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Voltage Stability Improvement and Losses Reduction in ESFAHAN Regional Power System

(Technical Report)

March 2012

Power System Planning Center, Esfahan Regional Electrical Company,
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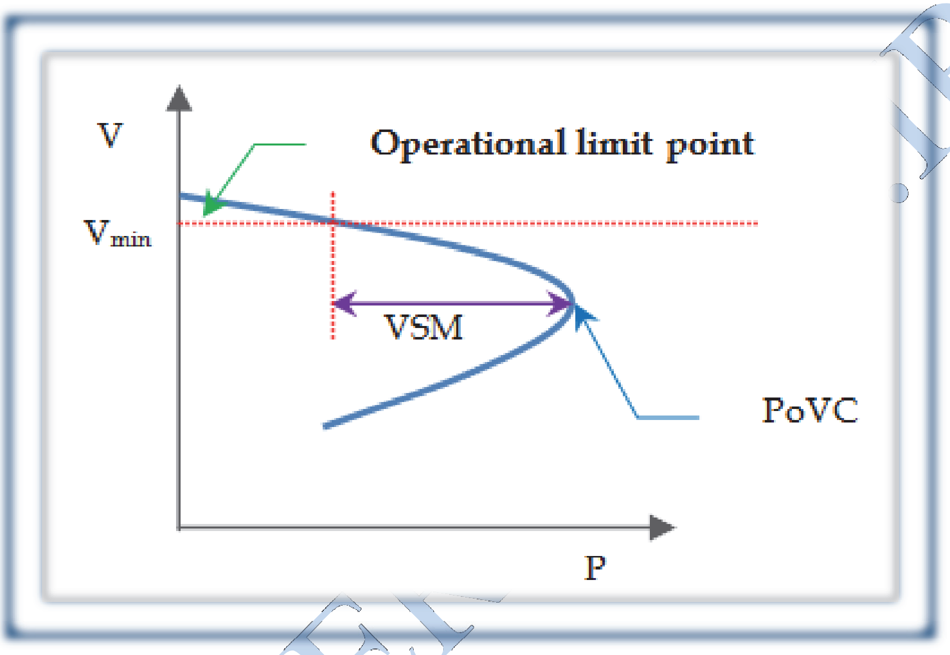

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Prepared by

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Contents

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Summary

Determining practical methods to voltage stability improvement in large power systems is the aim of this report which are based on methods and results of voltage stability studies in ESFAHAN regional power system in horizon of year 2017. Voltage stability improvement through reactive power compensation is one of the most important and conventional methods in this regard. Since this method is usually considered as multi-dimensional problem, all aspects such as investment and operation costs, technical limitations and other factors should be considered effectively. Hence, a multi objective function has been presented in this report which meet all technical and economical requirements. Problem constraints have been formed in an appropriate way to satisfy voltage stability and other limitations. Taboo search algorithm has been used to solve the optimization problem, so optimal location and appropriate size of reactive power sources have been determined. All algorithms have been provided using DIgSILENT programming language (DPL) to mechanize calculations. Numerical results show the ability of the applied method in losses reduction, voltage profile improvement and voltage stability margin enhancement.

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1. Introduction

Study of voltage stability surveys power system's ability in maintaining voltage in all networks' buses, under normal conditions and although after disturbances. Voltage instability will appear as voltage increasing or dropping in some buses that may cause loss of network integrity or loads shedding in a region which has voltage problem.

From time viewpoint, Voltage Stability (VS) studies are divided into two groups: long term and medium term. From disturbance viewpoint, it's divided into two groups: static small disturbance and dynamic large disturbance. Using dynamic method for VS analyses is not possible in large networks because it will be so time consuming. When particular simulation in special cases is required, using dynamic method simulation tools and processes in time zone is proper. In large and real power networks, VS studies are done statically, using analytical technique and based on power flow. Through years of study and industrial experiences it is proved that this process give exact and operational results. In this article, static studies of VS are done for VS assessment of ESFAHAN regional power system.

