Deliverable 6.6.7: Specification of coordinated voltage control method for practical implementation

Anna Kulmala

Tampere University of Technology, Department of Electrical Energy Engineering, Finland

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1 Introduction

This deliverable includes the specification of the coordinated voltage control algorithm defined in SGEM project. Some parts of the algorithm were already defined in deliverable 6.6.4. Minor modifications to the parts defined in 6.6.4 have been done and restoring and optimizing parts have been added.

2 The proposed voltage control method

The proposed coordinated voltage control algorithm uses substation voltage and real and reactive powers of active resources as control variables. Substation voltage is controlled by changing the voltage set point of the automatic voltage control (AVC) relay that controls the main transformer tap changer. The real and reactive powers of active resources are controlled by changing the real and reactive power set points of the resources. The algorithm is based on control rules and consists of basic and restoring parts. Basic control is used to restore network voltages to an acceptable level when either the network maximum or minimum voltage exceeds the feeder voltage limits. Restoring control aims to restore the real and reactive power of active resources closer to their original values when the network state allows it. It also restores the network voltages to a normal level if the voltages of the whole distribution networks have remained in an unusually high or low level for some reason (for instance disconnection of a large generating unit). The control algorithm has been developed based on [1], [2] and [3].

In addition to the rule based algorithm also an optimizing part can be included to the algorithm. The optimizing part can either replace the restoring part of the algorithm or operate independently as a supplement to the rule based algorithm. In the latter case the optimization can be executed more rarely.

Optimization can also replace the whole rule based algorithm if convergence of the optimization algorithm can be always guaranteed. Also, the computational time of the optimization algorithm should remain reasonable.

2.1 Basic control

The operational principle of the developed basic control is represented in Figure 1. The control algorithm consists of three parts: substation voltage control, reactive power control and real power control. The control is activated when either network maximum or minimum voltage exceeds its limit. At first, it tries to restore network voltages between acceptable limits by controlling substation voltage. If substation voltage control is not able to restore network voltages to an acceptable level, reactive power control is activated. The final control variable real power is used only if network voltage violations still exist after substation voltage control and reactive power control.

