Condition for Establishing Voltage Var Control Function Considering Quality of Input Data

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***Abstract*— establishing a complex function in real time operation such as the Volt Var control (VVC) function requires addressing some of the challenges related to quality of input data (measurements and estimated values). The paper deals with the topic of real time calculation in SCADA/EMS system for automatic regulation of voltage and reactive power in the transmission system. The paper addresses issues of measurement quality and their estimated values as input values for advanced network applications such as the Volt Var control function. Performance state estimation indices are presented for real time assessment of state estimation quality as well as other requirements for measurement quality for the establishment of VVC function.**

Index Terms*— State Estimation, Stete Estimator, measurement, Voltage regulation, Optimal Power Flow, Voltage Var Control

I. Introduction

The basic real time calculation in an Energy Management System (EMS) is the state estimation function. All other network applications in the EMS use the estimation state vector as input for their algorithms. Automatic voltage and reactive power control is one of the advanced real time network application which uses state estimator results as input for voltage and reactive setpoint calculations. Since the Volt Var control (VVC) function operates in an automatic operational mode in closed loop with direct impact to substation equipment, it is necessary to raise the quality of state estimation results to a higher level. The VVC calculations have a direct impact on the voltage and reactive power in the system and these calculations must be accurate.

II. State Estimator as a Part of SCADA System

The state estimation function is responsible for determining the actual state of the power network based on the current network model, available measurements and network topology. It provides a real time estimate of the steady state of the entire power system network. In figure 1 is shown an overview diagram of state estimation functions in ABB Network Manager SCADA system.

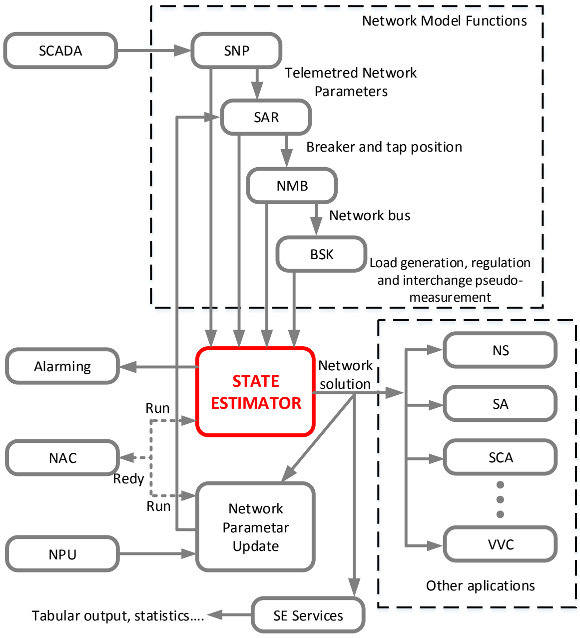

Fig. 1. Overview diagram of state estimation applications in ABB Network Manager SCADA system [1]

From Figure 1 the state estimation process consists of several functions that precede the state estimation process, and functions that follow the state estimation algorithm. The Network model functions build the network model and acquire measurement and topology data from the SCADA system. These functions are (from figure 1) the SNP (Telemetry snapshot) and SAR (Status and analog retrieval) functions which acquire real time measurement and breaker and switches positions from the SCADA system. These functions are followed by the NMB (Network Model Builder) function which creates the topological model of the network based on telemetry data and static data of the network and finally the BSK (Bus scheduler) function which acquires all the pseudomesurements for all measuring points which weren't available at the time of the snapshot due to telemetry failure or such. With all these functions correctly executed, the SE calculation is triggered. Some of the functions that follow the SE algorithm are the advanced real time calculations for power system secure operation and optimal performance. These are the SA (Security Analysis) function, SCA (Short Circuit Analysis), NS (Network Sensitivity) and VVC (Volt Var Control) function.

