REACTIVE POWER AUDIT IN SERBIAN TRANSMISSION NETWORK AND EFFECTS OF IMPROVING MEASURES

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ABSTRACT

Reactive power audit in Serbian transmission network is presented in this paper. Performed analyses indicated the need to reduce reactive loads of 110/X kV substations. Selection of 110/X kV substation, in which it is necessary to reduce reactive loads in predetermined total amount, is made by index method presented in this paper. Technical and economical effects of proposed measures for reactive loads reduction are analyzed in details.

INTRODUCTION

Serbian transmission network reactive load reached more than third of active load at year 2004 active peak (measuring is at 35 kV in 110/35 kV transformer substations (TS) and at 110 kV in other TS 110/X kV). Reactive load level was especially high at transmission network critical points - at termini of very loaded and long 110 kV loops, which caused significant active and reactive losses and high reactive load of generators.

The fact that Serbian transmission network was still part of II UCTE synchronous zone during 2004, not connected with the main part of the UCTE grid, caused that generator units outages could trigger load reduction even in cases with enough active generation at disposal. Such accident happened in May 2004, and speed up activities of Power System Public Utility to reduce reactive loads.

Performed transmission network analyses indicated critical TS 110/X kV in power system where reactive load reduction could be very profitable even from transmission network point of view. Decision about urgent reactive loads reduction in the amount of 200 Mvar was brought based on these analyses. Reactive loads reduction should be provided through low voltage reactive power compensation (LVRPC). Besides this, decisions were brought about reactive energy price rising and activating additional fixed capacitor batteries at industrial consumers based on possibilities provided by harmonic distortion analyses.

History of implementing reactive loads reduction measures and analysis of their effects are presented in this paper.

REACTIVE POWER AUDIT DATA

In order to analyze reactive power/voltage conditions, 400, 220 and 110 kV transmission network is modelled. Loads are modelled at measurement site in TS 110/X kV: at 35 kV in TS 110/35 kV and at 110 kV in other TS 110/X kV. That means that all 110/35 kV transformers were also included into model.

Quality 15-minutes active loads data base was available for all measurement sites (more than 250 sites). Lack of data for some sites and time periods could be compensated by analysis of previous periods or with data provided by distribution utilities.

Reactive loads were bigger problem. There were no 15-minutes reactive loads for a majority of measurement sites in Serbian transmission network. Although the process of installing new measuring and data acquisition equipment is in progress, up to the moment of its full functioning it is necessary to provide quality reactive loads data. Keeping in mind that active and reactive energy flows data are available for all measurement sites, as adequate replacement for actual reactive loads, calculated reactive loads were used. Reactive load was calculated as reactive and active monthly energy ratio multiplied by 15-minutes active load. The size of made error and its consequences were estimated by analyzing measurement sites with 15-minutes active and reactive loads at disposal.

For such measurement sites (there are 42 of them) comparison of actual and calculated reactive load was made for maximal and minimal transmission network regimes. Sums of actual and calculated reactive loads for 42 analyzed sites in maximal regime are almost the same, and in minimal regime sum of actual reactive loads is 26% bigger than sum of calculated reactive loads. That means that conclusions made for maximal regime are valid, and conclusions about potential overvoltages or generators underexitation states are too severe.

Analyses were performed for three representative cases in 2004:

- annual maximum state (13/2/2004 at 19:15 - modelled load at TS 110/X kV: 5585 MW and 1915 Mvar),
- annual minimum state (14/6/2004 at 3:15 - 1732 MW and 909 Mvar),
- chosen medium state (18/5/2004 at 19:45 - 3739 MW and 1739 Mvar). Moment just before aforesaid outage was chosen for medium state.

REACTIVE POWER/VOLTAGE CONDITION ANALYSIS IN MAXIMAL STATE

In order to perform analysis, almost isolated functioning of network is observed. Small exchanges with Republic of Srpska, Kosovo and Montenegro are considered with no significant influence to conclusions. Generators engagement is modelled according to actual. Since analysis was performed for optimal ratio of network transformers and non-sectionalized network (with all elements in function), and actual exchanges with neighbouring network were not considered, generators engagement is something different than realized. However, conclusions based on analysis are valid keeping in mind that effects of reactive loads reduction appeared mostly in 110 kV network and partly in 220 kV network.