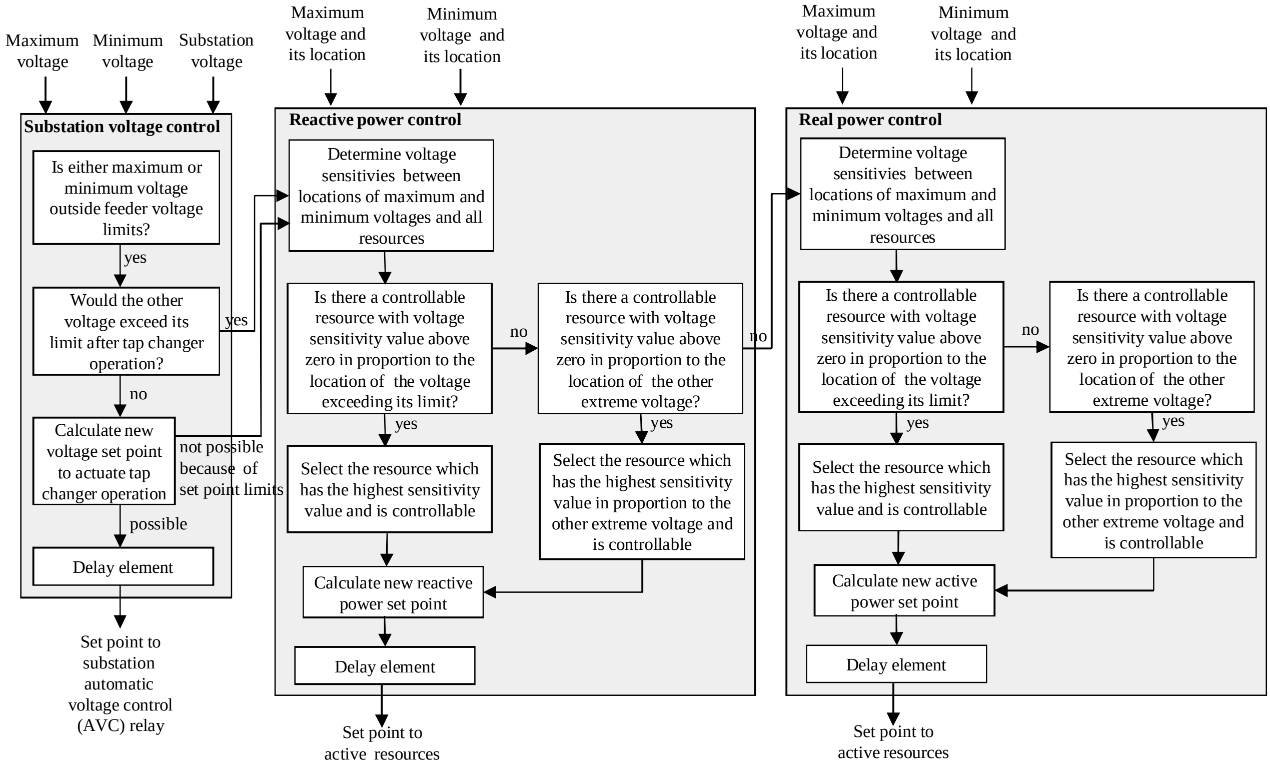

Figure 1. The operational principle of basic control.

2.1.1 Basic substation voltage control

A detailed flow chart of basic substation voltage control is represented in Figure 2. The operational principle is the following: If network maximum voltage exceeds feeder voltage upper limit and minimum voltage is more than a tap step above its limit, the substation voltage is decreased. Correspondingly, the substation voltage is increased if network minimum voltage is lower than feeder voltage lower limit and maximum voltage is more than a tap step below feeder voltage upper limit. If basic substation voltage control is unable to improve network, reactive power control is activated.

The first part in Figure 2 (Part 1) determines whether the substation voltage control should be used. If both voltages are between the feeder voltage limit, nothing is done. If maximum voltage exceeds its limit V_{upper} and the minimum voltage is higher than $V_{lower}+tap+marg$ (V_{lower} is the feeder voltage lower limit, *tap* the tap step and *marg* a safety margin), the AVC relay set point should be lowered. Correspondingly, if minimum voltage falls below its limit V_{lower} and the maximum voltage is lower than $V_{upper}-tap-marg$, the AVC relay set point should be lowered. If both voltages exceed or are too close to the feeder voltage limits, basic reactive power control is activated.

The second part in Figure 2 (Part 2) determines how many tap changer operations are needed to restore the voltages between acceptable limits. After determining the number of needed tap changer operations *n* the algorithm determines the new AVC relay set point. It is assumed that a tap changer operation changes all network voltages by an amount equal to the tap step. This is not completely true but is, nonetheless, an adequate approximation.

