Minimization of active power losses in a power transmission system – selected aspects of the computation problem scope

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The paper presents fundamental problems concerning optimization of reactive power flow at simultaneous minimization of active power losses performed in order to enhance voltage conditions in a power system. Calculations have been done in order to show that adequate control of reactive power production in generators as well as proper transformation ratio control of system transformers can contribute to the reduction of active power losses in the system and ensure adequate voltage conditions in all system nodes.

1. Introductory remarks on the questions of reactive power – flow

1.1. The significance of reactive power for a power system

For proper operation of a power system it is necessary that reactive power is kept balanced for both the generation and load. Reactive power compensation is an important element of operating the National Power System (NPS) [2]. Reactive power generates electromagnetic field that is needed for the operation of induction motors and transformers and proper operation of many loads. However, reactive power transmission causes an increase of active power losses and voltage drops as well as a reduction of the active power generation and transmission potential and higher investment outlays.

One of the classical optimization problems to be solved for a power system is to determine such a voltage level of generation units that could ensure optimal reactive power flow in the power system. Although there are various optimization problem objective functions that are referred to as OPF in the foreign literature and as ERO-Q in the Polish literature, it is searching for such values of generator voltages that could ensure minimization of active power losses that is the most frequently applied. However, practical experience shows that calculation problems related to the realization of that task often cause considerable difficulties in efficient application of optimization methods. The pertinent literature is ample and the presented paper refers only to some of its items.

1.2. Problems related to the deficiency of reactive power in the system

Deficiency of reactive power in the northern and central part of the Polish Power System was the reason for the occurrence of voltage failure in June, 2006.

Virtually all power plants located there operated at full reactive power load and thereby could not further maintain preset voltage values at their grid connections. As the demand for active and reactive power kept increasing, voltage at pivotal nodes of the system gradually decreased. The voltage decrease also concerned distribution substations of major system power plants and among them the distribution substation where to generating units of the Ostrołęka power plant were connected. The event that initiated the failure was an automatic cutout of both running generating units of the Ostrołęka plant [3].

According to the IRiESP [1], a transmission system operator performs control of reactive power voltage and flow in a meshed network in order to keep voltage levels at the grid nodes within allowable limits and ensure conditions for the National Power System operation stability. That task is realized at three levels: primary control – at the level of generators and transformers, secondary control – at the level of superior automatic regulation systems ARST and ARNE and tertiary control – at the central level. An optimization problem with the two first above-given levels taken into account has been solved in the paper in order to enhance voltage conditions.

2. Preliminary assumptions for the optimization problem solution

2.1. An analysis of the calculation environment and a test network

Power Factory software of the DigSilent company (DIgital SImuLator for Electrical NeTwork) has been applied to perform the task formulated in the paper. The software is used for modeling, analyses and simulations of a power grid. It makes possible to perform effective analyses of a power system for various elements of the system including transmission and distribution networks, industrial systems and dispersed generation. The tool can also be used for monitoring of real networks and running the process of their modernization and development. Owing to its numerous functions, the PowerFactory software is also perfectly applicable to solving of load-flow problems, performing short-circuit calculations, stability testing and many other tasks.

A modified CIGRE system has been used as a test system. It is composed of 8 generators, 20 lines, 30 distribution substations and 16 transformers (Fig. 1). Within the test network the following parameters can be distinguished: transmission voltages of 220 and 400 kV, voltage of 110 kV and mean voltage in power plant nodes.

2.2. Optimization performed with the use of the Digsilent software

A basic function of the applied simulation software is to perform load flow at preset assumptions such as limits of active and reactive power, transformer tapchanging or voltage sensitivity of loads Additionally, it makes possible to solve a load-flow problem with optimization options. The discussed optimization problem has been to control reactive power flow in such a way that active power losses get minimized. Within the assumed multi-node network, active power losses depend on many factors such as: the network operation arrangement and parameters of its elements, quantities of the transmitted active and reactive power, the maintained voltage levels, transformation ratio control [5].