2. The process of Voltage stability studies

In this article, VS studies is done by forming static files of system studies and by considering below terms which contain some special notes related to Esfahan power system limitations.

2.1 Forming static files

At the first level, 3 groups of static files are created for: peak , light and off-peak load conditions. These conditions are considered as minimum condition which should be

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considered. The load model, power sources and automatic control equipments must be considered during static files formation.

2.2 Forming zones

From VS viewpoint, complexity of power exchanges between zones with development of network, local nature of voltage control problem and dependency of VS to loads in the near buses, are most important reasons of dividing network into several zones. In case of vast power network, it should be divided to smaller zones based on system operation method.

2.3 Choosing snapshots

To analyze VS of large power systems, snapshots of system condition should be provided to study the performance of network's automatic equipment before operator reactions.

In Esfahan power network, accurate load models are not available, automatic control of equipments in sub-transmission level are usually inactive and tap changers of transformers in sub-transmission level are controlled manually, only two snapshots are chosen for studies: first, exactly after disturbance and the other just before the operator's reaction or Automatic Generation Control (AGC) reaction.

In the first snapshot which will be shown by T1, loads are considered voltage-dependent, tap changers and Over Exciter Limiters (OXL) are considered inactive and AGC are considered as an active control. In this snapshot, because of unavailability of accurate load mode in ESFAHAN power system, loads will be modeled as constant power for active part and as constant impedance for reactive part.

In the second snapshot which will be shown by T2, loads are modeled as constant power, governors are in service and OXLs are active. Tap changers which are controlled manually will be considered inactive as the first snapshot.

2.4 Event selection

At this level of instructions, proper events should be selected for voltage stability studies. For analyze of system behavior in case of different events, all single contingency for each power lines, transformers and power plants units are considered. According to operator's view, special mixed events should be considered. It should be noted that in lines event, reactors installed on that line should be exited with the line simultaneously. Also, if two transformers in a substation have only one breaker, simultaneous outage of both transformers must be considered. For lines with T-off conditions, all connections must be exited during event selection procedure.

2.5 Power exchange method

power exchange method is defined as a way to exchange the electric power between power generation and consumption zones. In this project, selected method is based on increasing loads in one zone and increasing electric power generation in other zones regarding their limitations. Loads and generations are increased step by step in 50 MW for each one.

This increase will be continued until to reach to one of the following constraints:

a) Power generation limits
b) Load flow constraints

In this regard, generations and loads are increased as below:

$$P_{Gj} = P_{Gj}^{0}\left(1+\lambda K_{Gj}\right) \tag{1}$$

$$P_{Di} = P_{Di}^{0}\left(1+\lambda K_{Di}\right) \tag{2}$$

$$Q_{Di} = Q_{Di}^{0}\left(1+\lambda K_{Di}\right) \tag{3}$$

where:

λ, is a scalar parameter that represents the increase in a zone load or generation unit. P_{Gj}, is the active power generation of j-th generator. P_{Di} and Q_{Di} are active and reactive parts of i-th zone loads respectively. 0 indicates the initial value of each parameter before increasing the power exchanges.

2.6 VS indexes

In this report, two indexes are introduced in order to examine the VS of power system zones which are calculated by (4) and (5) and are called VS Security Margin (SM^{VS}) and Static Security Margin (SM^{Static}) respectively.

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Esfahan, Iran, Tell: +983116934532

$$SM^{VS} = \frac{P^{Critical} - P_0}{P_0} > 0.05 \quad (4)$$

$$SM^{Static} = \frac{P' - P_0}{P_0} \geq 0 \quad (5)$$

In above equations, $P^{Critical}$ shows the maximum zone active power which can be increased before voltage collapse. Based on WECC instructions, minimum SM^{VS} should be more than 5% in each zone. Furthermore, a static security margin (SM^{Static}) is defined which shows the steady state voltage profile of each zone. As it has been shown in (5), it is necessary that each zone could meet the minimum voltage values for normal and contingency conditions which are 0.95 and 0.9 respectively. Also, loading of power system equipments in normal and contingency conditions must be less than 100 and 110% respectively.