The SE function is periodically triggered (usually once in a minute) or triggered by an event in the system. One task of State Estimator (SE) is to identify and reject bad or incorrect measurements and replace them with the estimated values. Also, task is to identify possible topology errors. Every measurement detected as erroneous is shown in the SE reports. These reports are a quick way of pointing to an incorrect or suspicious measurement or topology statuses that should be additionally checked. The most common reason for replacing the measured value with SE values is an incorrect switching state (topology error) and a large measurement dead band. Rarely the reason of a measurement replacement with SE value can be the defected measuring device or inaccurate network model parameter. An example of SE report of invalid measurements in a real time SCADA/EMS system is shown in Table 1.

TABLE I. EXAMPLE OF STATE ESTIMATOR REPORT OF INVALID MEASUREMENTS

Station	Measurement ID	Type		Meas. value	Estim. value	NO of detects
TREBI	TREBI 220TR1	2X	MW	74,9	116,8	86
PECSO	PECSO 400TR2	3X	MVAR	60,9	-53,1	118
TOPN	TOPN 400TR2	3X	MVAR	59,4	-47	118
GYOR	GYOR 400TR4	3X	MW	-130,8	-261,3	118
GYOR	GYOR 400TR4	3X	MVAR	-11,6	-59,3	118
HEPE	HEPE 220TR1	2X	MW	80,2	-19,8	118
HEPE	HEPE 220TR1	2X	MVAR	5,2	-22,7	118

III. VOLT-VAR CONTROL IN SCADA SYSTEM

Volt-Var control (VVC) function is an integral part of the SCADA/EMS system. It calculates the control actions for improving the security level or optimization of the current system state by user selected objective function. The input to the VVC calculation is the state vector from the SE function. The VVC function goal is achieving an optimal state in the power system with respect to voltage and reactive power. This is achieved by minimizing the defined objective function (for example minimization of active losses or security constrained dispatch) respecting all defined constraints such as voltage and current limits, maximal number of tap changer shifts, power factor of generators, etc.

Unlike other EMS functions (for example contingency analysis or security constrained dispatch) VVC is an executive function, i.e. all control variables that should be moved from its base case point are controlled and sent to the substations from the SCADA system in order to achieve the calculated optimal state of the network. The VVC function can be considered as a link between EMS and SCADA functions. The executive controls are calculated in the EMS systems and sent to all units in transmission network (transformers, generators, static var compensator, battery in the system and similar) from the SCADA system.

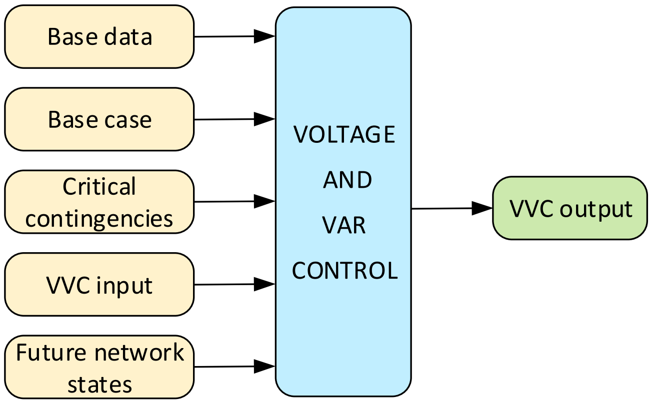

Fig. 2. VVC overview diagram [4]

In Fig. 2 is graphically shown major functions and data flows of VVC function. The input data for VVC are:

- Base data – contains system structure and network equipment parameters
- Base case – contains the base case network model and solution
- Critical contingencies – contains the most severe contingency cases from security analysis
- VVC input – contains the control and constraint data set edited by operator

After VVC calculation that take into consideration all above-mentioned inputs, VVC output is generated.

The core algorithm of the VVC function related to the EMS system is the optimal power flow function (OPF).

Due to the complexity of the OPF function, accurate operation of all functions preceding the OPF function is necessary for the correct operation of VVC. This means that the SE function in each cycle has to be correct and precise.

The intended use of the SE result must be considered when defining the criteria for accuracy metrics. The state estimator is required to as closely as possible represents the current condition of the network, indicate actual and near violations without triggering alarms for false positives.

