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Different Approaches to Short-term Optimal Voltage Scheduling Based On Voltage Control Zones Concept

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Abstract **- Optimal voltage scheduling procedure is usually a part of a day-ahead or hour-ahead planning phase, done by Transmission System Operator (TSO). It provides an implementation of a voltage control ancillary service that consists of a planning phase based on optimal power flow algorithm, real-time operation and accounting and settlement. Voltage control ancillary service model described in the paper is based on a division of power system into a voltage control zones. In every zone a reactive power market is formed. Reactive energy prices and voltage scheduling plan are determined through a two-step optimal power flow algorithm. Three algorithms are presented in the paper, differing in the design of optimization steps. Proposed algorithms are tested on IEEE 39-bus test system. Test results are compared and discussed. Article is concluded with the possible directions for continuation of the presented research.**

Index Terms **- ancillary services, electrical distance, optimal power flow, reactive power market, voltage control**

I. INTRODUCTION

IN deregulated electricity market environment voltage control ancillary service (VCAS) has to be properly recognized and efficiently implemented in order to preserve power system technical conditions regarding prescribed voltage ranges and voltage stability margins, as well as to manage reactive power flows thus maximizing the transmission of real power over long distances and minimizing transmission losses. Reactive power producers have to be remunerated for their availability to the power system, and for the reactive energy produced in lagging or leading part of a capability curve. Remuneration model has to give right incentives to market players in order to ensure further investments in reactive power capabilities [1], [2].

Local nature of voltage control brings a lot of obstacles in establishing a market based VCAS approach, but it is the most proper way to ensure transparent and non-discriminatory engagement of reactive power producers. Development of local reactive power markets can be a practical solution [3], [4]. Local approach can simplify the administration and management of reactive power market by the system operator and set the different standards for reactive power from region to region. Reactive power prices in one region should not affect the prices in other regions, reducing this way the overall cost of system operation and control.

Voltage schedule is done in the day-ahead or hour-ahead planning phase based on an optimal power flow (OPF) algorithm. OPF objective is then usually minimal procurement costs of active energy for covering transmission losses, but in deregulated environment minimal reactive energy procurement costs must not be neglected. There is an obvious relationship between these two costs and to minimize system overall cost both objectives have to be considered. One possible way is to handle the problem by simultaneous optimization of the objectives inside one cost function, which leads to the multi-objective optimization problem. Another way is to separate objectives and to solve them in steps [5], [6]. In this respect, three different approaches for short-term voltage scheduling are presented in the paper. All three approaches are based on a similar VCAS model, with implementation of a voltage control zones concept, but they differ in the optimal voltage scheduling procedure. The procedure is based on a two-step optimization algorithm. In every step a different cost function is minimized, depending on the approach.

In section II VCAS model is described, while in section III three approaches for optimal voltage scheduling procedure are presented. Proposed approaches are tested on IEEE 39-bus test system. Results are presented and compared in section IV. Final conclusions are given in section V.

II. VOLTAGE CONTROL ANCILLARY SERVICE MODEL

VCAS model is based on a voltage control zones concept where every voltage zone forms a single reactive power market characterized by a uniform reactive energy price. Zones are formed by splitting a power system or a part of power system into autonomous voltage sub-areas with sufficient reactive power reserves using electrical distance method [7]. Reactive power engagement of available generators as well as uniform reactive energy prices depends on generator's reactive power offers. Reactive power offers are submitted in a form of a reactive power cost curves [2].

Reactive power cost curve presents a relationship between generator's reactive power output in Mvar or Mvarh, and cost incurred to the providers or the payment the providers are

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expected to be paid for the voltage control ancillary service. Reactive power cost curve can have quadratic, Fig. 1, or piecewise-linear shape, Fig. 2. Generator's reactive power costs can be divided in three main groups:

1. Fixed or capital costs, presenting machine building and installation costs, together with cost of the equipment needed for reactive power production,
2. Variable or operational costs, mainly caused by active losses in the generator and step-up transformer due to the reactive current flow through the armature and excitation windings,
3. Opportunity costs, related to the special operating conditions when active power output has to be lowered in order to produce extra amount of reactive power. Opportunity costs are costs of lost profit and therefore depend mostly of active energy market price and in some smaller portion of generator's variable cost.