In order to have a reliable and stable voltage profile, both indexes should be satisfied simultaneously.

3. Optimal Capacitor Placement (OCP)

Usually, heavy loaded systems and some that have not sufficient reactive power sources are faced with undesirable voltage profile and even voltage instability. There are some initial actions to keep the voltage profile in the accepted rang such as increasing the transfer capability of the power system by replacing the low rated conductors with high rated conductors or rising the transformers capacity. The topology of the system and proper operation manoeuvres on transformer's tap changers are usually used to maintain a safe voltage profile. Beside these solutions, reactive power compensation through the OPC is one of the most important and common solutions to voltage stability problem. OPC is the calculation of optimal size and place of capacitors to meet the voltage constraints and improve the voltage stability margins.

Heretofore, capacitors placement were done based on simple engineering analysis and experiences of power system engineers. In last two decades, capacitor placement has been done using optimal methods. In capacitor placement problem, power flow equations are key constraints which are commonly considered.

Different researches showed that not only normal mode, but also contingency mode should be considered in power follow equations. As a matter of fact, OPC is a Security Constraint Optimal Power Flow (SCOPF) problem. By using the SCOPF model, optimal size and placement of new capacitors can be determined in such a way that it will results in desirable and stable voltage profile in both normal and contingency modes.

3.1 Objective functions

Capacitor placement problem can be formed by different objective functions such as minimizing costs of capacitors, reactive power costs, active power loss, generator's fuel costs or least voltage digression. Voltage stability-related goals can be determined as a part of objective function or they can be considered as constraints of the problem. Furthermore, using a multi objective function as a mixed goal in capacitor placement formulation is possible. For example minimizing investment cost, decreasing power loss, decreasing voltage digression along with increasing voltage stability margin could directly enter into the objective function.

3.2 Candidate buses

Since OPC problem uses a search algorithm to determine optimal place and size to install capacitor equipments, searching in all solution space can take too long time for big power networks. In the other hand, it is not possible to install new capacitors in some of buses because of special limitations and other operational aspects. Hence, we can choose a group of buses as candidate to install capacitor equipments using proper method, before starting to solve the problem.

In this project, using sensitivity analysis according to resource's effect on VS indexes, candidate buses are specified. One of the indexes that introduced for determining system's weak buses from view of VS, is sum of changes in reactive power generation of generators, caused by slight change in each bus reactive load. This index value is expressed as below:

$$S_{Qi} = \frac{\sum_{j\in\Omega_c} \Delta Q_{gi}}{\Delta Q_i} \tag{6}$$

In this equation, Ω_G is the set of system generators, ΔQ_i is change in reactive load of the i-the bus, ΔQ_{gj} is change in the generation reactive power of j-th generator and $L_L$is the set of system power buses. Value of this index in a system with high level of voltage stability margin will be approximately 1 in all buses, but in a system with low level of voltage stability, value of this index will be significantly more than 1 at least in one bus. Hence, these buses are the best place to install capacitors.

3.3 Proposed formulation

In this section, final formulation of OPC problem in Esfahan power system is presented to minimize capacitor's installation costs, loss of system's active power along with voltage stability constrains and limitations as below:

$$Min(\sum_{i\in C}[(Pc_i + Cost_{ci} Max_{k\in w, j\in L_L}(Q_{ci,k,j})x_i)] + Pv_i y_i + \sum_{j\in L_L} m_j T_j P_{loss,j} \tag{7}$$