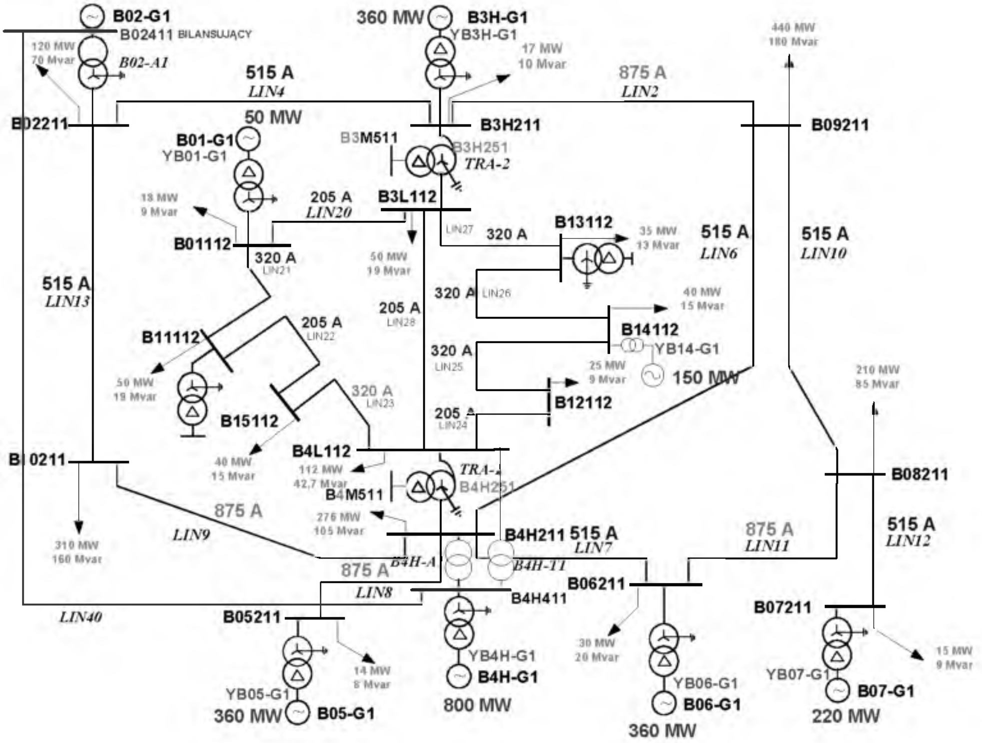
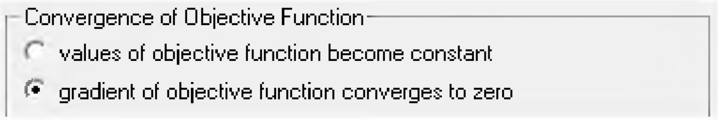


Fig. 1. Diagram of a test network that has been used for simulation calculations

The assumed effect related to the minimization of active power losses has been obtained by optimal control of reactive power production in selected nodes of the network and optimally used tap changers of system transformers. Reduction of active power losses has been realized at some constraining assumptions of keeping preset voltage levels at the observed nodes (Table 1), preventing overload of branches (lines and transformers), maintaining reactive power production at assumed levels. At load-flow calculations (without and with optimization taken into account) constraints have been set both on active and reactive power. The limits concern minimum and maximum values (Fig. 2).

Among the methods applied in order to perform optimization tasks the Digsilent uses the Interior Point Method. It is based on an iterative procedure of the objective function minimization and it is characteristic for the method that searching for the minimum starts at the interior point that is from a solution that meets the constraints and is located inside the area defined by it and next the current solution gets step-by step corrected in accordance with the direction of the objective function decreasing value.