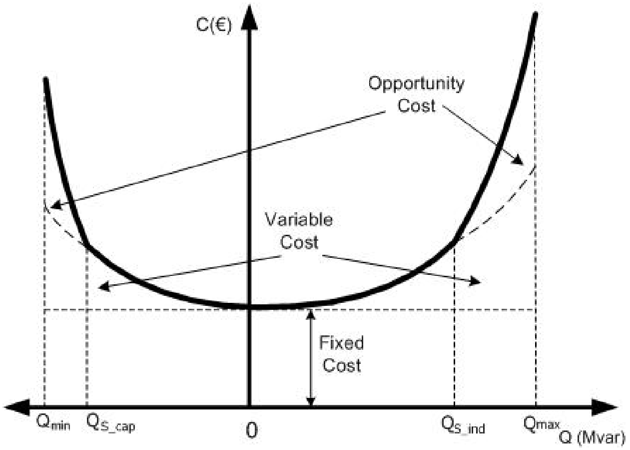

Fig. 1. Quadratic shape reactive power cost curve

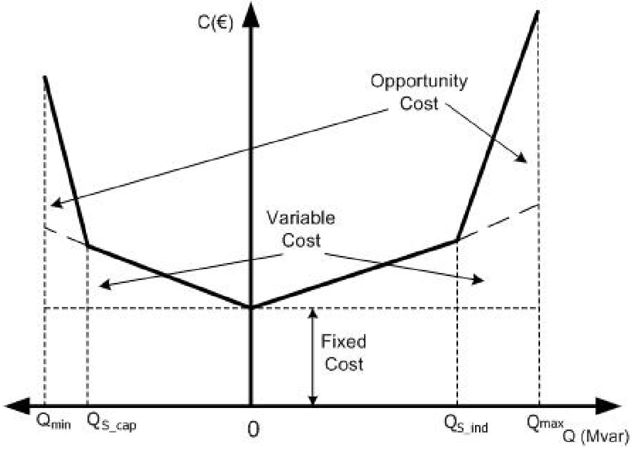

Fig. 2. Piecewise-linear shape reactive power cost curve

In real-time operational phase, during normal operating conditions, reactive power producers are following voltage schedule given by TSO. In case of disturbances remedial actions should be taken by the TSO, including extra demand for reactive power in order to prevent voltage instability or collapse. In accounting and settlement phase all generators are accounted for the availability time and reactive power energy they have produced/absorbed, based on pre-determined prices.

III. OPTIMAL VOLTAGE SCHEDULING PROCEDURE

Optimal voltage scheduling procedure is realized within two optimization steps, where every step presents an OPF calculation using different cost function. Basically, optimization has two aims: minimal procurement costs of active energy for covering transmission losses and minimal reactive energy procurement costs, with respect to power system security constraints. Necessary inputs for the calculation are load forecast, topology changes, active power generation schedules and energy exchange schedules. Direct output of the calculation procedure is an optimal voltage schedule, while the prices of reactive energy are indirect outcome of this process. Different approaches to the optimal voltage scheduling problem are presented and compared in the paper.

In the first approach, Fig. 3, it is assumed that generators are paid only for the availability to the system if the reactive power production is inside a mandatory region. Optimal voltage scheduling procedure is applied to network voltage zones separately. First optimization step minimizes transmission losses. Network compensation devices usage is maximized reducing that way the system operator's payment for voltage control ancillary service. Outputs are optimal positions of on load tap changing (OLTC) transformers, network compensation devices usage and voltage set points for generator's automatic voltage regulators for the given set of network constraints. If all the constraints are satisfied and system state is feasible then problem is solved. All generators are in mandatory reactive power operational boundaries and are paid only for the availability. If the system is highly loaded network compensation devices will probably not be able to satisfy given set of voltage constraints and system operator will be forced to engage higher generator's reactive power production by solving the second step optimal power flow algorithm. In the second optimization step reactive power procurement costs are minimized. Output is the generator's optimal voltage schedule. Reactive power pricing is based on nodal marginal pricing. Marginal prices in every network node are determined by the OPF algorithm as the Lagrange multipliers of the reactive power equality constraints [8].