The following paragraphs will present the state estimation function and its quality assessment through some examples from real measurements. The quality assessment is performed by identifying key indices which quantify the state estimation output quality required for establishing the VVC function in a TSO.

IV. STATE ESTIMATION QUALITY ASSESSMENT

Due to the inability to know the actual conditions of a power system, it is very difficult to judge the accuracy of the state estimator in real time operation. Nevertheless, what can be determined in real time operation is whether the SE result satisfies condition to be a power flow solution or if the SE state vector accurately fits the measurement model. This can be achieved through performance index calculation.

One of the key SE functions for the exact operation of the VVC function is the tap changer position estimation function. This function differs from other SE function since it estimates the state of a power system parameter. Erroneous operation might lead to erroneous OPF results and consequently to wrong operation of control actions. Similarly, estimating bus voltage values and generator reactive power output are other key values necessary for correct operation of VVC function, which will be elaborated in this paper.

A. *State estimation performance evaluation* [5]

The value of the state estimation objective function *J* at each iteration cycle determines the measure how the estimated model, i.e. the estimated state vector fits the measurement model.[5] This is a global index of the performance of the state estimator function. Deterioration of the value in real time operation might refer the estimated model does not fit the measurements. It doesn't give the value of how far the estimated value is from the measurement model.[5] For this purpose the convergence rate index can be used, i.e. the relative change of the objective function between two consecutive estimation cycles as shown in equation:

$$Mconv_{obj} = \left|1 - \frac{J^k}{J^{k-1}}\right| \quad [5] \qquad (1)$$

where, *J* shows how estimation solution fits to the measurements and *k* is the number of iteration.

(1) represent the relative change in the value of the objective function at the k^{th} iteration, evaluating its ability to converge [4].

B. *Estimation of tap changer position*

The state estimation algorithm can handle complex transformer ratios which have voltage taps, phase shift or both. These transformers are able to control voltage, active and reactive power flow at the same time. For the SE function, it has to be defined whether the transformer tap position should be estimated or not. If the tap position is monitored and the tap controller is active the position should be estimated. If this option is chosen, then the estimated tap position will be the input for the VVC function and high accuracy is necessary. Erroneous estimation of tap changer position in the SE process results in incorrect identification of one or several measurements as bad data. Each transformer tap estimation error can cause unwanted state in the transmission system if VVC sends command to the tap changer that is based on wrong estimated value.

Figure 3. shows the values of the estimated and measured tap positions of a transformer during 48h.

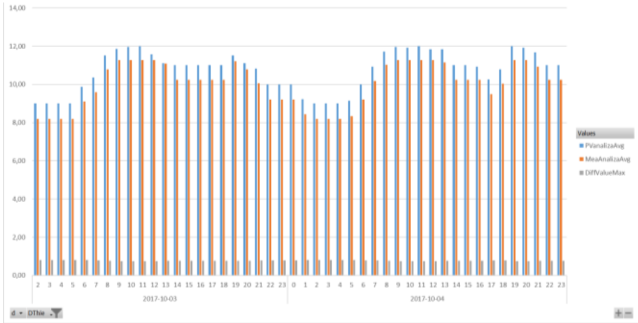

Fig. 3. Value of tap changer position and measured value

From figure 3 it can be seen that for this period the estimated bad measured value of the tap changer has different values of one tap position. Such error should be addressed and identified on time to avoid the unwanted future situation.

C. *Quality of the OPF function results*

In the Figure 4 is shown the calculation of the OPF function for a tap changer position during one day, hourly average value of tap changer position and measured value of tap changer position [7].