In this objective function, first phrase is the cost of installing capacitors in candidate buses which in this phrase, C is the set of candidate buses, W is the set of system's operational modes (modes after a contingency and normal operation modes), L_L is different levels of load, Pc_i is constant installation cost of switchable capacitors, Pv_i is constant installation cost for constant capacitors, $Cost_{ci}$ is variable installation cost for a capacitor unit and $Q_{ci,k,j}$ is required capacitor capacity for installation in i-th bus, in j-th load level, and in k-th operational mode. In addition, x_i *and* y_i are integer variables which can be 0 or 1 and they show that if reactive power equipments are installed in the i-th bus or are not installed. Second phrase in objective function is the cost of system's active power losses which in it, L_L is different load levels in planning horizon, m_j is coefficient for calculation of losses cost of i -th load level and its scale is $\$/MWh$. T_j is time period of j-th load level and $P_{loss,j}$ is network losses in T_j.

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This objective is subjected to following constraints which are described by (8) to (19):

$$P_{Gi,k,j} - P_{di,k,j} = \sum_{m=1}^{N_{bus}} |V_{i,j,k}||V_{m,k,j}||Y_{im,k,j}| \cos(\theta_{im,k,j} + \delta_{m,k,j} - \delta_{i,k,j}) \quad k \in t_c, j \in J_L, i \in N_{bus} \tag{8}$$

$$Q_{Gi,k,j} + Q_{ci,k,j} - Q_{di,k,j} = \sum_{m=1}^{N_{bus}} |V_{i,j,k}||V_{m,k,j}||Y_{im,k,j}| \sin(\theta_{im,k,j} + \delta_{m,k,j} - \delta_{i,k,j}) \quad k \in t_c, j \in J_L, i \in N_{bus} \tag{9}$$

$$P_{Gi,k,j}^{\min} \le P_{Gi,k,j} \le P_{Gi,k,j}^{\max} \quad k \in t_c, j \in J_L, i \in N_G \tag{10}$$

$$Q_{Gi,k,j}^{\min} \le Q_{Gi,k,j} \le Q_{Gi,k,j}^{\max} \quad k \in t_c, j \in J_L, i \in N_G \tag{11}$$

$$0 \le Q_{ci,k,j} \le Q_{c,i}^{\max} \quad k \in t_c, j \in J_L, i \in N_{candida} \tag{13}$$

$$0 \le Q_{ri,k,j} \le Q_{r,i}^{\max} \quad k \in t_c, j \in J_L, i \in N_{candida} \tag{14}$$

$$T_i^{\min} \le T_{i,k,j}^{\min} \le T_i^{\max} \quad k \in t_c, j \in J_L, i \in N_{tap} \tag{15}$$

$$|S_{im,k,j}| \le S_{im,k,\max} \quad i \ne m, i, m \in N_{bus}, k \in t_c, j \in J_L \tag{16}$$

$$\delta_{im,\min} \le \delta_{i,j,k} - \delta_{m,k,j} \le \delta_{im,\max} \quad i \ne m,\ j \in J_L,\ i,m \in N_{bus} \tag{17}$$