Second, Fig. 4, and third, Fig. 5, approach basically differ in the implementation of second optimization step, where second approach is a variant of third approach (when reactive power prices are near zero value). Based on submitted cost curves and planned system operating conditions reactive energy procurement costs are minimized in the first optimization step, as a part of the overall optimal voltage scheduling procedure. An auction is then performed taking into account only those providers accepted by an optimization algorithm. Uniform marginal price, determined by auction mechanism, is based on the „highest bid accepted“ principle. Every provider is paid the marginal price for produced or absorbed reactive energy. For every voltage zone a separate auction is performed, based on zonal OPF algorithm, and different zonal reactive energy prices are achieved. Zonal approach is guarantying that prices in one region are not affecting the prices in other regions.

Second approach implements minimization of transmission losses in second optimization step where final optimal voltage schedule is calculated.

In the third approach goal of second optimization step is simultaneous minimization of cost for procuring energy for covering transmission losses and for procuring reactive power energy, according to transmission losses and zonal reactive energy prices respecting power system planned conditions and security constraints.

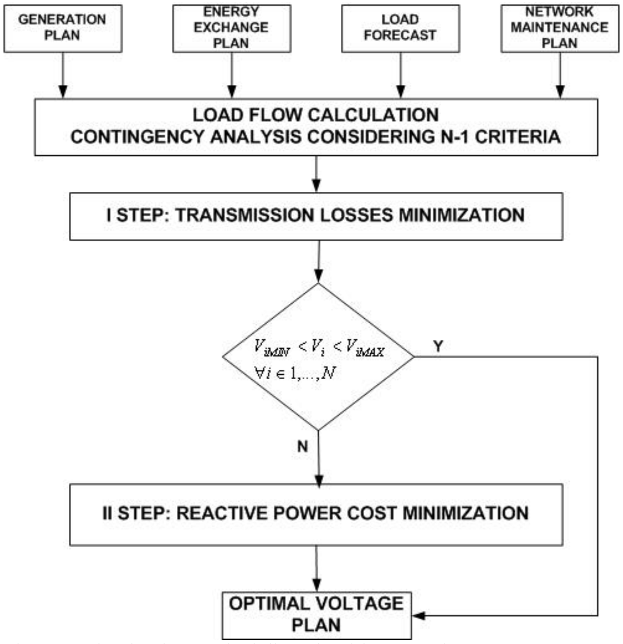

Fig. 3. Optimal voltage scheduling algorithm – Variant 1

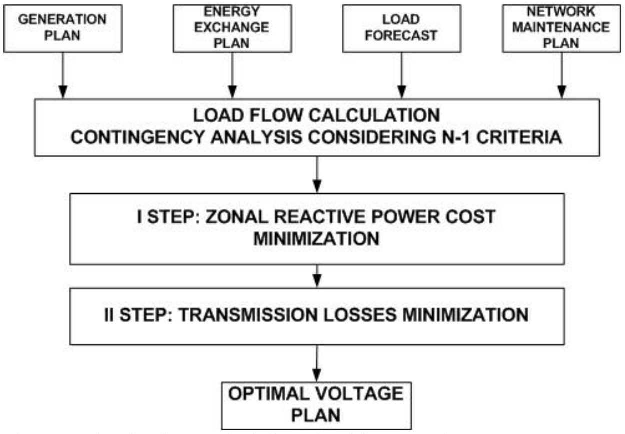

Fig. 4. Optimal voltage scheduling algorithm – Variant 2

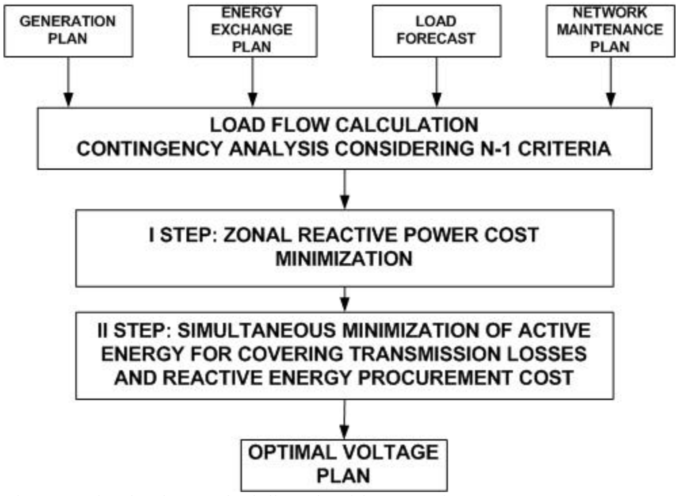

Fig. 5. Optimal voltage scheduling algorithm – Variant 3

IV. TEST RESULTS

Presented optimal voltage scheduling algorithms are tested on IEEE 39 bus test system. Using electrical distance method test system is divided in two voltage control zones, Fig 6. Six generators are included in first voltage zone, and four generators in second voltage control zone. Generator's reactive power capability data is given in Table I. Shunt compensation, 5x10 Mvar each, was placed at buses with the lowest voltage values. Two capacitors were put in first voltage control zone (nodes 4 and 5) and two in second voltage control zone (nodes 16 and 20).

