SE}-\Theta_{RE})\right]\Delta V_{RE}\right\}\end{aligned}.\tag{7}$$

Differential change in transformer reactive power loss is based on its model with injected powers (Fig. 2). Due to the assumptions set in the model, there is no active power loss since the series branch of the transformer model has only a susceptance.

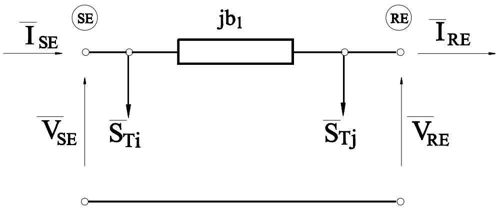

Fig. 2 Transformer injection model

Thereby, apparent power at the sending end of the transformer model $\overline{S}_{SE}$ is given as

$$\begin{aligned}\overline{S}_{SE}=&\left[\left(1-\frac{1}{t_r}\right)b_lV_{SE}V_{RE}\sin\Theta_{SR}-b_lV_{SE}V_{RE}\sin\Theta_{SR}\right]+\\&+j\left\{b_l\left(1-\frac{1}{t_r}\right)\left[V_{SE}^2\left(1+\frac{1}{t_r}\right)-V_{SE}V_{RE}\cos\Theta_{SR}\right]+\right.\\&\left.+b_lV_{SE}V_{RE}\cos\Theta_{SR}-b_lV_{SE}^2\right\}\end{aligned}.\tag{8}$$

At the receiving end of the transformer model, apparent power $\overline{S}_{RE}$ is given as

$$\begin{aligned}\overline{S}_{RE}=&\left[\left(1-\frac{1}{t_r}\right)b_lV_{SE}V_{RE}\sin\Theta_{SR}-b_lV_{SE}V_{RE}\sin\Theta_{SR}\right]+\\&+j\left[\left(1-\frac{1}{t_r}\right)b_lV_{SE}V_{RE}\cos\Theta_{SR}-b_lV_{SE}V_{RE}\cos\Theta_{SR}+b_lV_{RE}^2\right]\end{aligned}\tag{9}$$

Then, transformer active and reactive power losses are defined using (8-9) as it follows

$$P_{loss}^{tra}=P_{SE}-P_{RE}=0\,,\tag{10}$$

$$\begin{aligned}Q_{loss}^{tra}&=Q_{SE}-Q_{RE}=\\&=-b_l\left[\left(\frac{V_{SE}}{t_r}\right)^2+V_{RE}^2\right]+2b_l\frac{V_{SE}}{t_r}V_{RE}\cos\Theta_{SR}\end{aligned}.\tag{11}$$

By linearising (11) with respect to the set of variables (Θ_{SE}, Θ_{RE}, V_{SE}, V_{RE}), similarly as it is done in (5), differential change of reactive power loss is given as

$$\begin{aligned}\Delta Q_{loss}^{tra} = & -\left\{\left[2b_l \frac{V_{SE}}{t_r} V_{RE} \sin(\Theta_{SE}-\Theta_{RE})\right](\Delta\Theta_{SE}-\Delta\Theta_{RE})\right\}+ \\ & +\left\{\left[-2b_l \frac{V_{SE}}{t_r^2} + 2b_l \frac{V_{RE}}{t_r}\cos(\Theta_{SE}-\Theta_{RE})\right]\Delta V_{SE}\right\}+ \\ & +\left\{\left[-2b_l V_{RE} + 2b_l \frac{V_{SE}}{t_r}\cos(\Theta_{SE}-\Theta_{RE})\right]\Delta V_{RE}\right\}\end{aligned} \quad . \qquad (12)$$

Differential changes of the losses (6-7, 12) are considered as branch participation factors. They depend on the set of variables ($\Delta\Theta_{SE}$, $\Delta\Theta_{RE}$, ΔV_{SE}, ΔV_{RE}) and serve for conducting various sensitivity analyses.

For being considered in the power flow problem, total active power loss may also be formulated as

$$P_{loss}(\Theta,V) = \sum_{m=1}^{n} V_m \sum_{k=1}^{n} V_k G_{mk} \cos\Theta_{mk} \ . \qquad (13)$$

where *m* and *k* are buses in a network with total *n* buses.