$$SM_i^{VS} > 0.05 \quad i \in w_{contingency} \tag{18}$$

$$SM_i^{Static} \ge 0 \quad i \in w_{contingency} \tag{19}$$

In above equations, $P_{di,k,j}$ and $Q_{di,k,j}$ are respectively active and reactive parts of i-th bus in k-th operation mode, j-th load level in planning horizon. $P_{Gi,k,j}$, $Q_{Gi,k,j}$ are respectively active and reactive parts of generator units in i-th bus, k-th operation mode and in the j-th load level. $|V_{i,k,j}|$ and $\delta_{i,k,j}$ are voltage magnitude and angle in the i-th bus, $|Y_{im,k,j}|$ and $\theta_{im,k,j}$ are the magnitude and angel of im-th admittance matrix element. N_{bus} , N_G and N_{candid} are sets of all system's buses, generation buses and candidate buses to install capacitors respectively. $Q_{c,i}^{max}$ shows the maximum allowed capacity which can be installed in i-th bus. $T_{i,k,j}$, T_i^{max} and T_i^{min} indicate the tap position of i-th transformer, maximum and minimum position of tap in i-th bus of the system respectively. It should be noted that tap position is a discontinuous variable. $\delta_{im,\min}$ and $\delta_{im,\max}$ are respectively minimum and maximum allowed of voltage angle difference between two side of transmission lines whereas $\delta_{i,j,k}$ is voltage angle on i-th bus in k-th operation mode. $S_{im,k,j}$ and $S_{im,k,\max}$ are apparent power and maximum allowed apparent power of transmission lines respectively. finally, $w_{contingency}$ is the set of contingency cases.

3.4 Taboo Search algorithm

Because of non linear nature of recommended formulation, there is no quick and accurate classical algorithm which can find a an optimum answer to the problem. So, in this article we have used the Taboo search algorithm as an intelligent search algorithm to solve capacitor placement problem. This method can find optimum solution in a reasonable time. In addition, this method doesn't need too many repetitions to find solution and the final answer does not depend on initial guess. Because of these advantages the application of Taboo search method has been increased in power system studies since 1999. The number of neighbourhoods around the initial guess, movements and jumps are fundamental factors which must be determined depending on the problem scale.

4. Case Study

Esfahan Regional Electric Company (EREC) is located in the center of Iran, and its territory consists of Esfahan and Chaharmahal-Baktiyary provinces with 30 counties,60 district,122 cities,151 rural districts and 3395 villages. At this point EREC generating 11.6% of electrical energy and its subscribers consume about 10.81% of country's electrical energy. The total consumers in this zone are reaching 2.1 million, and its load at the peak of summer 2012 has been 3940 MW.

According to our surveys, the peak load in 2017 will be about 7237 MW for active and 2416 MVAR reactive power. Furthermore, active power generation of Esfahan's power plants will be about 6535 MW where losses in Esfahan power system will be about 114 MW. Expansion planning centre expect having more than 250 transmission and sub transmission substations in 2017.

5. Numerical Results

In order to evaluate voltage stability indexes, it is necessary to divide the power system into separate zones. This dividing is done based on some fundamental ideas as bellow:

- each 400 KV and 230 KV transmission buses are considered as head of one zone.
- local power plants and environs buses in sub-transmission level are also considered as head of an zone.

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- since sub transmission network has a convoluted structure, each substation may be placed in more than one zone. In this case, the zone of the substation is determined by comparing the injected power amount from different zones.

Considering above considerations, Esfahan power system was divided to 27 zones. Then, VS studies and OPC were done which we report them in following paragraphs.

5.1 Voltage stability indexes before OCP

Voltage stability studies have been performed on Esfahan power system based on instructions. As an example, study results of 12th zone in peak load condition has been presented in Fig. 1.

In this figure, T1 and T2 are indicators of first and second snapshot. C1 and C2 are indicators of voltage stability margin and static security margin respectively. All indexes are in MW. As it can be seen in Fig. 1, calculations have been done for normal and N-1 contingency conditions for all lines and transformers in this zone.