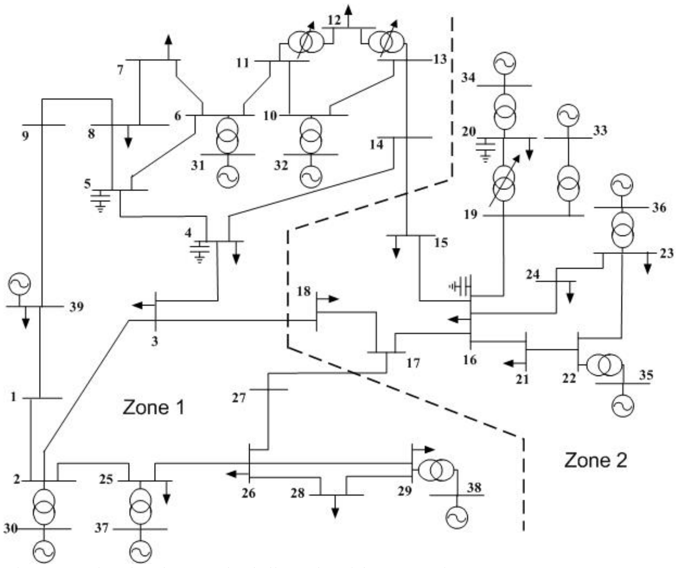

Fig. 6. Optimal voltage scheduling algorithm – Variant 3

In the first approach piecewise-linear generator's reactive power cost functions were used, Table II, where a1, a3 and a4 are slopes of the reactive power cost function. a0 is the availability price, corresponding to the mandatory region

In the second and third approach quadratic reactive power cost functions were used and cost function coefficients c0, c1 and c2 were determined for every generator, Table III.

TABLE I GENERATOR'S REACTIVE POWER CAPABILITY

Bus No.	Qs (Mvar)	Qmax (Mvar)	Qmin (Mvar)
30	155	200	-100
31	375	400	-200
32	488	520	-250
37	405	450	-225
38	514	540	-250
39	620	650	-300
33	392	420	-200
34	381	400	-200
35	403	430	-200
36	420	450	-225

TABLE II REACTIVE POWER COST FUNCTION SLOPES

Bus No.	a0	a2	a3	a1
30	1	0.04	0.40	-0.07
31	1	0.02	0.68	-0.08
32	1	0.03	0.28	-0.12
37	1	0.01	0.33	-0.05
38	1	0.03	0.58	-0.10
39	1	0.01	0.50	-0.06
33	1	0.03	0.33	-0.11
34	1	0.03	0.28	-0.10
35	1	0.04	0.63	-0.12
36	1	0.03	0.50	-0.09

TABLE III QUADRATIC REACTIVE POWER COST FUNCTION COEFFICIENTS

Bus No.	c2 (€/Mvar^2)	c1 (€/Mvar)	c0 (€)
30	0.0079	-0.2095	0
31	0.0036	-0.1439	0
32	0.0035	-0.2769	0
37	0.0045	-0.0170	0
38	0.0050	-0.0376	0
39	0.0058	0.0234	0
33	0.0053	0.2076	0
34	0.0031	-0.3925	0
35	0.0025	-0.3385	0
36	0.0026	-0.5700	0

Marginal reactive power costs of network compensation devices were set as constant, with value of 0.01€/Mvar. This cost includes both fix and variable part and can be set to any value that is ensuring network compensation engagement priority within the optimization algorithm. Proposed optimization algorithms were developed and solved using Matlab programming environment. Matpower code [9] was partially used. Mehrotra's predictor-corrector primal-dual interior point method was applied for solving both optimization steps [10], [11].