3. System Configuration

In order to compare active power losses in Croatian system before and after the UCTE reconnection, two time horizon frames and system configurations have been modelled. Proposed methodology includes regional steady state ac load flow analysis. The first time horizon frame for the completion of the study was set to year 2003 as existing system state (before reconnection) and the second one to year 2005 as near future (after reconnection). Croatian transmission network is modelled at 400 kV, 220 kV and 110 kV levels, while the rest of the UCTE network (from Portugal to Greece) is modelled at 400 kV and 220 kV levels (in Greece 150 kV also). Total power system model consists of 2936 busses, 4247 branches, 578 machines, 981 transformers and 1452 loads. It is made by using PTI PSS/E software package. The western UCTE part (the 1st synchronous zone) is modelled according to official annual UCTE reports, while the model of the eastern one (the 2nd synchronous zone) is based on database defined in [1]. It is also assumed that all war damages in this region will be completely rebuilt and in operation. Study results for the year 2005 showed that the (*n-1*) security criterion becomes satisfied assuming all war damages being recovered [2]. In each system configuration only winter peak load is considered as the most indicative in power loss analysis. Additional exchange scenarios East↔West are also included in the analysis [3]. The analysis is performed for the following scenarios of Croatian power system:

year 2003:

a1) wet hydrology; no import,
a2) average hydrology; import 600 MW from Hungary,
a3) dry hydrology; import 600 MW from Hungary,
a4) dry hydrology; import 600 MW from Hungary, transit 500 MW from Bosnia (BH) to Italy, and
a5) dry hydrology; import 600 MW from Hungary, transit 600 MW from Hungary to Italy.

year 2005:

b1) wet hydrology; no import,
b2) average hydrology; import 600 MW from Hungary,
b3) dry hydrology; import 600 MW from Hungary,
b4) dry hydrology; import 600 MW from Hungary, transit 500 MW from Bosnia (BH) to Italy,
b5) dry hydrology; import 600 MW from Hungary, transit 600 MW from Hungary to Italy,
T1a) dry hydrology; import 600 MW from Germany and Slovakia, transit Switzerland (800 MW) → [Bulgaria (100 MW), Greece (700 MW)],
T1b) dry hydrology; import 600 MW from Germany and Slovakia, transit Switzerland (800 MW) → [Albania (300 MW), Greece (500 MW)],
T2a) dry hydrology; import 600 MW from Germany and Slovakia, transit Switzerland (1500 MW) → [Bulgaria (300 MW), Greece (1200 MW)],
T2b) dry hydrology; import 600 MW from Germany and Slovakia, transit Switzerland (1500 MW) → [Albania (500 MW), Greece (1000 MW)],
T3a) dry hydrology; import 600 MW from Germany and Slovakia, transit Bulgaria (800 MW) → Italy (800 MW),
T3b) dry hydrology; import 600 MW from Germany and Slovakia, transit [Bulgaria (400 MW), Romania (400 MW)] → Italy (800 MW),
T4a) dry hydrology; import 600 MW from Germany and Slovakia, transit Bulgaria (1500 MW) → Italy (1500 MW),
T4b) dry hydrology; import 600 MW from Germany and Slovakia, transit [Bulgaria (800 MW), Romania (700 MW)] → Italy (1500 MW).

Each of the power transit scenarios (T1a–T4b) is founded on the most restrictive base case (dry hydrology; import 800 MW from Germany and Slovakia). Power flow exchanges for studied year 2003 are based on the real (a1-a4) and hypothetic (a5) scenarios. The UCTE reconnection opens new power exchange possibilities. Consequently, larger number of power exchange scenarios is analyzed for studied year 2005 than for studied year 2003.

4. Study Results

Analytical studies are based on ac load flow calculations by using full Newton–Raphson solution method. Total active power losses are determined for each voltage level (400 kV, 220 kV and 110 kV) separately.

In the following tables, results of active power loss calculation are presented for each defined power exchange scenario. Scenarios are marked by using abbreviations noted above. The highest value of total active power losses appear in 110 kV network in each analyzed scenario. The first five scenarios (a1-a5 and b1-b5) can be compared directly, since they refer to the similar (if not the same) power exchange scenarios for different time frames (2003 and 2005). Each compared scenario shows that total active power losses in Croatian power system will be significantly decreased after the UCTE reconnection. Figure 3 depicts a comparison of active power losses with respect to studied time frames at each voltage level and totals.