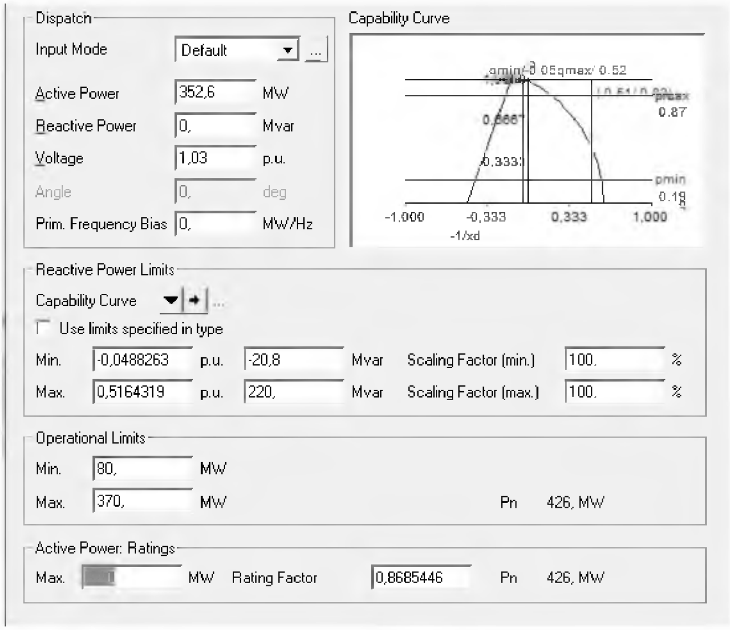
Convergence of Objective Function

○ values of objective function become constant

● gradient of objective function converges to zero

Table 1. Allowable voltage conditions in the NPS [1]

Rated voltage (kV)	400	220	110
Maximum working voltage of the system (kV)	420	245	123
Allowable minimum voltage (kV)	360	200	105



Dispatch

Input Mode: Default

Active Power: 352,6 MW

Reactive Power: 0, Mvar

Voltage: 1,03 p.u.

Angle: 0, deg

Prim. Frequency Bias: 0, MW/Hz

Reactive Power Limits

Capability Curve

☐ Use limits specified in type

Min.: -0,0488263 p.u. -20,8 Mvar Scaling Factor (min.): 100, %

Max.: 0,5164319 p.u. 220, Mvar Scaling Factor (max.): 100, %

Operational Limits

Min.: 80, MW

Max.: 370, MW Pn 426, MW

Active Power: Ratings

Max.: MW Rating Factor: 0,8685446 Pn 426, MW

Fig. 2. A method for introducing constraints on the production of active and reactive power in the Power Factory software

Mathematics uses various notions of convergence and among them finite convergence that takes place when there is such a number K for which $x^{(K)} = x^*$. It seems to be the best kind of convergence as far as optimization problem solving is concerned. However, the number of iterations can be large, which means that solution of the problem can take a very long time. Interior point methods do not work on the finite convergence principle, but they yield a good approximation of the solution in a much shorter time. The below given parameters can be used to change criteria of that iterative process. It can be assumed that the algorithm has yielded the solution if the three following criteria are met:

1. maximum number of iterations has not been reached;
2. all constraints accepted at formulating the optimization problem are met at the assumed accuracy degree, which means that:
   - all node equations are satisfied ,
   - all model equations are satisfied.

Realization of the method means that OPF (Optimal Power Flow) will internally minimize the Lagrange function solution.

Lagrange function is convergent if the objective function converges to a stationary point or the objective function gradient converges to zero [4].