Reactive energy pricing in the first approach is based on nodal marginal pricing, calculated in second optimization step, while other two approaches settle uniform zonal marginal price in first optimization step that is the same for both approaches. Table IV gives the reactive power production of available generators Qg and nodal marginal prices λ for first approach after second optimization step.

TABLE IV. REACTIVE POWER PRODUCTION AND NODAL MARGINAL PRICES

Bus No.	Qg (Mvar)	λ (€/Mvarh)
30	-100	0.019
31	224.44	0.024
32	69.37	0.027
37	148.32	0.011
38	79.31	0.028
39	305.05	0.007
33	169.06	0.031
34	122	0.028
35	49.02	0.039
36	223.3	0.029

In other two approaches all submitted generator's reactive energy bids were accepted by first step optimization and following reactive energy marginal prices were determined by auction procedure: 0.55 €/Mvarh for zone 1, Table V, and 1.09 €/Mvarh for zone 2, Table VI. The price of active energy for covering transmission losses is assumed to be 50 €/MWh and overall system cost comparison between proposed approaches is made, Table VII.

TABLE V. REACTIVE POWER COST MINIMIZATION AND AUCTION RESULTS FOR ZONE 1

Gen	Qg (Mvar)	Marginal price (€/Mvar)	Payment (€)
30	33	0.05	18
31	192	0.55*	106
32	178	0.35	98
37	62	0.20	34
38	56	0.01	31
39	191	0.07	105

* Zonal marginal price

Ploss is transmission losses value, Qtotal is generator's total reactive power production, Closs is cost for procuring energy for covering transmission losses, Cq is cost for procuring reactive power energy, and Ctotal is overall system cost. Values of Ploss and Qtotal are in the range of expected while cost values depend on assumed or calculated prices. There is an important difference between nodal marginal reactive energy pricing in compared to the uniform marginal reactive energy pricing. Nodal marginal pricing is claimed not to be covering all reactive power production costs. When this concern is coupled with the complexity and the volatility of nodal prices for reactive power, the method becomes practically hard to implement [1]. Uniform marginal pricing is more market oriented and transparent method, although bringing higher system costs in the presented case.

TABLE VI. REACTIVE POWER COST MINIMIZATION AND AUCTION RESULTS FOR ZONE 2

Gen	Qg (Mvar)	Marginal price (€/Mvar)	Payment (€)
33	120	0.52	131
34	153	0.73	166
35	184	1.09*	200
36	150	1.00	163

* Zonal marginal price

TABLE VII. OVERALL SYSTEM COST COMPARISON

Variant	Ploss (MW)	Qtotal (Mvarh)	Closs (€)	Cq (€)	Ctotal (€)
First	45.7	1290	2285	32.2	2317
Second	42.9	1440	2145	1152	3297
Third	45.2	1307	2260	1175	3435

Voltage profile comparison between proposed algorithms after second optimization step for Zone 1 and Zone 2 is given on Fig. 7. and Fig. 8., respectively. Calculated voltage profiles are very similar, what approves all three algorithms in the domain of network security. First algorithm has a lower voltage profile in zone 1 than other two approaches, what is expected considering that it minimizes operational cost of reactive power procurement in second optimization step while transmission loss minimization is a target in other two approaches. Therefore second approach gives the highest and well-balanced voltage profile as it minimizes losses only.