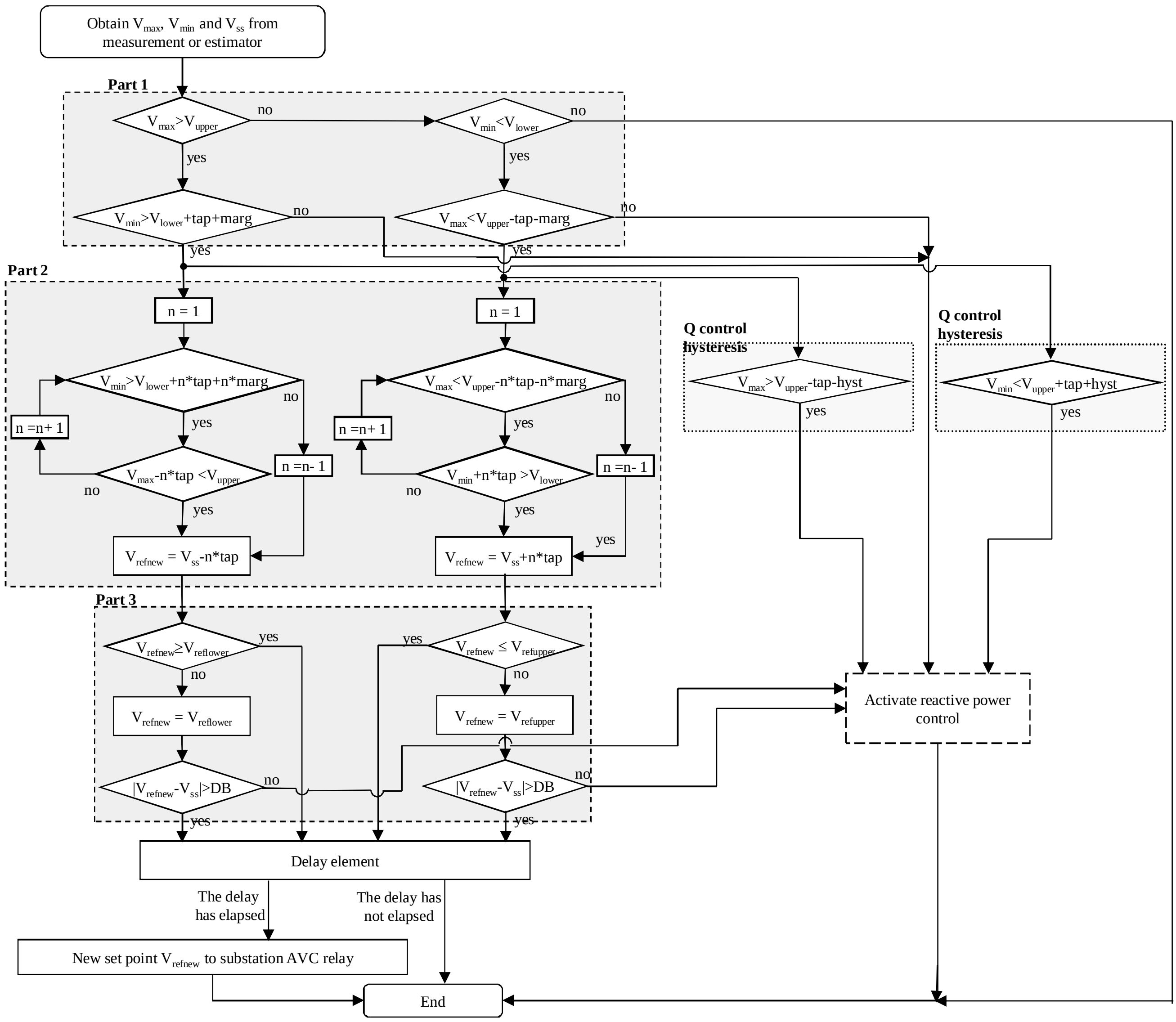

Figure 2. The flow chart of basic substation voltage control.

The third part in Figure 2 checks that the calculated new voltage set point is between the set point limits and verifies that the new set point will initiate a tap changer operation. If the new set point is outside the set point limits, the AVC relay set point is set to its extreme value (maximum or minimum). However, if this set point would not initiate a tap changer operation, the AVC relay set point is not changed and the reactive power control is activated.

The new set point is given to the AVC relay only after a predefined delay. The conditions for set point change have to be fulfilled for the whole delay time and the delay counter is reseted when the control action is executed.

As previously stated, the basic reactive power control is activated if either maximum or minimum voltage is outside the feeder voltage limits but the substation voltage control cannot be used to restore the voltages between acceptable limits (both maximum and minimum voltages exceed or are too close to feeder voltage limits or tap changer operation cannot be initialized because of set point limits). The reactive power control is activated also by the Q control hysteresis when either the maximum or minimum voltage exceeds its limit and the other voltage is only slightly more than a tap step away from its limit. This is done to avoid the situation where the other voltage is in turns less and more than a tap step away from its limit and no control part operates because the basic substation voltage control is in turns active and not active.

2.1.2 Basic reactive power control

A detailed flow chart of reactive power control is represented in Figure 3. The reactive power control operates only if the substation voltage control has activated it. The algorithm determines which resource to use by using voltage sensitivities. This assures that a minimum amount of reactive power control is used to restore the network voltages between acceptable limits. The determination of voltage sensitivity values is discussed in chapter 2.1.4.

At first, the reactive power control algorithm selects the active resource whose reactive power is controlled (Part 1 in Figure 3). If network maximum voltage exceeds the feeder voltage upper limit, the algorithm selects the controllable resource that has the highest voltage sensitivity value in proportion to the location of network maximum voltage. If multiple resources have the same sensitivity factor, the resource with the smallest sensitivity in proportion to its own location is selected. In this way, the resource electrically closest to the substation is selected and the distance of reactive power transfer is minimized. If there is no resource that can affect the voltage in the location of maximum voltage (i.e. all sensitivities are zero), the algorithm checks if increasing the network minimum voltage would be beneficial i.e. enable substation voltage control. If the minimum voltage is smaller that $V_{lower} + tap + hyst$, the substation voltage control cannot decrease the substation voltage. By increasing the minimum voltage, operation of substation voltage control can be enabled. The algorithm selects the controllable resource in the same way as before i.e. the resource with the highest voltage sensitivity value in proportion to the location of minimum voltage is selected. If no resource that can affect network minimum voltage is available, the reactive power control is not able to improve the network state and the real power control is activated. If minimum voltage is the one that exceeds its limit, the algorithm operates similarly but naturally selects first the resource that has the highest voltage sensitivity in proportion to the location of minimum voltage.