Table 1 Active power losses for studied year 2003

Active power losses (MW) for year 2003				
	Voltage level (kV)			
Scenario	400	220	110	**TOTAL**
a1	10.9	8.21	41.03	**60.14**
a2	20.5	8.42	49.65	**78.57**
a3	22.27	9.27	58.57	**90.11**
a4	16.1	8.2	51.82	**76.12**
a5	33.7	9.31	59.77	**102.30**

Table 2 Active power losses for studied year 2005

Active power losses (MW) for year 2005				
	Voltage level (kV)			
Scenario	400	220	110	**TOTAL**
b1	6.01	8.76	29.53	**44.30**
b2	7.22	6.3	29.8	**43.32**
b3	8.2	5.7	30.61	**44.51**
b4	12	7.11	30.6	**49.71**
b5	12.68	6.42	31.23	**50.33**
T1a	14.15	9.42	30.55	**54.12**
T1b	14.23	9.41	30.56	**54.20**
T2a	6.84	6.32	31.26	**44.42**
T2b	7.28	6.43	31.48	**45.19**
T3a	28.11	10.48	35.22	**73.81**
T3b	24.93	13.18	32.88	**70.99**
T4a	6.53	6.23	31.02	**43.78**
T4b	15.55	8.97	36.99	**61.51**

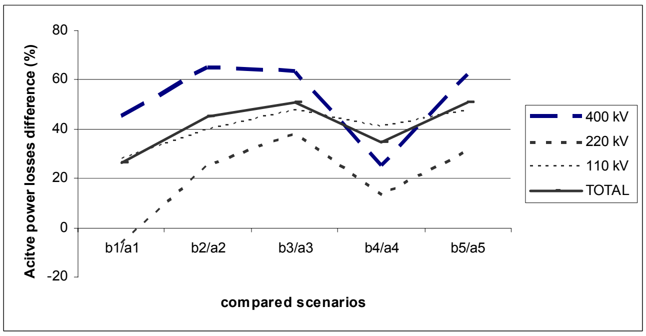

Fig. 3 Active power losses (difference for compared scenarios)

An average active power loss for studied scenarios in year 2003 is equal to 81.45 MW. Similarly, an average active power loss for respecting scenarios in year 2005 is 46.43 MW. This implies average reduction of 42.9%.

Total active power losses in large transit scenarios are presented in Figure 4. Large West ↔ East power exchanges are added to the base case characterised by the highest losses (a3). Figure 4 shows that large power transit scenarios added to the base case in 2005 (b3) will cause power losses with significantly lower values than in the 2003 base case (a3) with no transits at all. Depending on analyzed transit scenario, total active power losses in 2005 will be from 44 MW to 74 MW, while active power losses for the base case (a3) in 2003 are 90.11 MW.

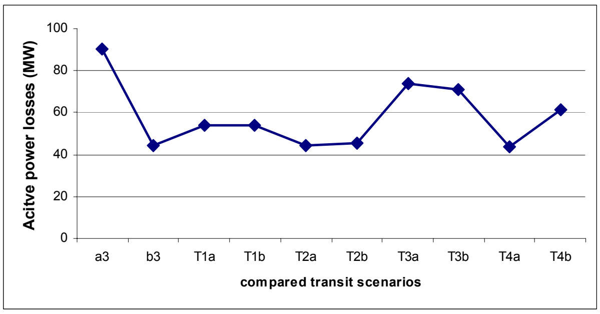

Fig. 4 Active power losses
(difference for compared power transit scenarios)

Due to new operating conditions the highest active power losses reduction in Croatian transmission network appears in 400 kV network (average reduction of 52.13%), while the lowest influence exists in 220 kV network (average reduction of 20.3%). Average loss reduction in 110 kV network is equal to 40.89%. But, it is important to point out that not only the UCTE reconnection is beneficial for reduction of active power losses in Croatia. Moreover, network topology is significantly changed in the studied period. Rebuilding/construction of two 400 kV substations (Ernestinovo, Zerjavinec) and operation of the 2nd circuit of interconnecting line Zerjavinec (HR) – Heviz (HUN) are also reflected on active power losses. Thermal ratings of total installed interconnection capacity of Croatian power system and neighbouring ones will be changed as shown in Table 3 [4].

Table 3 Thermal ratings of total installed interconnection capacities, *TIIC* (MVA)

Interconnection	**TIIC (MVA); 2003**	**TIIC (MVA); 2005**
HR-HUN	1318	2636
HR-BiH	1512	4898
HR-SLO	4635	4635
HR-YUG	/	1318
TOTAL	**7465**	**13487**

Performed analysis shows that the highest active power losses in the system appear on the Croatian – Hungarian interconnecting 400 kV line Tumbri (HR) – Heviz (HUN) (2003, single circuit), i.e., Zerjavinec (HR) – Heviz

(HUN) (2005, after construction of new substation 400 kV/220 kV/110 kV Zerjavinec, double circuit). Active power losses on the line Tumbri (Zerjavinec) – Heviz are presented in Table 4.