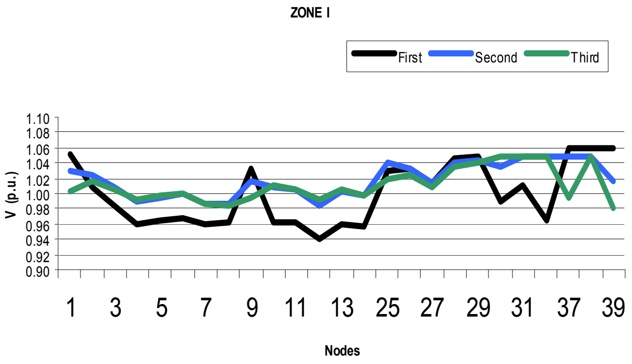

Fig. 7. Voltage profile comparison - Zone 1

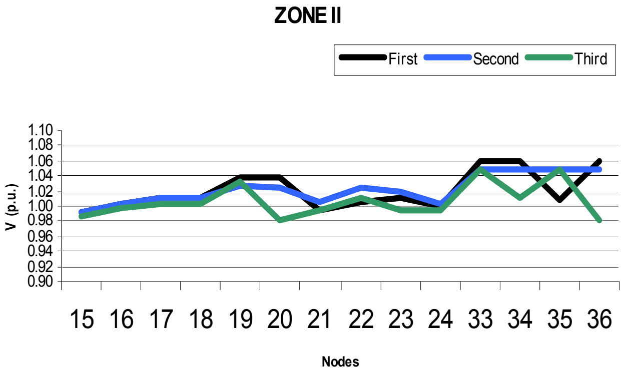

Fig. 8. Voltage profile comparison - Zone 2

Reactive power production comparison between proposed algorithms after second optimization step for Zone 1 and Zone 2 is given on Fig. 9. and Fig. 10., respectively. Capacitors have been engaged at maximum in all three cases. Generator's reactive power production differs between cases but not significantly. Minimization of reactive power costs gives slightly different reactive power allocation than transmission loss minimization.

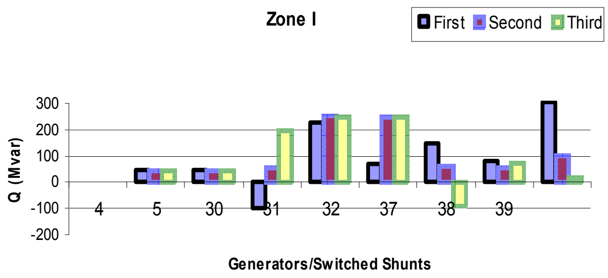

Fig. 9. Reactive power production comparison - Zone 1

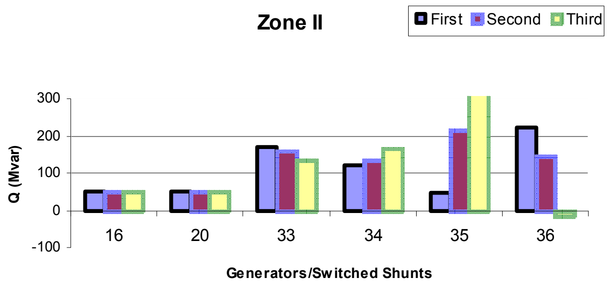

Fig. 10. Reactive power production comparison – Zone2

V. CONCLUSION

Three algorithms for short-term optimal voltage scheduling procedure are presented in the paper. Algorithms are based on voltage control zones concept and two-step optimal power flow algorithm, differing in the design of optimization steps. Test results approve all three algorithms in the domain of network security. Considering the system cost optimization it is shown that final results are reflection of prices values, having in mind that nodal marginal pricing is very different from uniform marginal pricing methodology. Therefore, first approach is not comparable with other two presented approaches considering reactive energy costs. Simultaneous minimization of cost for procuring energy for covering transmission losses and for procuring reactive power energy gives slightly higher overall costs than just loss minimization. It is due to the complexity of such approach and mathematical background has to be improved in the future. Nevertheless, final conclusion would be that loss minimization is justified as a cost function for optimal voltage scheduling in case of normal operating scenarios. When operational situation requires higher reactive power production, that cost should not be neglected, and coupling of ancillary services market for active and reactive energy should be implemented.

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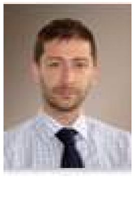
VII. BIOGRAPHIES



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