A new set point is calculated for the controlled resource only after a predefined delay. The conditions for set point change have to be fulfilled for the whole delay time and the delay counter is reseted when the control action is taken. If substation voltage control is active (and the reactive power control has been activated by Q control hysteresis) the reactive power set point is not changed because substation voltage is the primary control variable.

The second part of the algorithm (Part 2) calculates the new reactive power set point for the selected active resource. In Figure 3 the reactive power set point is changed in predefined steps. If state estimation is available, the new set point can also be calculated utilizing the state estimation as in [2].

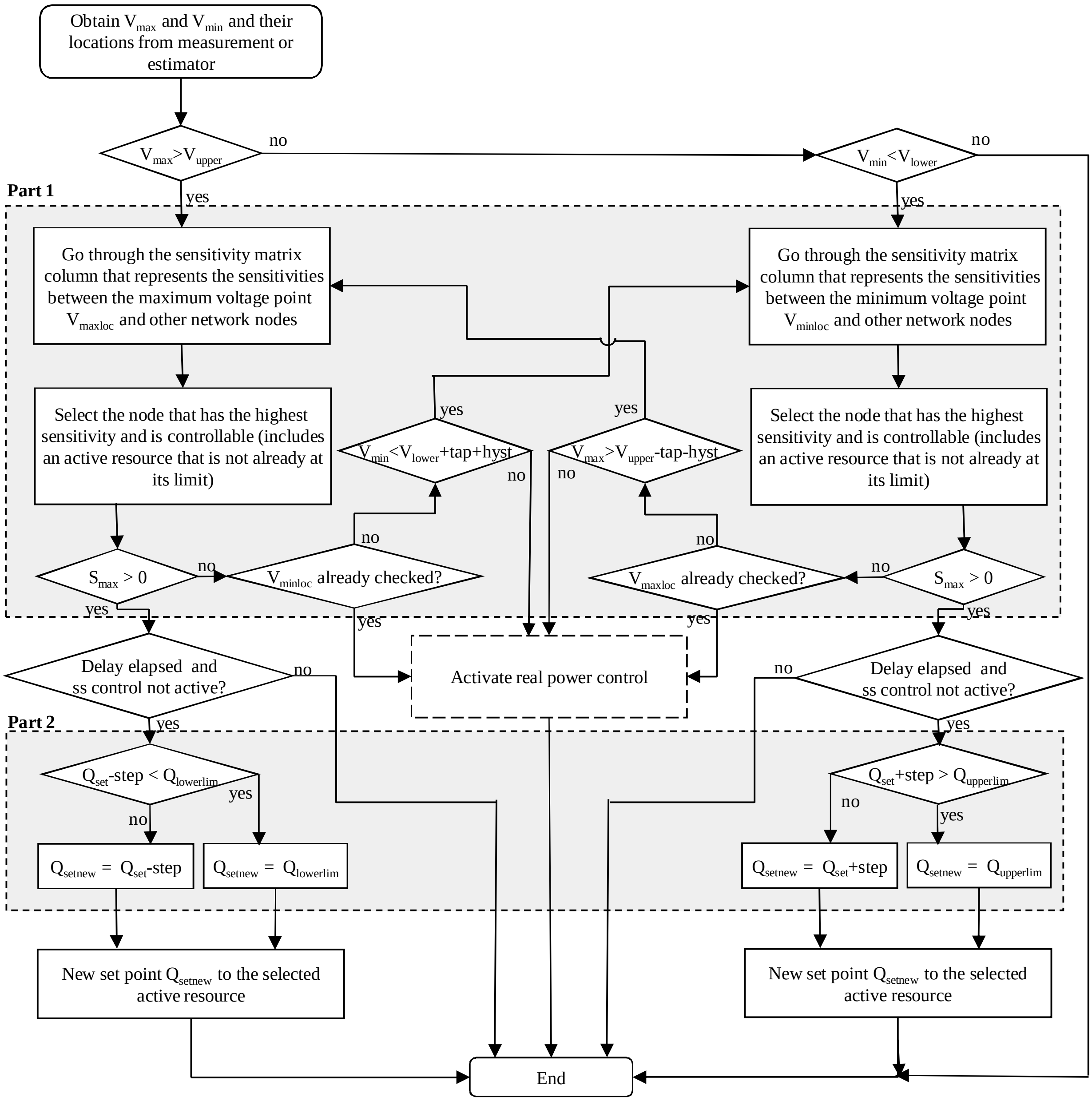

Figure 3. The flow chart of basic reactive power control.