Table 4 Active power losses on 400 kV interconecting line Tumbri (Zerjavinec) – Heviz (Croatian part)

Interconnecting 400 kV line Tumbri(Zerjavinec) (HR) - Heviz (H)					
scenario 2003	Losses (MW)	I(%)	scenario 2005	Losses (MW)	I(%)
a1	4.98	33	b1	0.307	14
a2	11.51	50	b2	0.823	15
a3	11.83	49	b3	0.885	15
a4	8.37	42	b4	0.684	14
a5	18.97	63	b5	1.544	22

Because of specific geographical position after the UCTE separation all power transactions over Croatian system in past 4 years (before reconnection) have been realized over the north-western part of the system, mostly through 400 kV line Tumbri – Heviz. South wing of Croatian power system was practically radial. Typical system states were fully modeled in scenarios of studied year 2003. After the UCTE reconnection and network rebuilding, transmission line loadings will be significantly decreased. The most heavily loaded elements in Croatian system for studied 2003 configurations are 110 kV lines in the north-western part of the system loaded around 100% of its thermal rate [5]. The most heavily loaded elements for studied 2005 configurations are transformers in the southern part of the system that are loaded 67% of its thermal rate.

Following presented mathematical background it is interesting to compare relations between active power losses and line loading, voltage level and voltage angles for specific case of Croatian – Hungarian interconnection for two analyzed time frames. Line length is reduced in 2005 with respect to 2003 time frame because of new 400 kV substation located closer to the Croatian – Hungarian border. Accordingly, line parameters are changed. The following figures shows impact of voltage (pu), voltage angles (°) and sending end active power (MW) on active power losses of the line (MW) for both time horizons.

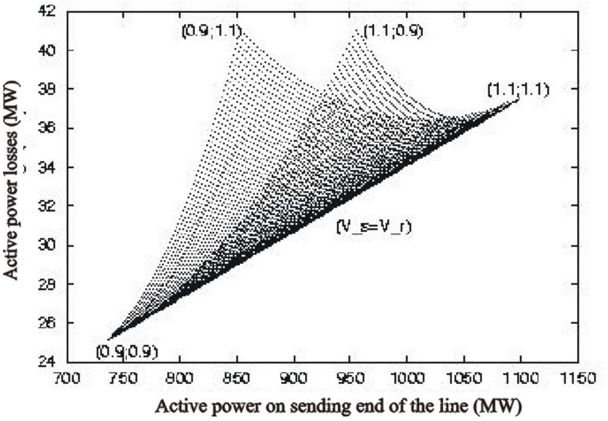

Fig. 5 Active power losses with respect to sending end active power (Tumbri) for voltage angle difference Δ=+20° (2003)

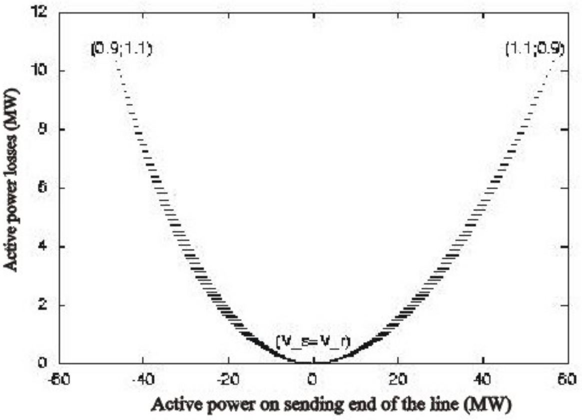

Fig. 6 Active power losses with respect to sending end active power (Tumbri) for voltage angle difference Δ=0° (2003)

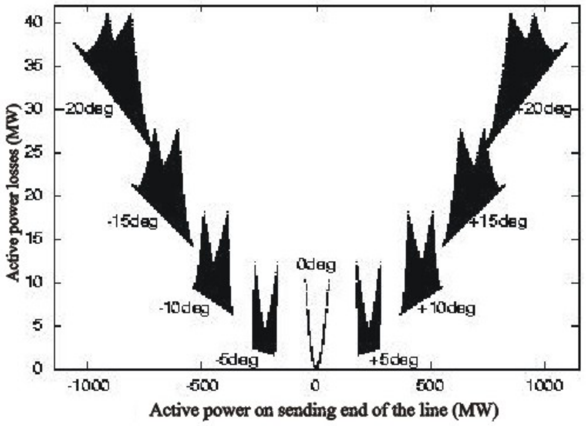

Fig. 7 Active power losses with respect to sending end active power (Tumbri) for set of voltage angle differences (2003)