Analyses showed that voltage conditions in 400 kV network were good, and it could be reached such state for peak load that only one 400 kV node (TS 400/110 kV Subotica 3) had voltage under nominal. It is significant to observe that, beside line HPP Djerdap - TS 400/110 kV Bor 2, which was at 66% of nominal current, other lines were under 50% of nominal current.

Voltage conditions in 220 kV network were also satisfactory. However, situation with 220 kV lines load was different because of several quite loaded lines. The biggest problem was with the first part of 220 kV main HPP Bajina Bašta - TS 400/220 kV Niš 2, namely line TS 220/35 kV Bajina Bašta - TS 220/110 kV Požega, loaded with ~260 MVA (with almost 4 MW loss along ~50 km long line) at peak load. The consequence is that voltage descent along 220 kV line HPP Bajina Bašta - TS 220/110 kV Kruševac 1 is over 10%. There were some 220 kV lines at 60-70% of nominal current, but there were no voltage problems due to their small length.

As to 110 kV network, by good management system, it was possible to reach regime where all voltages were over 104 kV (if all plants and lines are available). Realized state for the year 2004 peak load was worse because of the facts that referent voltages for regulation in TS 220/110 kV were lower than in analyzed state and 110 kV network functioned as radial in series of existing loops.

There were several parts of 110 kV network where long and heavy loaded lines produced notable voltage descents, and active and reactive power losses. Nine 110 kV loops were observed where voltage descents between supplying points and terminal TS 110/X kV were in 5-11% range. Extreme case was the loop formed by 152 km long lines with Alc 150 mm^2 conductor at 60-70% of nominal current where active losses were 5.5 MW, i.e. 6% of TS 110/X kV supplied active load. Unfortunately, some of these loops were supplied from problematic 220 kV main, so, their active and reactive losses additionally increased active and reactive losses at 220 kV main HPP Bajina Bašta - TS 400/220 kV Niš 2.

The fact is that bad voltage and reactive power conditions were consequences of insufficient network volume at some part of transmission network. It is necessary to emphasize that a series of big investments, with significant influence on 110 kV network state, was in progress during the 2004. This factor had to be considered at process of optimal choice of TS 110/X kV for reactive load reduction. Methodology for this choice is presented in next section.

METHODOLOGY FOR OPTIMAL CHOICE OF TS 110/X KV FOR REACTIVE LOAD REDUCTION

Survey of modern methods for planning reactive power sources in transmission network is given in [1]. Most of techniques to solve problem analyzed in presented papers belong some of listed optimization categories: (1) nonlinear programming, (2) linear programming, (3) mixed integer programming, (4) decomposition methods, (5) heuristic methods, (6) simulated annealing, (7) evolutionary algorithms, (8) artificial neural networks, (9) index methods.

Transmission network reactive power sources planning by index methods implies that values of indices formed by some network parameters indicate optimal nodes for reactive power sources installation. Some of index methods are: (1) sensitivity analysis, whish signifies nodes where reactive power sources installation has the biggest influence to increasing reserve in reactive power of generators [2]; (2) cost/benefit analysis, which through analysis for all nodes signifies node with the biggest effects of reactive power sources installation on operational costs of transmission network [3]; (3) voltage stability margin method, which indicates node for reactive power sources installation that has biggest ratio of voltage deviation in after accident state and normal state [4].

An index method was also used to create the optimal list of TS 110/X kV for reactive load reduction in Serbian transmission network. Creating the optimal list of TS 110/X kV for reactive load reduction was based on effects of that reduction to Serbian transmission network active and reactive power losses decrease. Criterion of active and reactive power marginal cost maximal values (for peak load) was used to find candidates for list. Optimal power flow part of CLF-OPF software was used to calculate marginal cost values. This is standard software in Serbian Power Systems Public Utility.

Function to be optimized in OPF is square function of active and reactive power generation at generator nodes. Based on experience with average price of 1 MW installed in thermal power plant and average price of 1 Mvar installed in capacitor facilities (ratio of these prices is about 100:1), linear coefficients for generated active and reactive power in optimized function were adopted to be 1 and 0.01, respectively, and square coefficients were adopted to be 0. Since active and reactive loads were constant during analyses, result of OPF was state with minimal active losses and with reactive losses as minor as possible.

