ONLINE CLOSED-LOOP OPTIMIZATION OF DISTRIBUTION NETWORK WITHOUT VERIFICATION OF DISPATCHER

Vlado KUBIC
ČEZ Distribuce, a. s. Czech Rep.
vlado.kubic@cezdistribuce.cz

David VRCHOVSKÝ
ČEZ Distribuce, a. s. Czech Rep.
david.vrchovsky@cezdistribuce.cz

Vít MACH-ŽIŽKA
Elektrosystem, a. s. Czech Rep.
mach-zizka@esys.cz

ABSTRACT

Generally, a 110 kV network fed in parallel by several transformers 400 and 220/110 kV, and more generators, requires huge demands on operating control. The operation must comply with strict requirements concerning supply reliability, an electric energy quality supply compliance, and economic indicators.

Thus, the reason for the connected network in this manner is a fact that it feeds the industrial region, where many factories with a high consumption are located. The supply interruption would cause a considerable damage, and concerning the chemical industry, also emergency cases could be a possible outcome with ecological effects. It was assumed sufficient for the reliable network control when the team of experienced operators had a quality control system SCADA at their disposal. However, during emergency and failure states the difficult, an uneasy situation arose. Therefore it has been decided to deploy the control system with the optimization function.

INTRODUCTION

The distributor cannot interfere with the production and consumption of the active power. Therefore the optimization function is used, by which is the reactive power controlled, supplied from the 110 kV system connected generators and 400 and 220/110 kV transformers. The function searches the state for the minimum of the active losses on all grid elements providing the compliance with all limit conditions. The exceeded limit correction is prior to the loss minimization. The optimization algorithm, so-called Volt-VAr-Control (VVC) fed by the results of Load Flow, which is preceded by the complete State Estimation including the transmission network (TS) 400 and 220 kV. VVC function does not directly control the generators. Computational and regulatory function are separated. Thus, the generators are regulated constantly provided even for the case of shut-down of the computational module. The generators are controlled by the regulatory automation that receives the voltage values from VVC for the particular 110 kV buses control, so-called pilot nodes (PN). The regulatory automation controls related generators through the secondary voltage regulation. It means that in all respected pilot nodes the required voltage levels are reached and sustained. The generators are controlled in the closed-loop and without the prior operator verification.

CONTROLLED NETWORK DESCRIPTION

Network range

The network was originally divided into the four independent areas. Each area was fed supplied by single 400 (220)/110 kV transformer and related generators. The network basic connection change was performed to connect all independent parts. Transmission capacities of the transmission lines as well as the transformers enabled such a change without additional investments. The consumption diversification also corresponded with this intention.

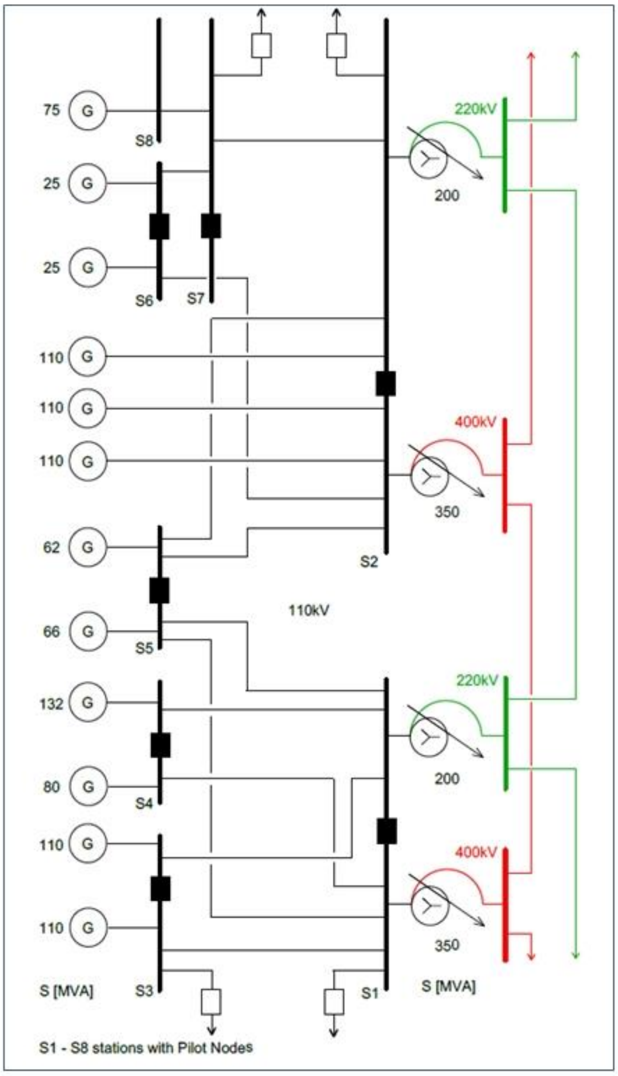

Fig. 1 - Source connection

The network characteristic data:

Load - active	937	MW
Load - reactive	185	MVAr
No. of transformers 400/220 kV	4	
Transformers – inst. output	1100	MVA
Number of generators	17	
Generators - inst. output	1105	MVA
Generators - regulatory scale	-136 /+640	MVAr
Number of buses	84	
Number of 110 kV lines	91	
Number of trans. 110/MV	104	

Network protection

However, for such a new connection it was essential to improve the network protection. Due to the connection being designed by parallel operation of two bridges, it was essential to short-circuit protect the bridge diagonals, and concurrently find and realize controlled network splitting locations. These protections can divide connected areas into two independent stable parts. Further it was essential to provide the protection to distinguish the short-circuits from exceeding overflows on 400 (220)/110 kV transformers over the 110 kV system. It could be caused with faulty connection TS after breakdown. Important stations were equipped with differential bus protections including the switch failure function. Secondary distance protections were deployed for creation of the backup with fast response. The short-circuits protections on busbar couplers assure certain function of automatic reclosing equipment.

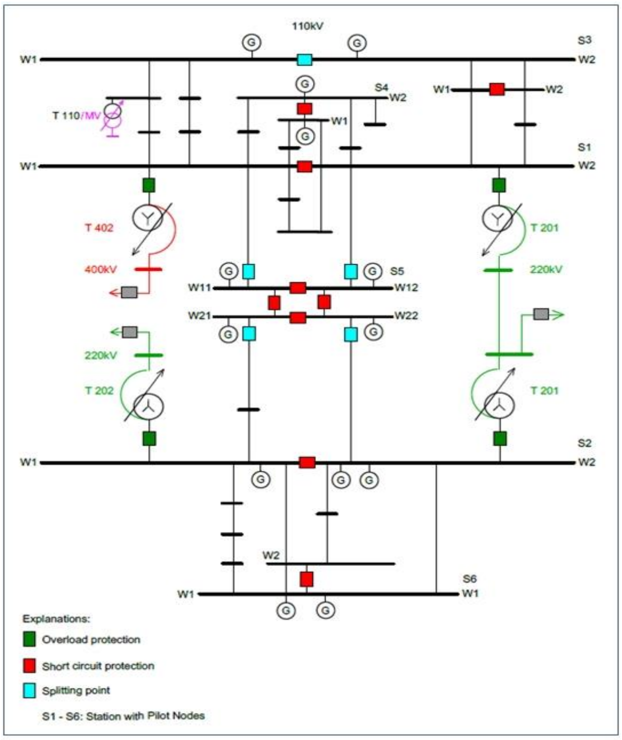

Fig. 2 - The grid protection principle [1]

OPTIMIZATION METHOD

The optimization is defined by variables, constraints and objective function. The objective function is optimization of active power losses by changing variables, in the course of maintaining constrains.

Control variables

Element	Variable	Limit	Num.
Generator	Q	Capability Curve	17
Transformer	TAP	High/Low	4

Reactive power limits of the generators are derived from the Capability Curves automatically according to actual active power. Required Q reserve can be configured for each of the generators.
The generator is used as control variable if availability signal from the power plant is sent.

Constraints

Element	Constraint	Limit	Num.
Bus	U	High/Low	88
Generator	U	High/Low	17
Transformer	Q	High/Low	4
Line	I	High	85

Voltage magnitude limits of the buses can be set absolutely or relatively towards to the input value.
The relative limits are set on selected buses of a 400 kV transmission system (TS) to prevent the Q flow changes on transformers 400 (220)/110kV. The other limits are set absolutely.
All of the constraints are considered as a hard. This means there is only one set of limits that needs to be satisfied.

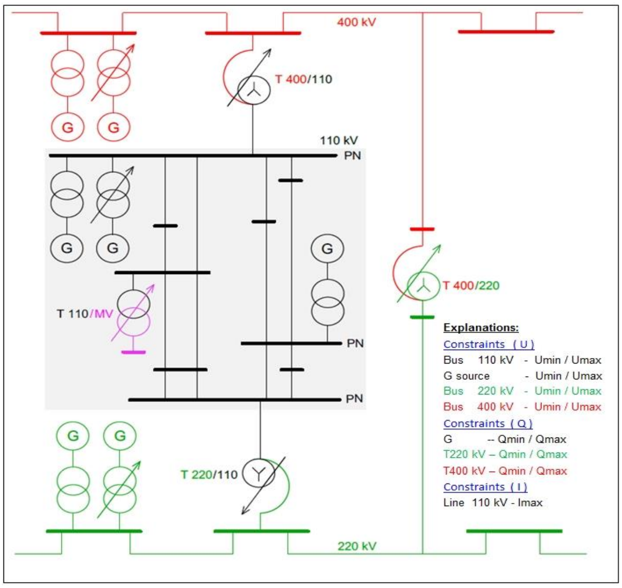

Fig. 3 - VVC principle

Objective function

The optimization objective is to minimize active power losses changing variables in the course of maintaining constrains.