3. Results of the performed simulations

3.1. Optimization of reactive power flow

This chapter presents results of a multi-case simulation that has been performed in order to show effectiveness of the discussed optimization assumptions. Although it has been performed for the minimization of active power losses, the obtained (optimal) reactive power flow contributes to the enhancement of voltage conditions in the analyzed system. Objective evaluation of the testing results has been based on the value of active power losses in the test system. For a basic case of normal network operation conditions and classical load flow, the losses of 53,69 MW have been obtained. The performed optimization (OPF1) has yielded results given in Table 2. Active power losses have been reduced down to the value of 47, 47 MW that is by over 11 %, lower and reactive power generation has been reduced by 11.6%. Changes in reactive power generation resulting from the performed actions are presented in a chart form (Fig. 3). As can be seen, in some power plants reactive power production has been reduced at considerably higher voltage levels at almost all network nodes (Fig. 4). In both cases the active power balance has been maintained (the power of loads remained unchanged - voltage sensitivity of loads has been neglected):

$$P_{\mathrm{gen}} = P_{\mathrm{load}} + \Delta P \;\rightarrow\; 1974{,}89\ \mathrm{MW} = 1921{,}2\ \mathrm{MW} + 53{,}69\ \mathrm{MW}\ \ (\mathrm{PF})$$

$$P_{\mathrm{gen}} = P_{\mathrm{load}} + \Delta P \;\rightarrow\; 1968{,}95\ \mathrm{MW} = 1921{,}2\ \mathrm{MW} + 47{,}75\ \mathrm{MW}\ \ (\mathrm{OPF1})$$

Table 2. Generation of active and reactive power of all generators before and after the optimization

	PF[1]		OPF1[2]	
	P [MW]	Q [Mvar]	P [MW]	Q [Mvar]
B02411-G1	352,60	201,08	352,60	219,40
YB01-G1	61,99	4,50	56,05	-41,47
YB05-G1	42,00	47,58	42,00	72,84
YB06-G1	352,60	92,17	352,60	106,36
YB07-G1	352,60	162,16	352,60	157,98
YB14-G1	195,67	88,92	195,67	76,57
YB3H-G1	117,28	66,92	117,28	108,77
YB4H-G1	500,15	566,16	500,15	386,72
total	**1974,89**	**1229,48**	**1968,95**	**1087,16**

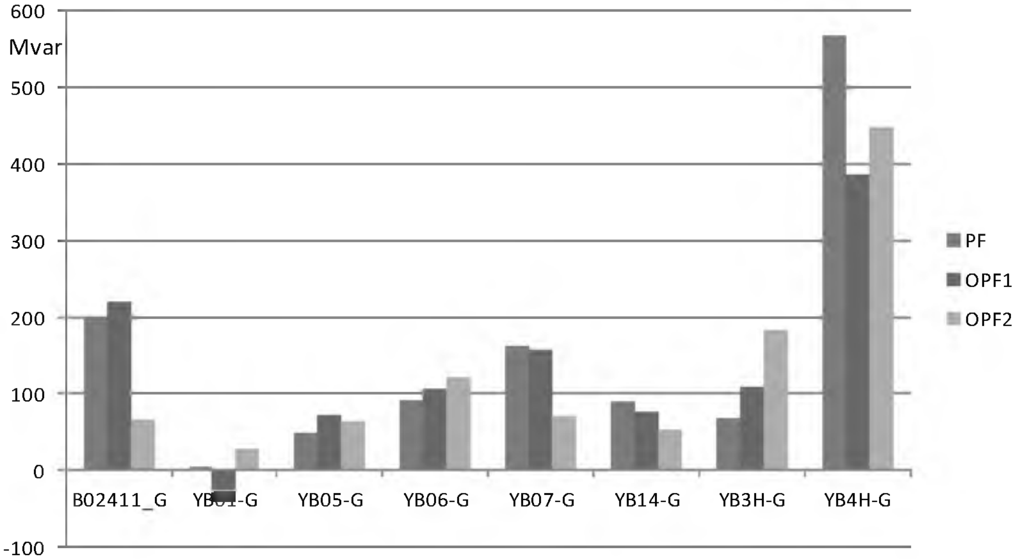


Fig. 3. Changes in reactive power generation for a normal power flow (PF) and two optimization types (OPF1 i OPF2)

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[1] Natural power flow (PF - Power Flow)

[2] Optimization of reactive power flow only (OPF1 – Optimal Load Flow)