Therefore, OPF was used to calculate marginal costs of active and reactive power for all TS 110/X kV as index values, and these values indicated nodes with the greatest effects of reactive load reduction in transmission network.

Reactive load reduction was modelled subject to defined constraints. Reduction by TS 110/X kV was modelled up to the reactive load level in annual minimal regime of transmission network. Overcompensation risk for picked TS 110/X kV was minimized in such way. Procedure of TS 110/X kV reactive load reduction modelling was iterative. Iterative reactive load reduction modelling enabled organizational and technical constraints consideration. These constraints defined maximal volume of reactive load reduction by distribution utilities that could be realized up to set deadline with their available resources.

Transmission network operation in minimal regime was analyzed after each iteration of reactive load reduction in order to notice potential overvoltages or generators underexitation states.

RESULTS OF METHODOLOGY APPLICATION AND EFFECTS OF PROPOSED MEASURES REALIZATION

List of TS 110/X kV with their maximal state loads, proposed reactive loads reduction, and expected effects of maximal active and reactive losses reduction after proposed measures application is presented in the following table (TABLE 1). TS 110/X kV are grouped by distribution utilities, which were base for forming organizational and technical constraints for optimization procedure.

TABLE 1 - List of TS 110/X kV for optimal reactive load reduction

Substation name	Load peak (13.2.2004. at 19:15)		Modelled reactive power reduction (Mvar)	Substation name	Load peak (13.2.2004. at 19:15)		Modelled reactive power reduction (Mvar)
	P (MW)	Q (Mvar)			P (MW)	Q (Mvar)	
Vršac 1	13.99	5.84	6	Svrljig	8.23	2.32	0.5
Vršac 2	25.17	9.31	4	Knjaževac	18.14	5.30	2.5
Bela Crkva	13.02	3.68	2	Zaječar 1	18.40	2.25	0.5
Senta 1	9.42	2.28	1	Zaječar 2	19.49	6.49	3.5
Senta 2	14.96	5.59	2	SIP	13.43	3.99	2
Ada	20.30	7.61	3	Majdanpek 1	8.40	4.06	2
Kikinda 1	24.49	5.48	4	Majdanpek 2	7.55	3.79	1.5
Kikinda 2	25.73	7.54	5	Negotin	21.17	7.24	0.5
Odžaci	33.70	11.62	6	Sm. Palanka	39.94	10.11	5
Alibunar	19.57	9.14	2	Velika Plana	36.62	10.25	5
Beograd 10	55.94	19.54	9	Petrovac	33.24	15.67	2
Mladenovac	47.80	13.74	6	Sevojno	5.85	0.62	1
Beograd 11	71.12	17.17	7	Sušica	23.76	9.68	3.5
Novi Pazar 1	46.48	14.17	10	Ivanjica	17.69	7.32	4.5
Novi Pazar 2	9.50	2.48	2	Nova Varoš	9.16	4.28	2
Raška	29.32	10.97	10	Užice	41.71	15.03	4
Sjenica	8.04	3.26	1	Leskovac 1	28.77	9.80	4
Aleksandrovac	18.61	7.87	3	Jablanica	31.83	12.44	4
Lešnica	18.24	9.10	3	Belo Polje	12.67	4.54	2
Loznica	46.33	22.68	8	Lapovo	34.85	12.16	2
Trstenik	26.07	8.80	5	Kragujevac 3	36.17	12.29	1.5
Kraljevo 1	22.46	8.55	4	Stragari	5.81	1.97	0.5
Čačak 1	44.29	16.41	6	Kragujevac 8	12.14	4.13	1
G. Milanovac	29.78	11.87	4	Kragujevac 1	33.26	11.31	1
Kruševac 2	39.18	16.57	4	Kragujevac 5	22.70	7.72	1
Prokuplje	47.71	13.77	6	Vranje	50.32	10.36	4
Kuršumlija	17.14	6.93	6	Bujanovac	35.55	15.07	4
Aleksinac	42.27	13.70	5	Total			200
Peak active loss reduction (MW)			~8.6	Peak reactive loss reduction (Mvar)			~80

Expected active and reactive losses reduction grouped by network elements and voltage levels for maximal and medium network regimes are presented in TABLE 2.