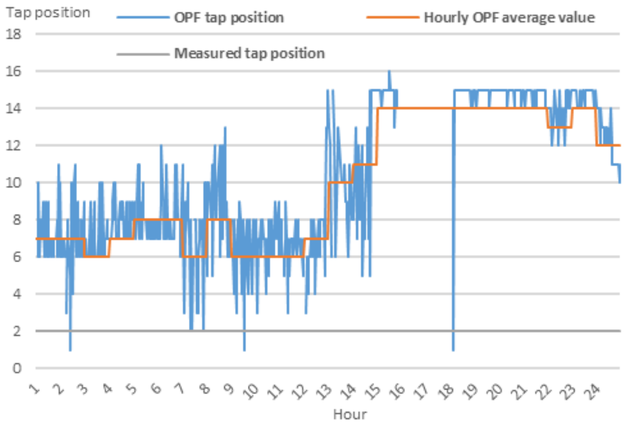

Fig. 4. OPF tap changer position, hourly average OPF value and measured value [7]

The optimal tap changer position from the example shown in figure 4 changes its value 390 times during one day (OPF function is cycled every 2 minutes). These commands should not be sent to a tap changer to conserve lifetime of the tap changer. The approximate number of tap changer operations is around 5000 times during the year. It is approximately 13 changing of tap changer position during the day. That number can be achieved if is calculated average value for every hour, like is shown in the figure 4.

A good option for preserving the lifetime of a tap changer is to use the day ahead reactive power generation and tap changer position plan. This option enables better usage of the reactive, active and passive elements in accordance with the daily consumption diagram. The curves for 24 hours of planned positions can be built ahead for weekkdays and weekends. That can be possible because of similarity of network state during working days and during the weekend.

In the figure 5 is shown tap changer position during weekdays and average value line [7].

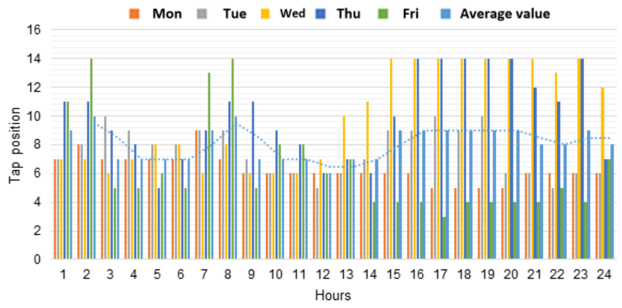

Fig. 5. Value of tap changer position during weekdays and average value line [7]

D. Estimation of generator reactive power

Since the generators as active elements have the possibility to improve the voltage state of the network with their reactive power, to achieve accurate estimation of generator reactive power, it is necessary to have accurate models of generators with correct P-Q diagram and all its constraints.

This type of estimation, as a part of VVC function should have the ability to adjust at least two types of limits, one by generator P-Q diagram and one by defined generator power factor. Limits by P-Q diagram are necessary for knowing all generator possibilities. Limit by generator power factor is necessary if some generators contribute in reactive power regulation only in an obligatory range of power. Due to network codes, generators are obligatory operate in the power factor range from -0.95 to 0.95 by request of the TSO.

E. Quality of voltage estimation related to power system modeling

The following tables show the results of analyzing quality of estimation of voltage measurements in the Croatian TSO. Percentage in the table present how many estimated values were within defined limits. The set limits were ±3 kV for 400 kV substations and ±2 kV for 220 kV substations from measured values.

TABLE II. QUALITY OF VOLTAGE ESTIMATION FOR 400 KV SUBSTATION

Substation	***Percentage of estimated values that are in range ±3 kV***
TS Ernestinovo	99,82 %
TS Tumbri	99,82 %
TS Žerjavinec	99,71 %
TS Melina	99,82 %
TS Velebit	99,17 %
TS Konjsko	99,60 %

TABLE III. QUALITY OF VOLTAGE ESTIMATION FOR 220 KV SUBSTATION

Substation	***Percentage of estimated values that are in range ±2 kV***
TS Đakovo	57,04 %
TS Mraclin	95,42 %
TS Melina	86,67 %
TS Pehlin	92,58 %
TS Zakučac	99,81 %
TS Plat	99,82 %

In the Table III is possible to see that estimation for substation TS Đakovo is not accurate. This is because this substation has two 220 kV tie lines to Bosnia and Herzegovina and estimation of reactive power for BiH network is not accurate because that part of the network is not modeled in the detail.