[3] Optimization of reactive power flow and transformation ratio (OPF2 – Optimal Load Flow)

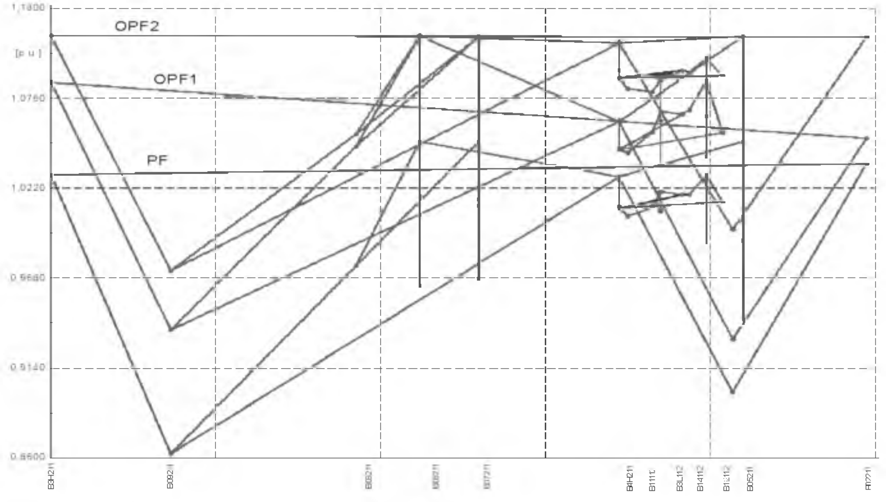


Fig. 4. Voltage profiles at selected nodes of the CIGRE grid for three alternative power flows

3.2. Optimization of reactive power flow and tap changers of system transformers

The performed testing, aside with a standard approach related to the optimization of reactive power production in power plants, has also taken into account the possibility of using transformer tap changers. Taking advantage of those two control methods has resulted in further reduction of active power losses. Table 3 presents results of the performed optimization actions (OPF2).

Active power losses have been reduced to the value of 44 MW that is by 18 %, and the reactive power production has been reduced by 16%. In the both cases the balance of active power has been maintained.

$$P_{gen} = P_{load} + \Delta P \ \rightarrow \ 1974{,}89 \text{ MW} = 1921{,}2 \text{ MW} + 53{,}69 \text{ MW} \ \ \text{(PF)}$$

$$P_{gen} = P_{load} + \Delta P \ \rightarrow \ 1965{,}20 \text{ MW} = 1921{,}2 \text{ MW} + 44{,}00 \text{ MW} \ \ \text{(OPF2)}$$

Voltages at the presented nodes are discrete, broken lines show only topological connections and not voltage changes between the indicated nodes. The lines illustrate load of the branches (lines, transformers) and green color denotes load of up to 80% while red color denotes values exceeding 80%.

Comparative presentation of the calculation results can be also done in the form of a network load-flow diagram with the obtained calculation values plotted into it. Fig. 5 presents a section of the CIGRE grid (locality of the B3H211 node) for three alternative simulation cases. The following parameters are presented for lines, generators and transformers: active power in MW, reactive power in Mvar and their load factor. For distribution substations the parameters are: node voltage in kV, node voltage in relative units and voltage angle in degrees.

Table 3. Generation of active and reactive power by all generators before and after the optimization

	PF[1]		OPF2[3]	
	P [MW]	Q [Mvar]	P [MW]	Q [Mvar]
B02411-G1	352,60	201,08	52,30	65,91
YB01-G1	61,99	4,50	42,00	28,11
YB05-G1	42,00	47,58	352,60	64,29
YB06-G1	352,60	92,17	352,60	120,49
YB07-G1	352,60	162,16	195,67	70,39
YB14-G1	195,67	88,92	117,28	51,80
YB3H-G1	117,28	66,92	352,60	183,44
YB4H-G1	500,15	566,16	500,15	447,97
total	**1974,89**	**1229,48**	**1965,20**	**1032,39**