TABLE 2 - Expected active and reactive losses reduction by network elements and voltage at maximal and medium state

Network elements	Peak active loss reduction (MW)	Active loss reduction at medium state (MW)
110/X kV transformers	0.2	0.2
110 kV lines	4.2	3.0
220/110 kV and 220/35 kV transformers	0.2	0.1
220 kV lines	3.5	2.2
400/220 kV and 400/110 kV transformers	0.1	0.1
400 kV lines	0.4	0.4
Total	8.6	6.0

Based on performed analyses it was concluded that proposed way of reactive loads reduction does not endanger normal network operation in minimal state considering overvoltages, generators underexitation states or need to decrease level of security (by switching off some lines) because of transmission network reactive power surplus.

Proposed measures effects

Two measures for TS 110/X kV reactive loads reduction were realized during 2005: (1) LVRPC in the amount of ~200 Mvar by TS X/0.4 kV that are supplied from TS 110/X kV in proposed list; (2) activating additional fixed capacitor batteries in the amount of ~22 Mvar at industrial consumers based on possibilities provided by harmonic distortion analyses.

The amount of ~200 Mvar of low voltage capacitor batteries were provided based on TABLE 1. However nominal line to line voltage of these batteries is 440 V, so, if they operate in network with 400 V line to line voltage, reactive power that they would generate is ~165 Mvar. Majority of batteries are installed where the effects in distribution network are the greatest respecting losses reduction and voltage conditions improvement: at TS X/0.4 kV supplied from long and loaded rural feeders with significant voltage descents. Therefore, capacitor batteries certainly generate amount of reactive power less then 165 Mvar.

Performed analyses of actual active and reactive loads of TS 110/X kV selected for reactive loads reduction derived following conclusions:

1. Significant increase of maximal active load and active load in transmission network maximal regime is observed at TS 110/X kV with realized bigger amount of LVRPC. System peak load arise 7.5% in 2006 refer to 2005. In series of compensated TS 110/X kV percentage is significantly bigger. It is possible that for some of them, this is the consequence of taking load due to network development, and for some, this is the consequence of network reconfiguration after accidents. However, there are TS 110/X kV where these changes are impossible because they are isolated from their adjacent TS 110/X kV. Several examples are TS: Raška (increase of maximal load for 18%), Trstenik (18%), Sjenica (28%), Novi Pazar 1 and 2 (together - 16%).

More than average increase of active load in these TS is consequence of reduced consumption effect eliminating. This effect appears due to bad voltage conditions, but intensive LVRPC, especially applied to TS X/0.4 kV supplied from lengthy and loaded rural feeders, reverses this effect.

2. Despite significant increase of active loads (by individual TS and overall), reactive loads mostly decrease. Although overall increase of active load in compensated TS is about 215 MW, total reactive load is about 188 Mvar lower. Only five TS 110/X kV has greater reactive then active load increase rate, and realized LVRPC in their supplied TS X/0.4 kV is symbolic. There is reactive load increase in 21 of 94 analyzed TS 110/X kV, but these are TS with great active load increase rate or low amount of realized LVRPC. Significant reactive load decrease by TS released part of their capacity, but also part of capacity of supplying lines, and supplying TS 220/110 kV, TS 400/110 kV and TS 400/220 kV. For example, transferred active power by TS 110/35 kV Raška, Trstenik, Kraljevo 1 and Leskovac 1 are magnified 18%, 18%, 15%, and 20% respectively, and their currents are magnified only 11%, 12%, 8%, and 17% respectively.