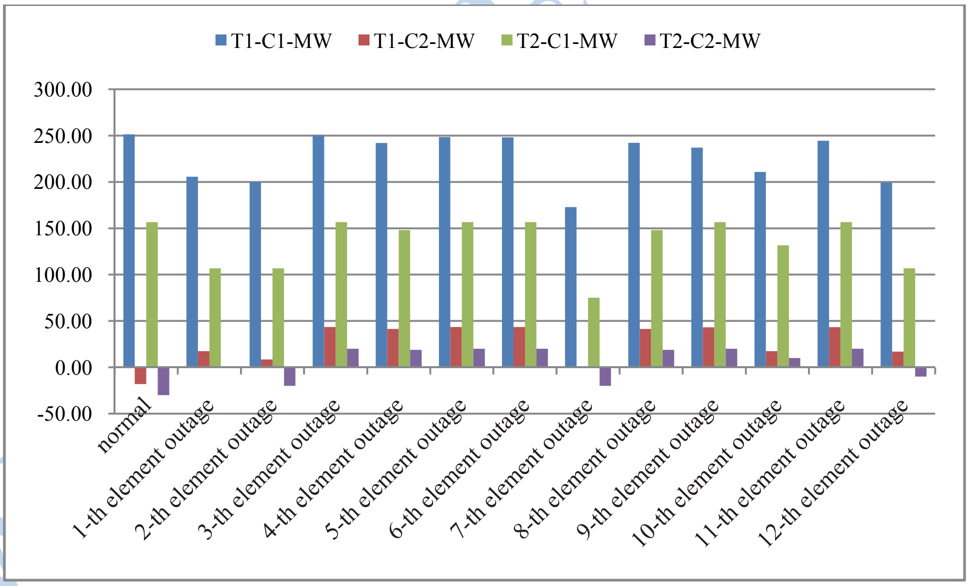

Fig. 1: Voltage stability results of the 12th zone

The evaluation of VS indexes for all zones have been done similarly. Results showed that voltage stability margin was desirable in all zones but from system's static margin view, 19 zones did not satisfy the Static Security Margin (SM^{Static} were less than 0) which it means that in the normal condition and N-1 contingencies, voltage profile is

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out of its allowed rage. Fig. 2 shows the voltage magnitude in p.u for substations of Esfahan power system.

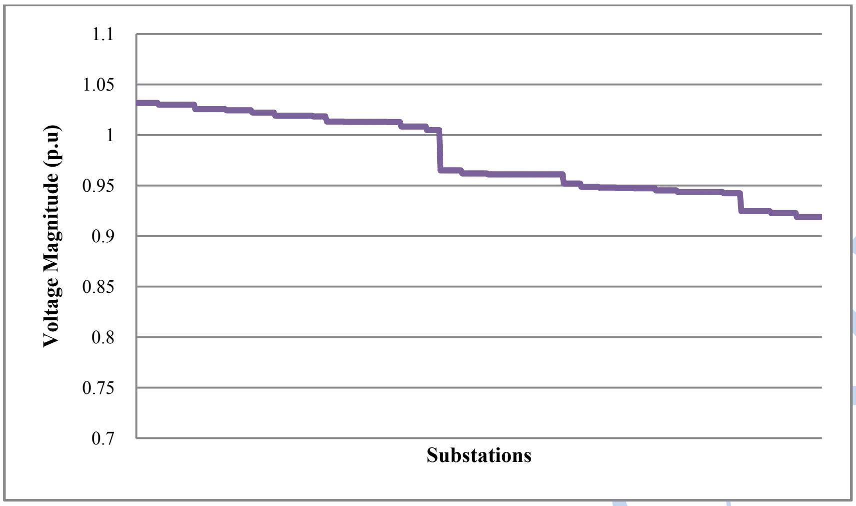

Fig. 2: voltage magnitude for substations of Esfahan power system before OCP

As can be seen from the line graph, voltage magnitude is less than 0.95 p.u in some substations, therefore, an OPC is needed to improve the voltage profile in 2017.

5.2 candidate buses determination and OPC solution

According to the section 3.2, candidate buses for all zones were determined. Then appropriate weighting factors were estimated and OPC problem was solved using Taboo search algorithm. Fig. 3 shows the optimal solution procedure for objective function using Taboo search algorithm.