2.1.3 Basic real power control

The flow chart of real power control is represented in Figure 4. The real power control is very similar to the reactive power control. The first part (Part 1) of the algorithm selects the controllable resource using voltage sensitivities in the same way as the resource was selected in the reactive power control. The voltage sensitivity values are naturally different for reactive and real powers but the operational principle of the first algorithm part is the same. If the algorithm is unable to find a controllable resource, it outputs an alarm signal that tells that restoring the voltages to an acceptable level is not possible using the control variables available.

The second part (Part 2) is a bit different because the CVC algorithm does not control the whole real power set point of the active resources but only gives commands to decrease or increase the power. This is due to the fact that the real power output of active resources (generators or loads) is in normal state determined by factors not related to voltage control (e.g. wind speed). The CVC algorithm outputs a signal P_{out} that is added to the original active power set point. In Figure 4 the output signal is changed in predefined steps. If state estimation is available, it can be utilized when determining the new set point.

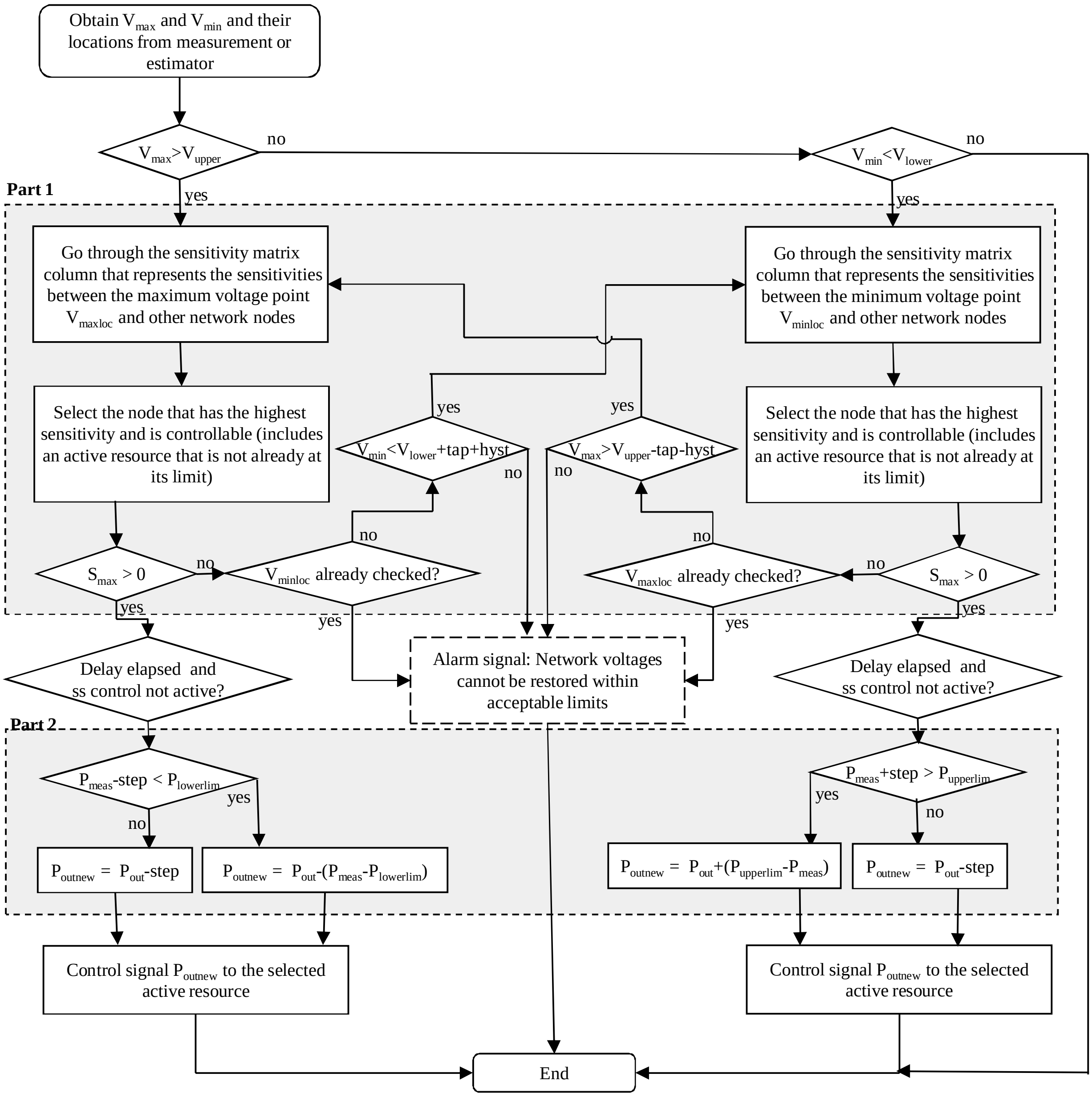

Figure 4. The flow chart of basic real power control.