Element	Number
Line	85
Transformer	21

Implementation

VCC calculation is implemented using full AC power flow equations. It is used instead of more common linearized DC approximations. All of the equations are expressed in rectangular coordinates. If we consider the constraints, variables and objective function defined above, we obtain a large scale Nonlinear Programming Problem (NLP).

Three different solvers can be used to solve the NLP:

- IPOPT is probably the most advanced solver nowadays at a free disposal of initiative COIN-OR. Implements the Primal-Dual Interior Point Filter Line Search algorithm. This is used as a main VCC solver.
- KNITRO is solver of the company ZIENA. Implements of three different algorithms based on the Interior Point Methods. It has been used only for the evaluation purposes during the VVC development frame. It is not available for a production HW.
- ESNLP is solver designed and developed by the company ELEKTROSYSTEM of own. There is implemented the Newton Method with penalty functions.

The most error-prone part of the development frame is the code of the Power Flow equations and their first and second derivatives, which are used to assemble the Jacobian and Hessian matrices. Therefore, the code of the equations was not written “by hand”. Instead of it was generated automatically by Maxima (a computer algebra system) on the symbolic level.

Efficiency

For reliable VVC function, the whole of 110 kV network, including TS of all the Czech Republic, comes into the calculation. The calculation for the given region processes 5700 measured values and 4200 element states, which are determinant for the system topology.
The calculation usually converges in 15-25 iterations. The calculation on the HW machine equipped with Intel Xeon processor with frequency 2.67GHz spends 400 - 800 ms.
The calculation behavior corresponds with the description according [2].

NETWORK CONTROL

It now has been 10 years since the first experiments with VVC function deployment in the CEZ Distribuce, a.s. network. It has gradually been perfected and extended. In 2013 the control system change took a place which now can extend the optimization function onto complete DS and even include the Q flow monitoring on 400 (220) / 110 kV transformers of the TS.

The VVC results transmission into reality

The calculation module which consists of SE, LF, VVC runs in interval of 20 seconds. The results are transmitted into the regulatory automation if they meet the parametrically conditions:
- Loss mitigation reduced > 0.2 MW or 2%
- Voltage violation on buses is > 0.2%
- Q violation on generators is > 0.2%
- I flow violation on branches is > 10%
- Q flow violation on TS transformers is > 5 MVAr

The regulatory automation keeps required voltage in the pilot nodes with accuracy of +/-0.1 kV. The change of the 400/110 kV and 220/110 kV transformers tap positions according to the VVC calculation is performed by the control operator manually when changing the grid connection and load changes.

Network control reliability

It has been verified in practice that in such complicated network, the control operator cannot permanently monitor and verify VVC results. Therefore, it has been decided to deploy the optimization in the closed-loop without verification by the control operator. This had been preceded by the calculation reliability analyses and safety and deployment of the safety bars. These bars contain following elements:

1. Unreliable VVC result will not be transmitted into the regulatory automation
2. Regulatory automation will not accept the out-of-limit values
3. Regulatory automation monitors the actual generators TG limits
4. Generators TG control system monitors its own limits
5. SCADA - the alarm for the control operator
6. Control operator has an option to input different voltage values
7. Control operator has an option to shut down the regulation

In actual operation, only points of 1, 2 and 3were used.

In case of not transmitting the VVC results into the regulatory automation, the last input voltage value is retained.

Practical experiences from operation

For VVC evaluation to be objective it is necessary to take into account all influences. There is significant influence not only from the system load or the supply dislocation, but also from the actual network connection. Therefore, for the evaluation the basic network connection has been used. Load system was 80% of the maximum. For the initial a voltage value the basic setting was 118 kV and level regulators of insensitivity of +/- 2 kV was used.

Results:

Q supply redistribution

The required supply changes of the reactive power from the generators varied from -36 to +9 MVAr and the change of the transformers tap positions from 0 to 2 taps.