For a more accurate voltage estimation, it is necessary to identify bad voltage measurement in the system. One type of bad voltage measurement are measurement with big average difference between two measurements. i.e. measurements with set dead bands. A dead band (neutral zone or dead zone) is a band of input values where the output is zero (no action occurs). One of the main reasons for setting dead bands is to prevent measurement oscillation or repeated activation-deactivation cycles. The example of voltage measurement with set dead zones and their estimated values is shown in Figure 6.

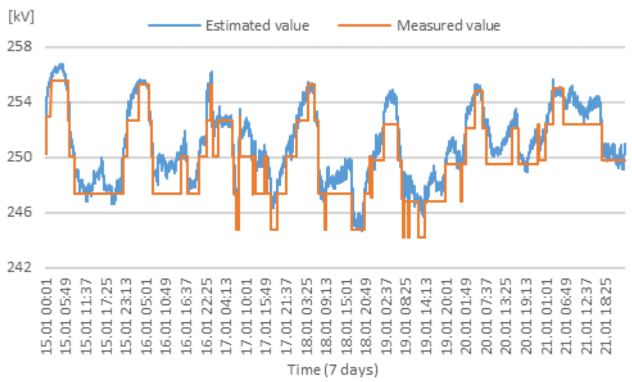

Fig. 6. Example of voltage measurement with set dead zones and their estimated values in 220 kV substation during 7 days

Estimated value line in Figure 6 is a good indicator of the accurate operation of SE that assumes the correct value of voltage.

In some cases, voltage measurement without set dead bands also can be wrong. One example is shown in Fig. 7, where one busbar section voltage differs from other busbar section voltage measurement, although they are connected together.

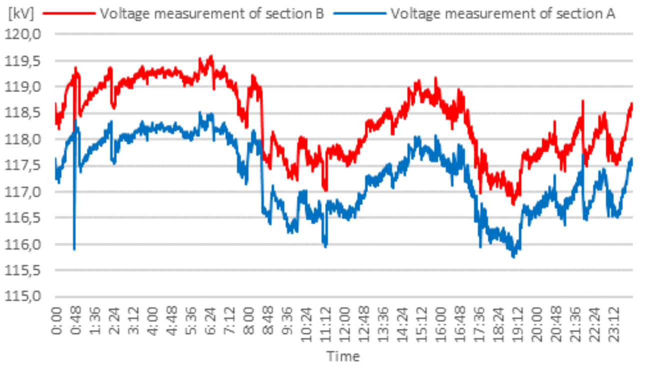

Fig. 7. 24 hours graphs of two connected busbar section voltage measurement

Example from Fig.7 shows constant offset of 1 kV for one busbar section voltage measurement. From single line diagram is very difficult to recognize which measurement is wrong. In that case it is necessary to observe the wider network area and voltages in nearby stations to find out which measurement is wrong. In Fig 8. is shown nearby network area where is easy to recognize wrong voltage measurement. In this case wrong voltage measurement differs from the other section voltage and from voltage measurements in nearby substations.

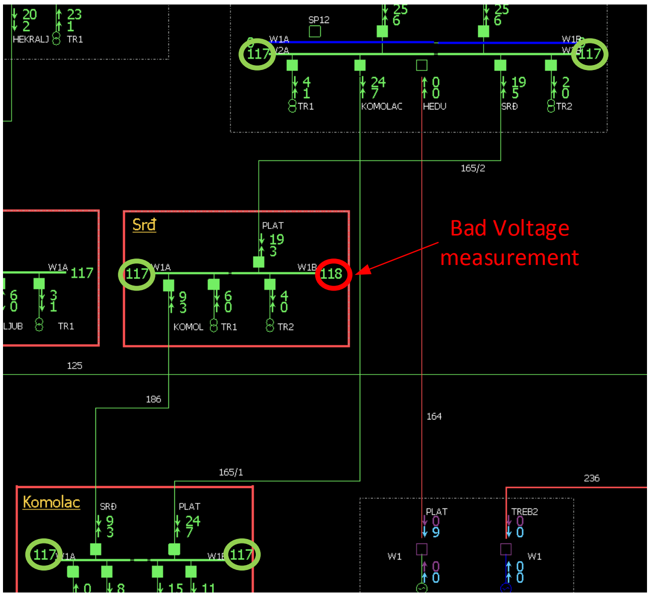

Fig. 8. Network scheme with green marked accurate voltage measurements and red marked wrong voltage measurement.