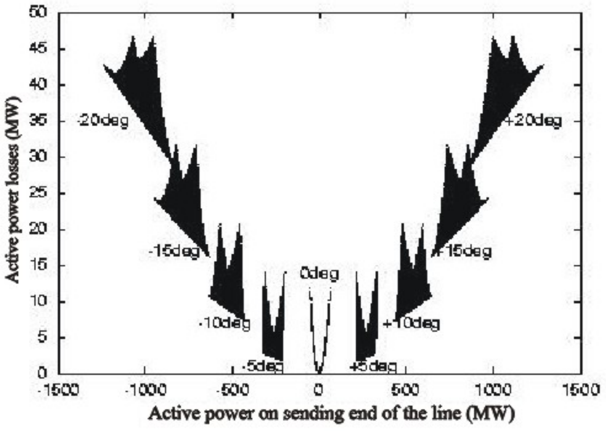

Fig. 8 Active power losses with respect to sending end active power (Žerjavinec) for set of voltage angle differences (2005)

Comparison of two interconnecting lines (year 2003 and 2005) presented in Figures 7 and 8 shows that for the same active power at sending end, same voltage levels and angle difference, active power losses will be higher on the line Zerjavinec – Heviz (2005). To the first sight it seems unexpected, since Zerjavinec – Heviz is shorter line with consequently lower resistance. So, active power losses will be higher on the shorter line under same voltage and angle values. Under decreased resistance (length) and non-changed voltage, obviously current will be increased. Current change influence is obviously dominant with respect to resistance change ($P_{loss} = I^2 R$).

In reality, voltage and angle values will be significantly changed in period 2003 – 2005. Also, line resistance will be changed because of second circuit that will be in operation 2005. Accordingly, line loadings in 2005 will be significantly lower than in 2003 (see Table 4).

Evaluation of total active power losses with respect to the UCTE reconnection and rebuilding of Croatian transmission system could be better with larger number of different cases. But, Croatian power system is located on the border of main UCTE grid during last years and it does not work under normal conditions. Croatian power system is not being recovered yet. Possible exchange scenarios are topologically limited. Thus, typical five scenarios for winter peak load are analyzed here.

5. Conclusions

This paper presents results of active power loss analysis given for specific situation in Croatian transmission network with respect to the UCTE reconnection and network recovery. Using detailed model of Croatian and neighbouring power systems, comparison of total active power losses is obtained for time horizons 2003 – 2005. Significant reduction of total active power losses is expected because of two processes that are accomplished simultaneously: the UCTE reconnection and recovery of Croatian transmission network. Network recovery has dominant role in the loss reduction in comparison to the UCTE reconnection itself. But, Croatian network reconstruction is a necessary pre-condition for the UCTE reconnection. Thus, it is difficult to separate these two processes. This calculation anticipates possible impact of new operating conditions on active power losses in Croatia in planning phase. Detailed calculations should be performed at operational level concerning energy losses. Moreover, impact of each individual transaction to total active power losses should be evaluated in real time.

6. References

[1] P. Miller, T. Cerepnalkovski, D. Bajs, G. Majstrovic, S. Mijailovic, M. Vukovic, P. Miksa, N. Gamov, N.Rusanov, 'Study on Regional Transmission Planning Project', *Study report commissioned by the Southeast European Cooperative Initiative (SECI) - Project Group on "Development of Interconnections of Electric Power Systems of SECI countries for better integration to European System"*, 2002

[2] D.Bajs: *'Development of Croatian power system till 2030 – Transmission network, Masterplan'*, Energy Institute 'Hrvoje Pozar', Zagreb, Croatia, 2001

[3] G.Majstrovic: *'Transit possibilities over Croatian transmission network in short and middle term time horizon' Study Report commissioned by the Croatian Electric Power Company*, Energy Institute 'Hrvoje Pozar', Zagreb, Croatia, December 2000

[4] G.Majstrović, D.Bajs: *Possibilities Of New Interconnection Lines Building between Croatia and neighbouring systems', Study Report commissioned by the Croatian Electric Power Company*, Energy Institute 'Hrvoje Pozar', Zagreb, Croatia, March 2000

[5] N. Dizdarevic, G. Majstrovic, D. Bajs, M. Majstrovic, 'Congestions in the transmission network', *Study Report commissioned by the Croatian Electric Power Company,* Energy Institute 'Hrvoje Pozar', Zagreb, Croatia, April 2003, [Online]. Available: www.eihp.hr/~ndizdar