Evaluation of Requirements for Volt/Var Control Implementation in Transmission Grid

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Evaluation of Requirements for Volt/Var Control Implementation in Transmission Grid

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***Abstract*—The objective of the Volt Var Control (VVC) function is maintaining system voltage within predefined limits and minimizing system active power losses by controlling reactive power flow. The main focus of this paper is to review and evaluate the technical requirements to implement a centralized VVC function within an existing SCADA/EMS system in a transmission system operator. The paper focuses on the implementation of a centralized VVC function. The function is based on an optimal power flow algorithm with input from the state estimation function and output to the SCADA control functions. The challenges of the implementation are related to the limitations of the existing network model and mathematical modelling of network elements, input data, measurement quality and state estimation output reliability. The paper presents some of modification in the network model and EMS (Energy Management System) functions that will improve quality of VVC results.**

Keywords—Volt Var Control, Optimal Power Flow, voltage regulation, reactive power

I. Introduction

The Croatian transmission system operator is in the process of integration of a VVC (Volt VAr Control) function for voltage and reactive power regulation. The necessity for implementing a VVC function is caused by high voltages in the 220 and 400 kV transmission network. The characteristic of the power system network is the high ratio between daily maximum and minimum consumption [1]. This causes the high fluctuation of the voltages during the day and night. Recently, increased voltage values in the grid have been recognised during several periods in the year, which are cyclically repeating. Each of the recognised periods is different and distinctive. The periods of highest voltages in the Croatian transmission system occur twice in a year, in the late spring and early autumn. These are two periods when the daily energy consumption was at the lowest and the voltages were very high. Also, during holiday periods which last several days (when energy consumption is significantly lower) voltages at network nodes reached the highest annual values [2]. One additional non-electric variable, which has an impact on voltage values, is the air temperature. The nodes in which the highest voltage values have been reached are located in the southern part of the Croatian power system where reduction of high voltage values is difficult. The period, in which is particularly unfavourable lowering the high voltage is the dry period of the year when the energy generation of the southern part of the system is minimal. During the period of high daily energy imports, voltage regulation becomes a much more complex issue.

For this reason, the implementation of an automatic function for voltage regulation is a necessity for optimization of reactive power and lowering the high voltages in the system. The basic algorithm of the VVC function is the optimization algorithm of the OPF (Optimal Power Flow) function based on the interior point method. The execution of the VVC output (tap positions and reactive power setpoints) will be executed by the SCADA (Supervisory Control and Data Acquisition) function.

The VVC function will be implemented for controlling transformer and the VSR (variable shunt reactor) tap position, the reactive power output of generator units and SVC (static VAr compensator) that will contribute in voltage and reactive power regulation [3].

The objective function of the algorithm is the minimization of active power losses, while complying with the predefined constraints, for example, voltage and branch flow limits. In a situation where the power system voltages are above the limits, the optimization algorithm will try to find a solution where the limits will be satisfied. In that case, the objective function of minimizing the losses may not be met, but the voltages and branch flows will be in their limits or at least closer to their limits.

The VVC function is a complex function, that combines EMS (Energy Management System) and SCADA functions. Unlike other EMS functions (for example contingency analysis or security constrained dispatch) VVC is an executive function. All control variables (tap positions, reactive power set point) that should be changed from its base case position to a newly calculated, optimal position, are controlled by the SCADA system in order to achieve the optimal state of the network.

VVC function as executive function has a direct impact to equipment in substations. Inaccurate input in VVC can cause

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a worst state of the power system, then, it was in the base case. Because of that, it is necessary to raise the quality of data that is used as input in the VVC. Accurate network model and calculations in the SCADA/EMS system are the basis for establishing VVC function. Before entering VVC function into operation, it is important to identify all necessary changes in the network model that should be done before entering VVC function into operation, in order to have more accurate power calculations.

In this paper will be presented some of changes and activity that should be done on the network model in the SCADA/EMS system before entering VVC function into operation.