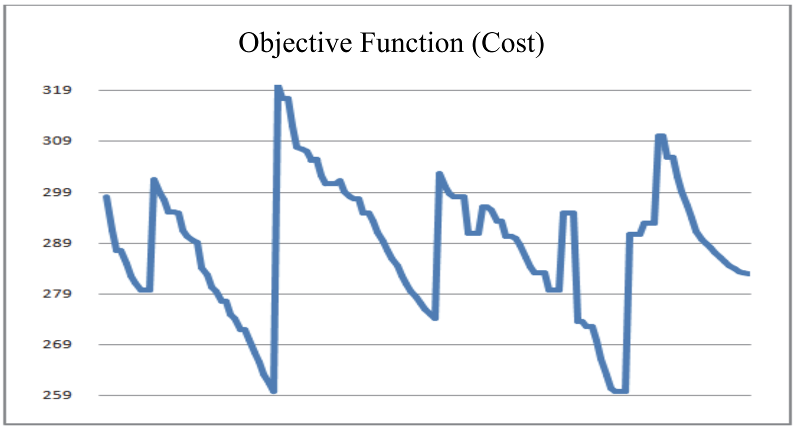

Fig. 3 : Taboo search results to find the optimum solution

TABLE I shows candidate buses and also their devoted capacities respectively, Since each step of capacitors in Esfahan power system is 2.7 MVAR, determined sizes have been rounded to actual values which are multiples of 2.7.

TABLE I: Candidate buses and devoted capacities

Number	Zone	Substation	Devoted Capacity (MVAR)	Number	Zone	Substation	Devoted Capacity (MVAR)
1	E1	SE1001	0	16	E6	SE6009	5.4
2	E1	SE1008	0	17	E7	SE7007	16.2
3	E3	SE3009	18.9	18	E7	SE7012	5.4
4	E3	SE3012	13.5	19	E9	SE9002	10.8
5	E3	SE3014	8.1	20	E11	SE11006	8.1
6	E3	SE3017	0	21	E14	SE14014	0
7	E3	SE30019	13.5	22	E14	SE14015	10.8
8	E3	SE30023	8.1	23	E17	SE17013	0
9	E3	SE30027	0	24	E19	SE19007	16.2
10	E3	SE30032	10.8	25	E20	SE20001	13.5
11	E5	SE50062	0	26	E23	SE23036	0
12	E5	SE50067	13.5	27	E24	SE24082	16.2
13	E5	SE50083	0	28	E25	SE25082	21.6
14	E5	SE50092	0	29	E25	SE25096	10.8
15	E5	SE50098	0	30	E28	SE28003	0

As can be seen in this Table, 30 substations were introduced as candidate buses while only 18 buses of this set were selected to install capacitors. Totally, 221.4 MVAR capacitor capacity were devoted to 15 zones.

5-3 Voltage stability indexes after OCP

After installing capacitors in selected substations, VS studies were repeated and their results have been reported in TABLE II for zones that did not satisfy desirable values of VS indexes before capacitors placement. So, this Table reports static security margin in mentioned zones.

TABLE II: Static security margin before and after OCP

Number	Zone	SM^{Static} (%) Before OCP	SM^{Static} (%) After OCP	Number	Zone	SM^{Static} (%) Before OCP	SM^{Static} (%) After OCP
1	E1	-7.79	9.87	11	E14	-7.17	5.06
2	E3	-34.29	8.83	12	E17	-8.81	15.04
3	E4	-5.86	13.33	13	E19	-41.38	15.32
4	E5	-13.8	14.63	14	E19	-7.9	17.43
5	E6	-7.42	6.2	15	E20	-22.56	21.84
6	E6	-12.07	15.81	16	E22	-9.53	11.02
7	E7	-8.66	15.39	17	E23	-8.08	9.7
8	E9	-10.12	12.06	18	E25	-21.63	16.21
9	E12	-7.9	7.42	19	E26	-14.62	12.02
10	E14	-10.92	17.54				

Negative value of $SM^{Static}(\%)$ means that voltage of buses or equipments loading have been out of their allowed ranges before stating VS studies in reported zones. As can be seen in Table II, $SM^{Static}(\%)$ has been increased significantly after OCP.