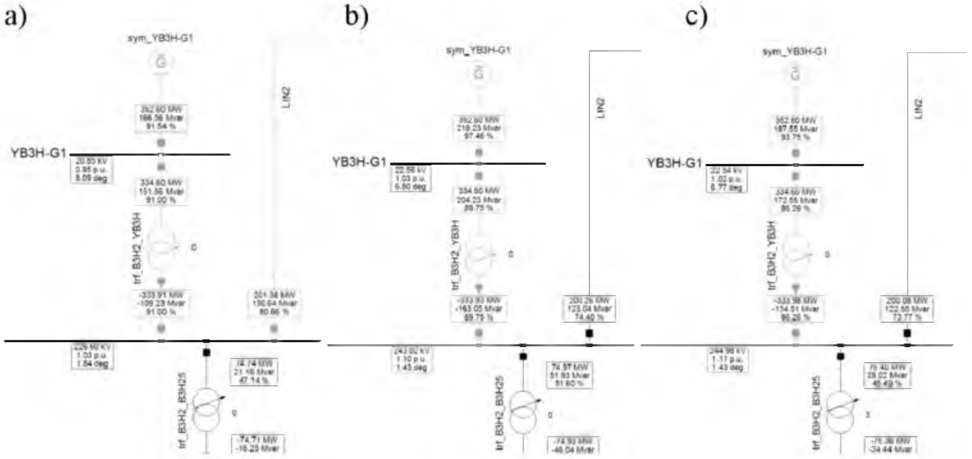
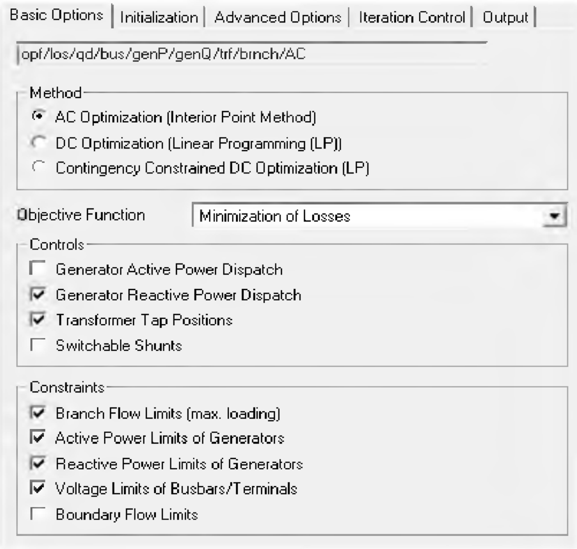


Fig. 5. A section of the CIGRE grid for three alternative simulation cases: a) natural power flow (PF - Power Flow); b) optimization of the reactive power flow only (OPF1 – Optimal Load Flow); c) optimization of reactive power flow and transformation ratio (OPF2 – Optimal Load Flow)

The above given data indicate that at a natural power flow (Fig. 5a) voltage values are rather low, at the power plant node as well as at the system node 220 kV. The LIN2 line load exceeds 80 %. For alternative cases that include optimization (Fig. 5b and c) voltage values are distinctly higher and the line load is lower (below 75 %). Additionally, in the case of full optimization (both of reactive power and transformation ratio), a tap in the system transformer tap changer has changed.



Basic Options | Initialization | Advanced Options | Iteration Control | Output

opf/los/qd/bus/genP/genQ/trf/brnch/AC

Method
- ● AC Optimization (Interior Point Method)
- ○ DC Optimization (Linear Programming (LP))
- ○ Contingency Constrained DC Optimization (LP)

Objective Function: Minimization of Losses

Controls
- ☐ Generator Active Power Dispatch
- ☑ Generator Reactive Power Dispatch
- ☑ Transformer Tap Positions
- ☐ Switchable Shunts