II. Reqirements for Qouality of EMS Model for the Integration of Volt Var Control Function

A. *Network model*

The mathematical representation of a network submitted for optimization is of great importance for a high quality optimization result. The modelling of power system components must be as close as possible to real system components. All the discrepancies will result in deterioration of the optimization result and consequently can cause an unwanted state of the power system.

B. *State estimation*

The state estimation algorithm is responsible for determining the actual state of the power system. Based on the actual network model, available measurements, indication and topology, it estimates the value of the state vector [4] (flow diagram of state estimator is shown in the Fig. 1, [5] [6]). State estimation vector as output from state estimator, represent the current network state and it is used as input for all real time network applications (Volt VAr Control (VVC), Optimal Power Flow (OPF), Security Analysis (SA), Short Circuit Analysis (SCA), Security Constraint Dispatching (SCD), etc.).

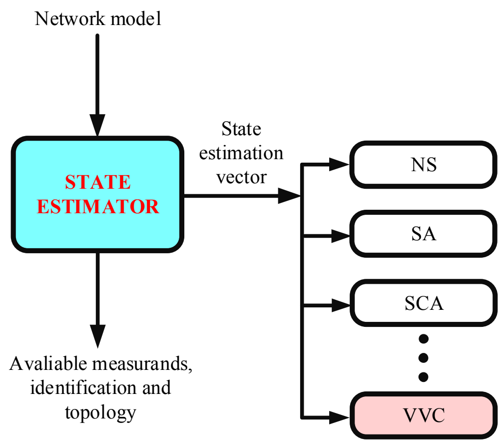

Fig. 1. Flow diagram of EMS functions

C. *State estimator convergence rate*

The state estimator program executes periodically in a predefined time interval. For example, this time interval can be set to a time interval of each minute. Performance data of the can be collected after each SE run, by the SE application, including times when SE fails to produce a valid solution. The time intervals when the SE fails to converge should be monitored, stored and analysed. A periodical SE convergence rate extract gives an overview of the global SE performance and indicates on possible issues,. An example of a monthly SE convergence rate is given in Fig. 2. The average monthly SE convergence rate for this SE program is 99.15 %. Lower SE convergence rates should be taken with caution if used for advanced calculations such as VVC function.

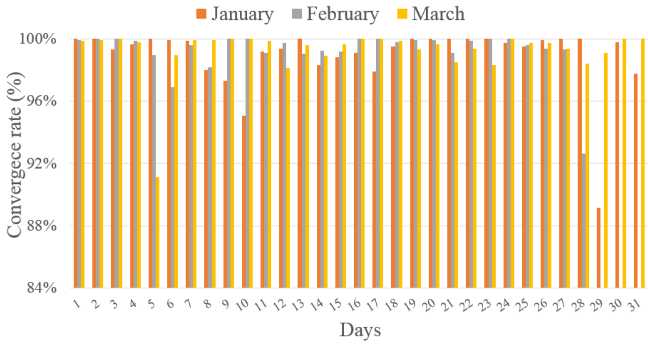

Fig. 2. Monthly SE convergence rate

However, the SE convergence rate varies during the day. Some hours in the day may be more prone to lower convergence rates than others. This may be caused due to maintenance in the power system (which causes erroneous measurements or switch statuses) or in the SCADA/EMS system (switchovers, population of the SCADA/EMS database etc.) which causes interruptions in the SE program. Usually this process occurs during business hours, which can be clearly seen in Fig. 3. The highest rate of non-converged SE runs coincide with the office hours.

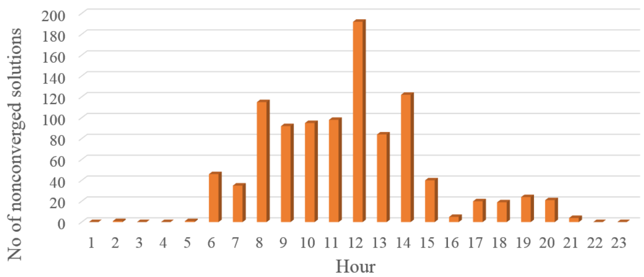

Fig. 3. SE convergence rate depending on hour

D. *State estimation quality indices*

State estimator reduces the impact of large errors and provides the best estimation of the current state of the power system. The VVC function requires accurate output from state estimator to perform calculations as accurate as possible. Errors in the base case solution will affect the results of the VVC function that will have an impact on the VVC control actions [7]. The question, which arises while implementing a VVC function, is how to assess the quality of the state estimation result, which will be the base case for the VVC algorithm? In literature, many measures are mentioned [8]. For example, a measure of complex power flow estimation accuracy can be calculated as [8]:

$$M_{PF} = \left(\sum_j \frac{\left|\vec{S}^{\,mea}_{j,from} - \vec{S}^{\,estim}_{j,from}\right| + \left|\vec{S}^{\,mea}_{j,to} - \vec{S}^{\,estim}_{j,to}\right|}{MVA_j^2} \right)^{\frac{1}{2}} \qquad (1)$$

where:

$\vec{S}_{j,from}^{mea}$ - complex measurement of apparent power in first point of the branch

$\vec{S}_{j,to}^{mea}$ - complex measurement of apparent power in second point of the branch

$\vec{S}_{j,from}^{estim}$ - complex value of estimated apparent power in first point of the branch

$\vec{S}_{j,to}^{estim}$ - complex value of estimated apparent power in second point of the branch

MVA_j - limit of the branch capacity

Another important task for state estimator is to estimate the voltage magnitude and the relative phase angles at the system nodes (state vector). The phasor voltage error can be calculated as [8]:

$$\left\|\vec{V}^{error}\right\|_2 = \left(\sum_j \left|\vec{V}_j^{mea} - \vec{V}_j^{estim}\right|^2\right)^{\frac{1}{2}} \tag{2}$$

where:

$\vec{V}_j^{mea}$ - measured complex phasor voltage at the j-th bus

$\vec{V}_j^{estim}$ - estimated complex phasor voltage at the j-th bus

If (1) and (2) returns low values, the estimated values match the system conditions, i.e., estimation of power flows, voltages and angles are accurate. The indices in (1) and (2) can be calculated in real time and give to the operator a warning in case of the deterioration of state estimation results.

State estimation quality test is performed for Croatian SE network model. The total number of estimation cycles was 10080 (for a period of 7 days while the estimation cycle period is 1 minute). The $\left\|\vec{V}^{error}\right\|_2$ is calculated for the 10 minute period (10 estimation cycles). Given a series of 10 estimation cycles which is a fixed subset size, the first element of the moving norm is obtained by taking the average of the initial fixed subset of the number series. Then the next norm value is calculated by the 'shifting forward' the subset; that is, excluding the first number of the series and including the next value in the subset.

A variation of the voltage error norm during a four day period for three different nodes is shown in Fig. 4. The norm varies depending on the part of the day, being lowest during daytime and highest during night hours. This can be explained with very high voltages in the transmission network during low loading periods.

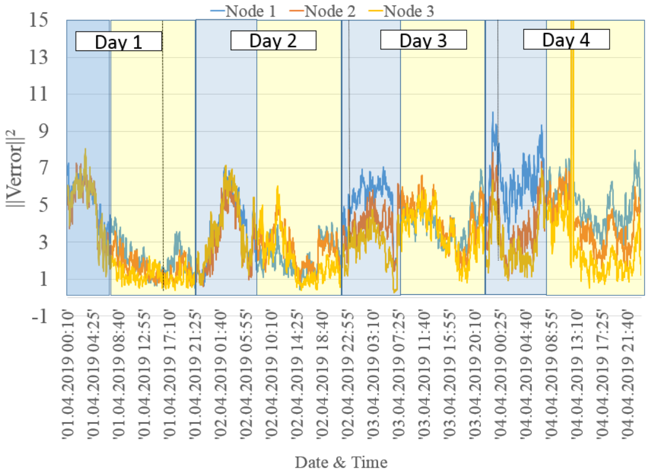

Fig. 4. Variation of the voltage error norm during four days period for three different nodes

The $\left\|\vec{V}^{error}\right\|_2$ norm as stated before varies during the day. Fig. 5 shows the density of the norm in dependence of the hour during the day for six different 400 kV nodes in the Croatian power system. The norm exceeds the predefined threshold for night hours, while during daytime the norm is below the threshold. The values of the norm in node 1 and node 6 exceeds the threshold more often than in other nodes. This is a good indication of possible error in the measurement (for example high dead bands). The total $\left\|\vec{V}^{error}\right\|_2$ for the entire 400 kV network is given in Fig. 6.