5.4 Voltage profile improvement and losses reduction after capacitor placement

Fig. 4 shows the voltage magnitude in p.u for substations of Esfahan power system before and after the OCP.

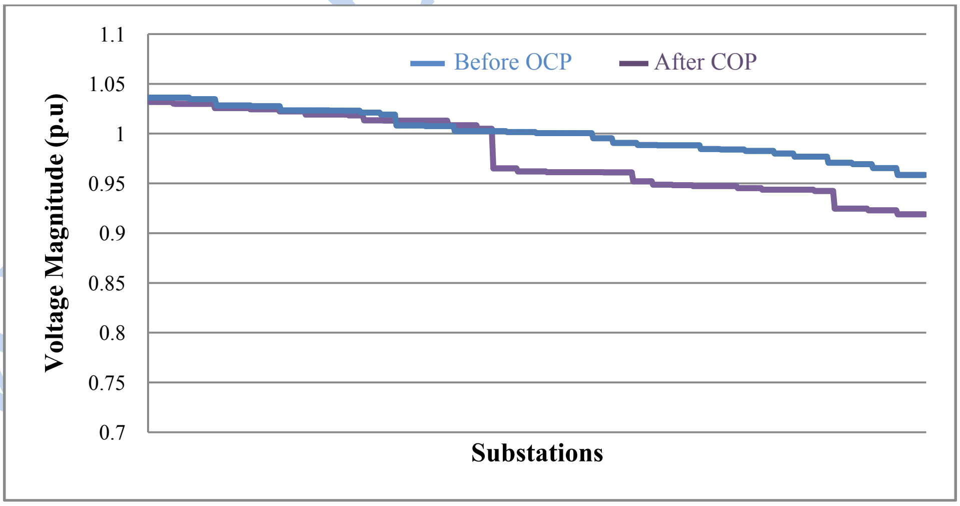

Fig. 4: voltage magnitude for substations of Esfahan power system before and after the OCP

It is crystal clear that voltage profile has improved after OCP and all substations are in the acceptable range. Furthermore, Fig. 5 shows that system losses have decreased about 8.3% after OCP.

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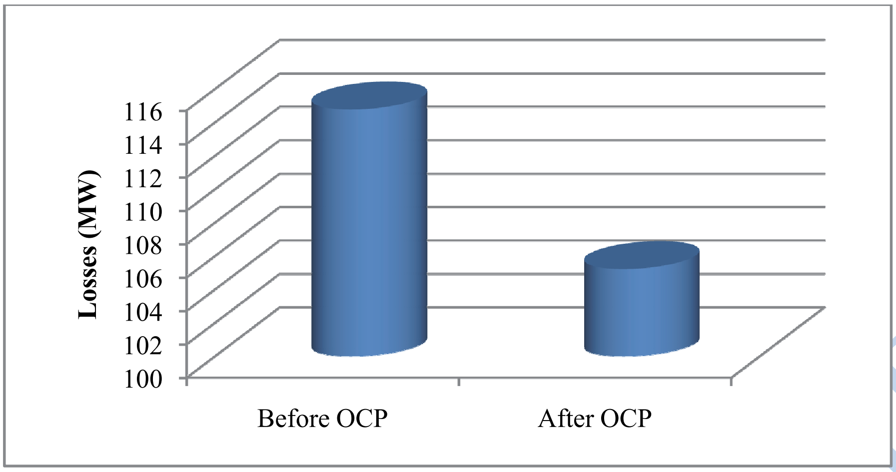

Fig. 5: System Losses before and after OCP

6. Conclusion

According to the results of voltage stability and studies, it is necessary to install 221.4 MVAR capacitor capacity in specific substations which are reported in Table I in order to improve voltage stability and static security margin of ESFAHAN power system and also decreasing system losses through an optimal capacitor placement method which has been introduced in this report to minimize costs and consider all technical and operational constraints and limitations.