Constraints
- ☑ Branch Flow Limits (max. loading)
- ☑ Active Power Limits of Generators
- ☑ Reactive Power Limits of Generators
- ☑ Voltage Limits of Busbars/Terminals
- ☐ Boundary Flow Limits

Fig. 6. Optimization task configuration in the Power factory software

Fig. 6 presents how the optimization task has been configured in the Power Factory software. The configuration window has been organized into many tabs like (Controls) – where quantities to be optimized can be selected (reactive power - for the OPF1 case, reactive power and the tap changer position – for the OPF2 case). As it has been mentioned at the beginning of this paper, the optimization task realization is subject to a few constraints. Selection of the elements that are subject to constraints during the simulation can be done using the (Constraints) tab. In the presented example the constraints concern lines (maximum allowed load), generators (maximum production of active and reactive power), distribution substations (allowable range of voltage values – Table 1)

4. Conclusions

The algorithm that has been used for the simulation purposes makes possible to determine optimal reactive power production by generation units with technical requirements fully met. Among the requirements there is maintaining of allowable power flows in the branches as well as keeping node voltages within the allowable range. In this paper, the minimum of active power losses has been accepted as an optimization criterion. The objective has been realized by an adequate control of reactive power production and of the transformation ratio. This is the way to ensure optimal voltage levels at the power supply network nodes as well as at the connection nodes of generation sources. Voltage changes for the discussed three alternative cases (PF, OPF1 and OPF2) are presented in Fig. 7.

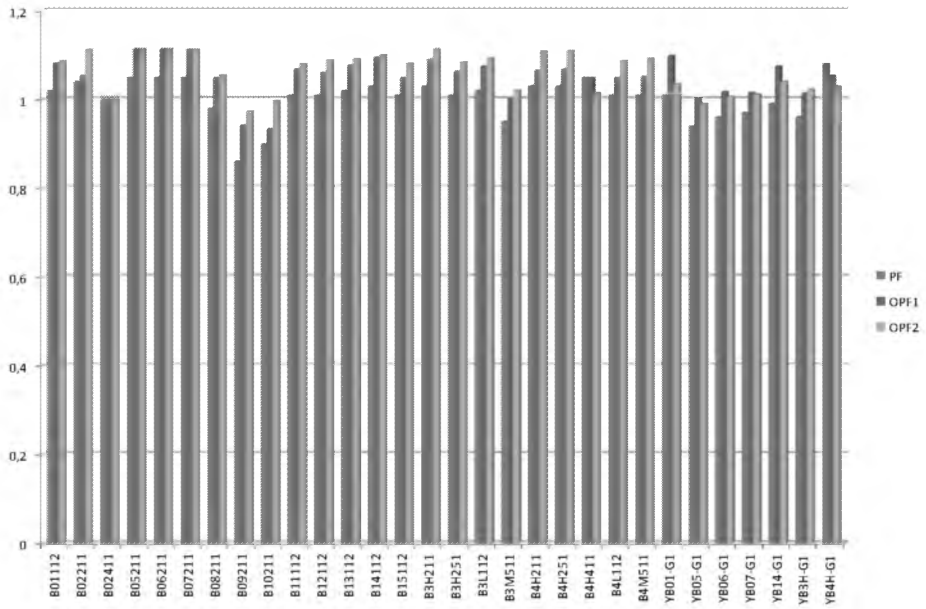


Fig. 7. Voltage changes at nodes of the analyzed network before and after the optimization has been performed

With the application of an interior point method an 11% reduction of active power losses has been obtained using only a control of reactive power production in selected generators. and when the control has been extended onto transformation ratio of system transformers the active power loss reduction has reached 19%. Another form of comparing the discussed simulation cases is a voltage profile characteristic presented in Fig. 4. For the B09211 node, voltage increase value has amounted to almost 9 % for the OPF1 case and to almost 13 % - for the OPF2 case. Voltage increase can be also observed at the remaining nodes and owing to the applied optimization method allowable voltage conditions set in Table 1 have not been exceeded.

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