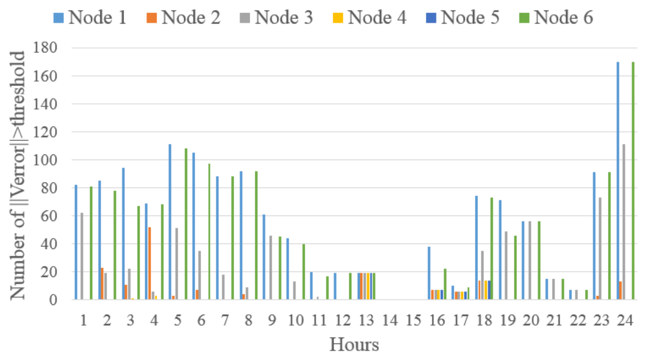

Fig. 5. Number of $\left\|\vec{V}^{error}\right\|_2$ norm threshold exceeded during day for 6 400 kV nodes

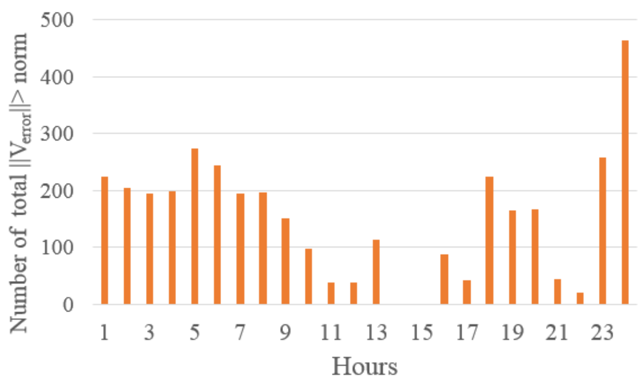

Fig. 6. Total umber of $\left\|\vec{V}^{error}\right\|_2$ norm threshold exceeded during day

E. *Input data to VVC function*

The VVC function calculates the control actions to improve the current system operating state and to optimize the operating state under user selected objective function. It is executed in the real-time frame. The VVC function interfaces with the state estimator function and the network model. Since the state estimator (SE) result is used as the base case for the optimization function, its accuracy is at most concern for the successful and secure operation of the VVC function. Accordingly, the network model, especially the model of the control variables (regulating elements and compensation devices) must be modelled in a way to fairly represent the real element.

F. *Tap changer estimation*

The challenge of the tap changer estimation process can be categorized as the problem of the tap changer modelling and the tap changer estimation process.

The estimation of a tap changer position is an estimation of a network parameter (rather than a measurement). For the tap position estimation, several conditions have to be met [9], [10]:

- At least one side of the power transformer should have power measurement,
- The transformer regulated bus must have a voltage measurement
- The transformer branch has to be observable in the state estimation.

If all the above requirements are met, the tap changer position can be estimated. The estimation of the tap changer position tries to find "best fit" position, unlike estimation of other measurements (voltage, current, power, etc.) which estimate a discrete value. Finding the "best fit" solution may potentially make an inaccurate estimation and one or several nearby measurements can be wrongly identified as bad data. It is necessary to properly assess whether to estimate the tap position or take the measurement value of tap position as accurate value.

The other challenge facing the tap changer estimation problem is the modelling of the tap changer characteristic. Tap changer characteristic can be linear and non-linear. Some commercially available SE algorithms support only linear characteristic in which case the estimation of the tap position for a non-linear tap changer may be inaccurate. Fig. 7 shows a possible inaccurate estimation of tap changer position.