Název	Typ	Val.typ	Min	Max	LF	OPF	OPF - LF
E_ME_0001:G1	gener	Q	-11.29	42.15	**-4.30**	**4.65**	8.94
E_MO_0004:G10	gener	Q	-4.15	15.37	**0.00**	**7.94**	7.94
E_MO_0004:G13	gener	Q	0.00	15.08	**1.20**	**8.68**	7.48
E_MO_0004:G11	gener	Q	-5.30	18.26	**0.00**	**6.42**	6.42
E_MO_0013:G21	gener	Q	-3.80	16.06	**0.48**	**6.40**	5.92
E_CV_0012:G4	gener	Q	-10.00	55.00	**21.32**	**26.52**	5.20
E_CV_0012:G3	gener	Q	-10.00	55.00	**23.43**	**27.90**	4.47
LN_VYS_:T201	trafo	TAP	1.00	19.00	**7.00**	**9.00**	2.00
TP_CHT_:T402	trafo	TAP	1.00	16.00	**5.00**	**7.00**	2.00
E_MO_0013:G20	gener	Q	-12.94	24.79	**-2.42**	**-0.68**	1.74
E_MO_0013:G6	gener	Q	-11.76	26.01	**-2.64**	**-1.12**	1.52
E_UL_0006:G4	gener	Q	0.00	15.90	**0.00**	**0.62**	0.62
ETEM:gTG1	gener	P	1092.53	3092.53	**2092.53**	**2092.59**	0.06
LN_VYS_:T402	trafo	TAP	1.00	19.00	**7.00**	**7.00**	0.00
TP_CHT_:T201	trafo	TAP	1.00	13.00	**8.00**	**8.00**	0.00
E_MO_0013:G4	gener	Q	-11.97	26.88	**4.82**	**-1.01**	-5.83
E_TP_0005:G4	gener	Q	-20.00	90.00	**28.22**	**-7.69**	-35.90

Tab. 4 - Q supply division change

Voltage values

As seen in the diagram below, the progression of the voltage values with the VVC function on and off from 7:00 to 15:00. It is apparent that with help of VVC the voltage was controlled in the within the limits of 118.6 to 119.0 kV. During time of disconnection of VVC function was the voltage controlled with help of the secondary block regulator, which preserved the last input value from VVC converted to the applied voltage. The voltage was being kept within the limits of 13.33 – 13.40 kV. It is apparent from the results that, even though the secondary block regulation responded to the load elevation influence in the network, the voltage in the pilot node decreased for 0.8 kV. This change is under the level voltage regulators sensitivity abilities of 400/110 kV transformers which is in given pilot node +/- 1.77 kV. After switching on the VVC, there was an elevation of the applied voltage to the value of 13.59 kV, and thus the voltage in PN returned to its original value. This change would not be significant, if there were not 7 pilot nodes connected concurrently into the network. Even with such small uncoordinated changes of the Q supplies, there is an increase of losses.

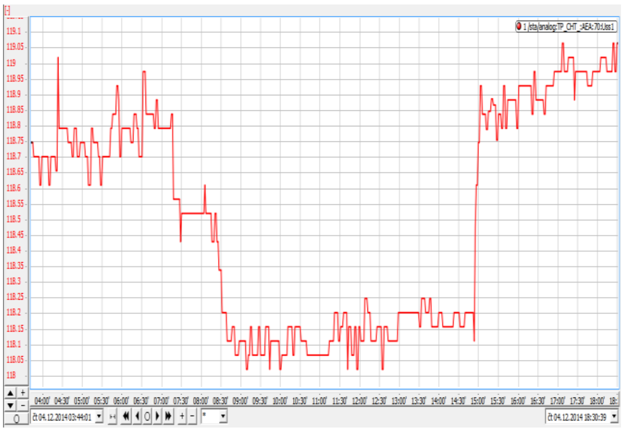

Fig. 5 - Voltage progress

Active loss mitigation

The 110 kV lines, 400 (220)/110 kV transformers and generator block transformers are included in the optimization. 110/MV transformer taps are controlled by the local transformer automations, therefore they are not included in the optimization.

It is apparent from the values presented that even though the losses on the lines decrease about 7% (tab.6), the total losses decreases only about 2.5% (tab.7). The reason of such a situation origins in the fact that 110/MV transformers are not included in the optimization and their loss are approx. 60% of total loss. We can also see the inverse influence of the voltage level on the transformer winding loss and the no-load loss (tab. 9).