Voltage measurement from example shown in Fig 7. and Fig. 8 should be excluded from SE calculations.

F. *Deviation of estimated state variables from real values*

One of the performance indices, which quantifies the accuracy of the state vector (voltage magnitudes and angles) which can be calculated in real time is:

$$Macc_V = \left|\vec{V}^{error}\right|_2 = \left(\sum_j \left|\vec{V}_j^{true} - \vec{V}_j^{est}\right|^2\right)^{\frac{1}{2}} \quad [5] \qquad (2)$$

where: V_j^{true} represent the real voltage vector and V_j^{est} represent estimated voltage vector.

(2) indicates the deviations of estimated state variables (in this case voltage vector) from real values [5]

Due to (2) for the Croatian TSO EMS model was performed calculations of deviation estimated voltage vector from real values. The square difference between estimated voltage vector and real values calculated as:

$$\left|\vec{V}_j^{true} - \vec{V}_j^{est}\right|^2 \qquad (3)$$

is shown in Fig. 9 through histogram. In histograms is ploted the frequency of result occurence, divided into classes (bins) from 0.000001 to 0.01.

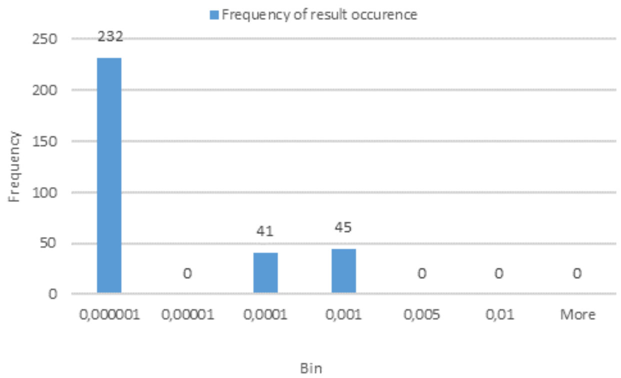

Fig. 9. Frequency of result occuren for nodes Croatian TSO EMS model calculated from (3) (the square difference between estimated voltage vector and real values)

Out of total 318 nodes, 211 is in Croatia and 107 is in the rest of modeled network. The total deviation of estimated voltage vectors calculated from (2) is 0.1126.

Result from Fig. 9 and total deviations of estimated voltage vector in the amount of 0.1126 showing very high accuracy of estimated voltage magnitudes and angles.

G. *Improvement the qouality of state estimation*

As mentioned before, improving the quality of state estimation is necessary condition for establishing the VVC function. This improvement relates to state estimator parameter adjustment and network model improvement. Those things can be done by continuously monitoring state estimator reports. Big anomalies can be detected by online monitoring of state estimator reports, that is shown in the table 1, and some smaller anomalies, that are not constantly present can be detected by monitoring daily state estimator reports in which is possible to see how long the state estimation was incorrect.

In EMS every measurement has a weight and it represents how this measurement is trusted to be accurate. Therefore is important to identify trusted measurement and measurement with questionable accuracy and accordingly set adequately weight on each measurement.

Conclusion

One of the necessary conditions for establishing VVC function is accuracy of EMS calculation. To achieve accurate results of EMS calculations it is necessary to have an accurate network model and correctly adjusted all parameters of calculations. Also, is very important to identify inaccurate measurements in the system and exclude them from EMS calculations.

VVC function has a direct impact on the reactive power and voltages in the system, so it is necessary to constantly monitor accuracy of EMS calculations in order to correct all errors and anomalies on time and avoid unwanted situations.

Acknowledgment

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