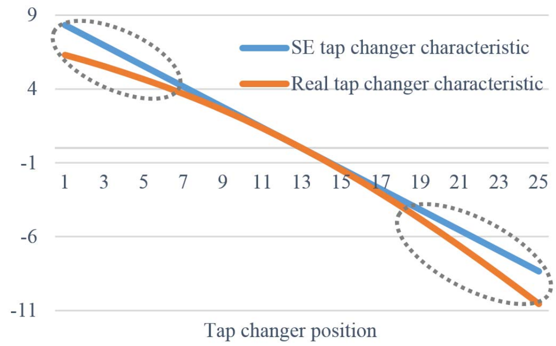

Fig. 7. Example of inaccurate SE tap changer characteristic

In case from Fig. 7, where the non-linear characteristic is linearized in the network model, the estimation of tap changer position is inaccurate if the tap is at the highest or lowest positions (the rounded parts of the characteristic). For such cases, a recommendation would be to use the tap position measured value rather than estimated, for the VVC input.

G. *Voltage estimation*

For establishing VVC function, it is necessary to have accurate input of voltage measurements into VVC function. VVC calculations based on inaccurate voltage measurements can cause the worst state of power network, then it was in initial case. To avoid that situation, it is necessary to identify all bad voltage measurements.

Voltage measurements with high set dead bands (high difference between two measurements), like is shown in Fig. 8, should be identified as bad measurement. This kind of measurements with high dead bands should be periodically telemetered, for example, every 10 seconds or every minute, or if this is not possible, then this measurement should be excluded from EMS. Difference between measured and estimated value from Fig. 8, increases the error of state estimation vector and should be fixed before entering VVC function into operation.

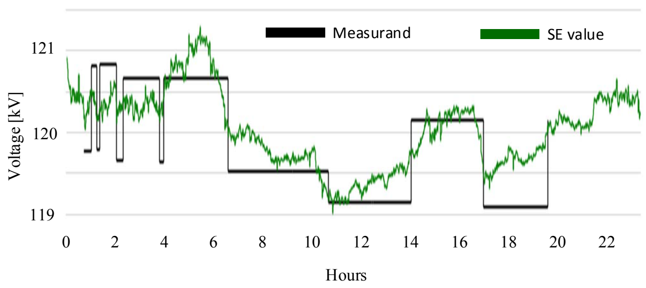

Fig. 8. Example of inaccurate SE tap changer characteristic

H. *Wind power generator units modelling*

Wind power generator units are connected to the transmission network through power electronic devices and power transformers. In the EMS network model, a wind power plant is represented as one generator unit connected directly to transmission network, without a power transformer (i.e. without the power transformer at the PCC (Point of common connection)).

This way of modelling is implemented due to the regulated bus priorities. If both the transformer at the PCC and the WPP (Wind Power Plant) regulate the same bus (in the network model) there will be a conflict in the optimization algorithm and consequently in the VVC function. For this reason, the WPP is directly connected to the HV (high voltage) bus. Such way enables the VVC to control the voltage of the HV busbar by controlling the reactive power production of the WPP.

Fig. 9 shows the example of modelling a wind power plant connected to the transmission network with the power transformer at the PCC and without the power transformer.

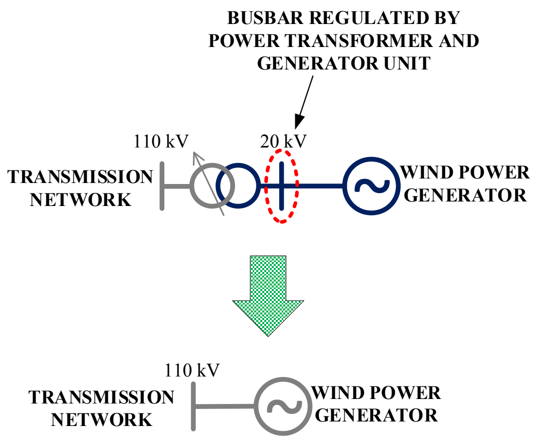

Fig. 9. Connection of wind power plant to the transmission network: with power transformer and directly, without power transformer