Tab. 6 - Loss mitigation on lines total (MW/%)

Ln-1	Ln-2	Ln-dif	Ln-dif%
5.4328	5.0565	-0.3763	93.07

(LF sign. black column, VVC sign. green column)

Tab. 7- Loss mitigation total (MW /%)

Oblast	Total-1	Total-2	Total-dif	Total-dif%
LN_VYS_:T402,...	**13.2260**	**12.8882**	**-0.3378**	**97.45**

Tab. 8 - Loss mitigation on lines - detail (kW/%)

Název	Ln-1	Ln-2	.n-dif	Ln-dif%
V145:1	105.5	60.5	-45.0	57.34
V168:1	82.0	49.4	-32.6	60.27
V142:1	423.7	408.0	-15.7	96.30
V141:1	423.7	408.0	-15.7	96.30
V338:1	195.3	180.0	-15.3	92.17

Tab. 9 - Loss mitigation on transformers total (MW/%)

TrPk-1	TrPk-2	TrPk-dif	TrPk-dif%	TrP0-1	TrP0-2	TrP0-dif	TrP0-dif%
2.4465	2.3514	-0.0951	96.11	4.8383	4.9967	+0.1584	103.27

(Tr PK sign. winding loss, Tr Po sig. no-load loss)

Tab. 10 - Loss mitigation on block transformers (kW/%)

Název	Total-1	Total-2	Total-dif	Total-dif%
LN_VYS_:T402	164.5	139.1	-25.4	84.59
TP_CHT_:T201	72.7	63.3	-9.4	87.03
ME_EME1:TB1	215.6	206.7	-8.9	95.86
MO_EKY_:TB1	95.5	87.9	-7.6	92.01
CV_EPR1:TB4	373.1	368.6	-4.5	98.79

Regulatory accuracy

The real loss mitigation following the performed regulation is, in most cases, lower than the VVC calculation has set. This is due to the regulatory inaccuracy. The estimated values are used for the VVC calculation, thus the absolute accuracy, but the regulation progresses with help of the measured values with limited accuracy that degrades the regulation result. To remove this defect by changing the equipment with the higher accuracy class is not possible. There is solution to argue for, namely using the estimated values for regulation too.

Such a test has been performed and the impact on the regulation progress was significant. When using estimated values, the measurement inaccuracy influence was removed it was also possible to use more accuracy control of voltage 110 kV level on +/-50V. The biggest difference between measured and estimated voltage value was recorded on 0.6 kV level. The measured value was lower, which caused Q supply from the resources in this PN to be elevated to 57 MVAr instead of requested 32 MVAr. It became evident in a way in which Q flow was 25 MVAr instead of expected close to zero on respected lines. In this case the change of the measuring elements was performed.

The test demonstrated that the regulation with help of estimated values is an efficient one. This way of regulation juxtaposes huge amount of requirements on whole EMS calculation mode, i.e. its continuity and flawlessness. In this case the psychological effect is also not insignificant especially when the control operators are used to using purely measured values.

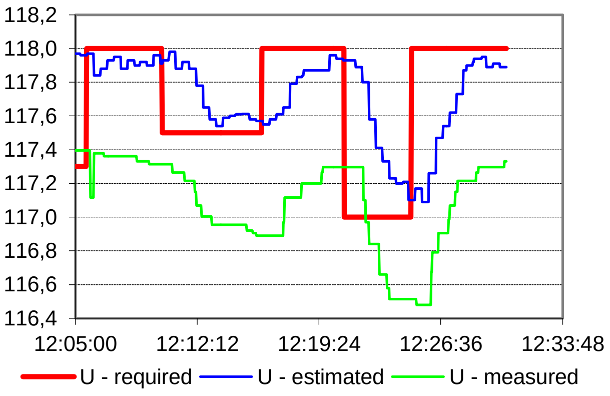

Fig. 11 - Measured and estimated voltage [5]

RESULTS

Optimization VVC online closed-loop function deployment has enabled to change the basic connection of network, thereby giving the operator a bigger flexibility when maintaining the equipment and fundamentally increasing the feeding reliability. Even under extreme weather conditions, when some of DS equipment was destroyed together with TS, the customers were been not disconnected in this part of distribution system.

Voltage and flow values are permanently monitored. Values are sustained within required limits.

The voltage fluctuation has been decreased in 110 kV network and thereby decreasing number of voltage regulations at 110/ MV transformers.

The transmission of the reactive power is controlled on 400 (220) /110 kV transformers in co-operation with the TS operator.

The loss minimization criterion could be applied only with design of basic connection. After VVC online close-loop function deployment, the loss is minimized permanently regardless the system connection.

CONCLUSION AND OUTLOOK

CEZ Distribuce, a.s. cannot perceive the optimization function only as an experiment, on contrary, it sees it as a part of 110 kV network control. Another two regions will obtain this function in 2015, thereby covering almost 30% of 110 kV DS in operation.

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