3. Serbian transmission network losses decrease that is consequence of reactive power compensation can be estimated by comparing two states of that network. One state is realized maximal state for 2006 (6002 MW and 1723 Mvar) and other is analyzed peak in 2006 with assumed power factor from year 2004 peak (before reactive

loads reduction) for TS 110/X kV with recorded reactive power compensation (6002 MW and 1979 Mvar). Losses difference between these two states is 10.26 MW. Considering maximal active losses price of 175 €/MW, annual loss cost decrease is about 1.8 million €.
Realized LVRPC investment was about 1.1 million €, and activating additional 22 Mvar fixed capacitor batteries at industrial consumers investment was about 29000 €. Considering only transmission network active losses reduction, total reactive loads reduction investment repaid in only eight months. Considering distribution network effects, which are greater than transmission network effects, total investment repayment time is less then four months!
Reactive power losses are significantly lower - 115 Mvar, which means that generators reactive power production difference is greater than reactive load difference.
4. 110 kV network voltage conditions are better. By comparing two aforementioned states, 21 TS 110/X kV with voltage less than 108 kV are segregated. For some of them voltage conditions improvement at 110 kV side is considerable: TS Novi Pazar 1 and 2, and Raška (for about 4 kV), TS Vršac 1 and 2, and Bela Crkva (for about 1.1 kV), TS Kuršumlija and Prokuplje (for about 1 kV).
5. Selection of low voltage capacitor batteries volume for installation at TS X/0.4 kV proved to be reliable solution. Selected batteries were preliminary analyzed for THD and apparition of resonance at 5th, 7th, 11th, and 13th harmonic. Up to now, there were no incidents with installed batteries and accumulated experience is about 400 Mvar years.

Further reactive loads reduction realization

High profitability of 200 Mvar LVRPC induced decision about further 170 Mvar LVRPC and 30 Mvar medium voltage reactive power compensation (MVRPC). Selection of TS 110/X kV for reactive loads reduction by LVRPC was carried out based on the same methodology, already presented in this paper. Estimated effects of reactive loads reduction in Serbian transmission network, based on detailed techno-economical analyses, are still great. For analyzed maximal state, active losses would decrease 6.2 MW, and LVRPC investment would repay in just one year, considering effects in transmission network only.
MVRPC analysis (compensation in TS 35/10 kV) was more complicated because it demanded: load flow analyses in distribution networks at maximal and minimal states; detailed analyses whether proposed compensation is satisfactory considering space for capacitor battery and its connection unit; harmonic distortion of capacitor current detailed analyses during appearance of maximal voltage harmonic distortion at 35 kV side of supplying TS 110/35 kV or at 10 kV side of analyzed TS 35/10 kV. Installation of capacitors with resonance at 9th harmonic (which is inhibited by YΔ connection of 35/10 kV transformer) proved as economically optimal solution subject to technical constraints.
Economical effects of reactive loads reduction through 30 Mvar MVRPC are lower then effects of LVRPC. Average price of this compensation is 28000 €/Mvar (taking into account connection equipment), therefore, 4.3 times more then LVRPC. Profitability rate of total investment to MVRPC (857000 €) is about 31%, considering active losses reduction in transmission and distribution networks.
Reactive load reduction still does not endanger normal network operation in minimal state considering overvoltages, but generators underexitation states or need to decrease level of security (by switching off some lines) because of transmission network reactive power surplus are possible for this level of compensation.

CONCLUSIONS

Motives that provoked actions to reduce reactive loads in Serbian transmission network are presented in this paper. List of TS 110/X kV for reactive loads reduction is suggested based on proposed index methodology and using data of 2004 maximal and minimal states of network. Total of reactive loads reduction is 200 Mvar. List is created subject to usual technical constraints for transmission network functioning, and organizational and technical constraints that determinate maximal volume of reactive load reduction by distribution utilities, that can be realized up to set deadline with their available resources. Low voltage reactive power compensation is realized based on this list during 2005.
Analyses showed a series effects of compensation: active loads increase because of voltage conditions improvement, better use of installed capacities of network elements, maximal transmission network active losses reduction for about 10 MW (profitability rate considering only transmission network effects is 170%!), transmission network voltage conditions improvement, reliability of selected low voltage capacitor batteries etc.
Taking into account effects of realized measures new cycle of reactive loads reduction initiated, with the plan to realize 170 Mvar LVRPC and 30 Mvar MVRPC. Expected effects of these measures are also great: expected profitability rate of LVRPC considering only transmission network effects is ~100%, and expected profitability rate of MVRPC considering transmission and distribution networks effects is ~30%.

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