I. Monitoring of power calculation quality

Assessing the quality of the network model, measurement values and state estimation accuracy is most important for successful implementation of control actions through a VVC algorithm. The network model should be periodically checked and updated in order to have all parameters aligned with the real situation in the system. Also, it is necessary to identify all bad measurements that increase the total error of power calculations. One way of checking the quality of power calculations is to create reports from the EMS system from which the user can quickly assess the quality of the power calculation. These reports show the quality of the power calculations for the selected time and may indicate bad measurements, loss of communication with substations or wrong parameters in the network model. A case of a high increase of bad measurements is shown in Fig 10. It represents the SE quality report for a 24 hour period (power calculations in this case runs cyclically every minute), with a calculated total error of active power (blue line), total error of reactive power (purple line), number of unobservable stations (orange line) and the number of bad measurements (red line). The bad measurement trend and the total active power trend have an increasing path after the loss of the communication link with a part of the external network, which occurred in the SCADA system. The communication interruption lasted for several hours, which caused an increase in the number of bad measurements.

III. Volt VAR Control Output Constraints

The core algorithm of VVC function related to EMS system is OPF function [6]. The difference is that VVC function has an additional option for sending commands to the equipment in the substations. The main function of the VVC is to find the optimal solution with respect to the selected objective function and all constrains.

Fig. 11 represent the flow diagram of VVC function. Input data in VVC is state estimation vector from state estimator. Based on input data VVC function calculates optimal network state with respect to all constraints and selected objective function. Calculated results from VVC are voltage and reactive setpoints and control actions that should be performed to achieve a calculated optimal state of the power system.

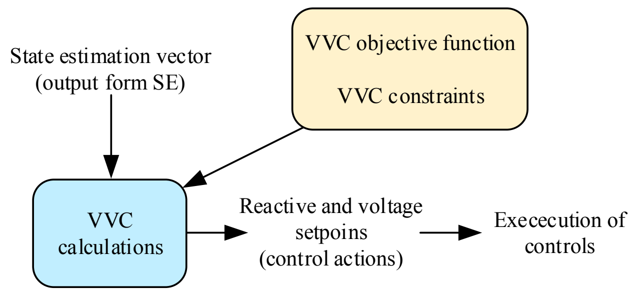

Fig. 11. VVC Flow diagram

Based on calculated data and depending on the VVC operation mode, commands are sent to equipment in substation manually or automatically. For automatic sending of commands, besides accurate calculations, it is necessary properly set output constraints, especially tap changer positions and generator reactive power output.

In Fig. 12, blue line represents OPF / VVC output for tap changer position. Such frequent changing tap changer position (around 400 times per day) is not acceptable for tap changer and should be limited, for example, maximum 10 - 15 times per day and no more than one tap position up or down per cycle due to conserve equipment lifetime, (red blocks in the Fig.12 represent VVC output constraints).

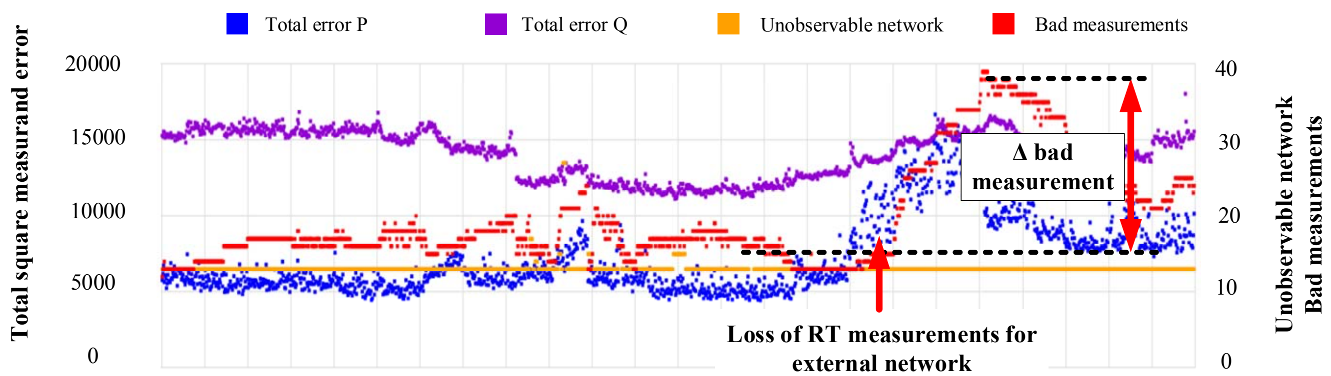

Fig. 10. Example of SE quality daily report

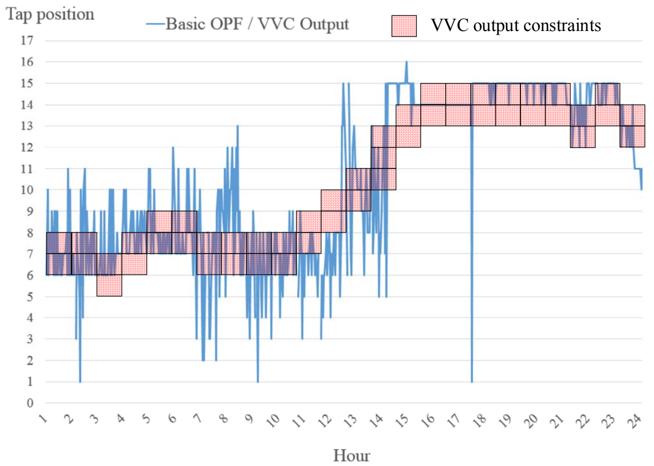

Fig. 12. VVC / OPF output for tap changer position and VVC output constraints

The limit for generator reactive power output is defined by the capability curve of generator (P-Q diagram). If some generator contributes only in the obligatory range of reactive power regulation, (for Croatian transmission system that range is power factor ±0.95) [11] then original capability curve has to be limited to obligatory range. In the Fig. 13 is shown original capability curve of generator (blue line) and limited capability curve for an obligatory range of reactive power regulation (red line).

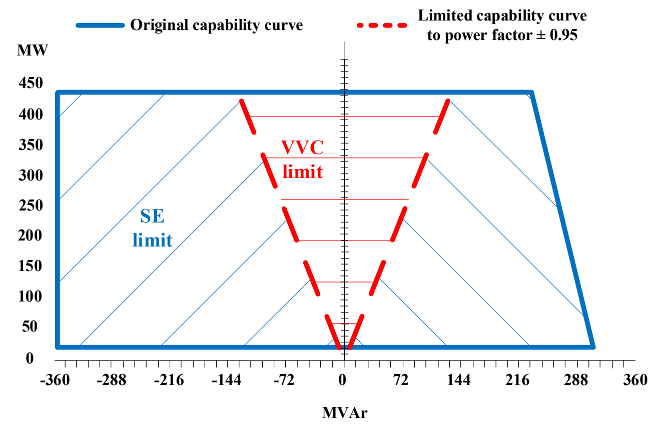

Fig. 13. Original (SE) and limited (VVC) capability curve of generator

Limited capability curve from Fig. 13 is an example of capability curve that can be used in VVC for generators that contribute only in the obligatory range of voltage and reactive power regulation (power factor ±0.95). An original capability curve can be used in VVC for generators that contribute with all their reactive power output capabilities.

CONSLUSION

For establishing a VVC function, it is necessary to make some pre-steps that include the modifications in the network model to comply with the VVC algorithm. VVC results, which contain the optimal position of tap changers are reactive power outputs of the generators and compensating devices, are sent through the SCADA system to the element in the transmission network. It is necessary for the VVC function to have accurate power calculations in the EMS system. A single wrongly calculated value sent to the element in the system may cause an unwanted state of the transmission network. It is of great importance to monitor EMS quality reports on a regular basis and fix all defections timely.

Also, it is very important to properly set constraints to VVC output. Uncontrolled output, besides unwanted network state may cause the damage of equipment in the transmission network.

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