2.1.4 Defining voltage sensitivities

The voltage sensitivities are used in the algorithm to determine which resource is used for reactive power and real power control. The sensitivities are determined by an approximate method proposed in [4]. Some simplifying assumptions have been made in the method. Constant current models are used for loads and generators and the phase difference between voltages is assumed to be negligible. As a result of these assumptions, the voltage sensitivities can be represented by the following simple equation:

$$\begin{cases} [S_{I_p}] = -[R] \\ [S_{I_q}] = -[X] \end{cases}$$

where $S_{I_p} = \begin{bmatrix} \frac{\partial V_1}{\partial I_{p1}} & \cdots & \frac{\partial V_1}{\partial I_{pn}} \\ \vdots & \ddots & \vdots \\ \frac{\partial V_n}{\partial I_{p1}} & \cdots & \frac{\partial V_n}{\partial I_{pn}} \end{bmatrix}$ the voltage sensitivity matrix in proportion to active node currents I_p,

$S_{I_q} = \begin{bmatrix} \frac{\partial V_1}{\partial I_{q1}} & \cdots & \frac{\partial V_1}{\partial I_{qn}} \\ \vdots & \ddots & \vdots \\ \frac{\partial V_n}{\partial I_{q1}} & \cdots & \frac{\partial V_n}{\partial I_{qn}} \end{bmatrix}$ the voltage sensitivity matrix in proportion to reactive node currents I_q,

R is the real part and X the imaginary part of the impedance in the impedance matrix $[Z]$. The main diagonal elements of $[Z]$, (Z_{ii}) are equal to the sum of the branch impedances forming the path from the origin (the substation) to the node *i*. The off-diagonal elements (Z_{ij}) are equal to the sum of the branch impedances forming the path from the origin to the common node of the paths formed by the origin and the nodes *i* and *j*, respectively. Node *i* is the node whose voltage change is analyzed and node *j* the node whose reactive or active power is changed to control the voltage at node *i*. Hence, the controllable resource at node *j* can affect the voltage at node *i* the more the longer (electrically) the common path from the origin to nodes *i* and *j* is. This is quite sensible.

In this method the voltage sensitivities are calculated based on only network impedances whereas in reality also other variables such as substation voltage, voltage at the node *i* and net active and reactive node currents affect the sensitivity value [4]. Hence, the method only gives approximate values of the sensitivities. However, these are adequate for the purpose of selecting the controllable resource. The benefit of the method is its simplicity and the fact that the sensitivity matrix needs to be updated only when the network switching state changes. All data needed for determining the sensitivity values is already available at the distribution management system (DMS).

In this method, it is assumed that reactive and real power control affects voltages only on the feeder they are connected to because the origin is defined to be the substation. This is not, naturally, completely true because there is impedance also in the feeding HV network and the substation transformer. If also these impedances are wanted to be taken into account in the voltage sensitivity calculations, the origin should be defined to be the node representing the ideal voltage source behind the HV network impedance.

There are also more accurate methods to determine the voltage sensitivities [5]-[8].

2.2 Restoring control

The operational principle of the developed restoring control is represented in Figure 5. Also the restoring control consists of three parts: substation voltage control, reactive power control and real power control. Restoring control is activated only when basic control is not needed that is when all network voltages are within the acceptable range. In restoring control, the control blocks operate in reverse order compared to basic control. In restoring control, real power control is activated first. It tries to restore the real powers of all active resources as near as their original value as the network state allows. If restoring active power control is not needed (all active powers are at their original values) or cannot operate because the network state does not allow it, restoring reactive power is activated. The restoring reactive power control has similar objectives as the restoring real power control i.e. it tries to restore the reactive powers of all resources as near to their original values as the network state allows. If restoring reactive power control is not needed or cannot operate, restoring substation voltage control is activated. The restoring substation voltage control aims to restore network voltages to a normal level if the voltages in the whole distribution network have remained in an unusually high or low level.

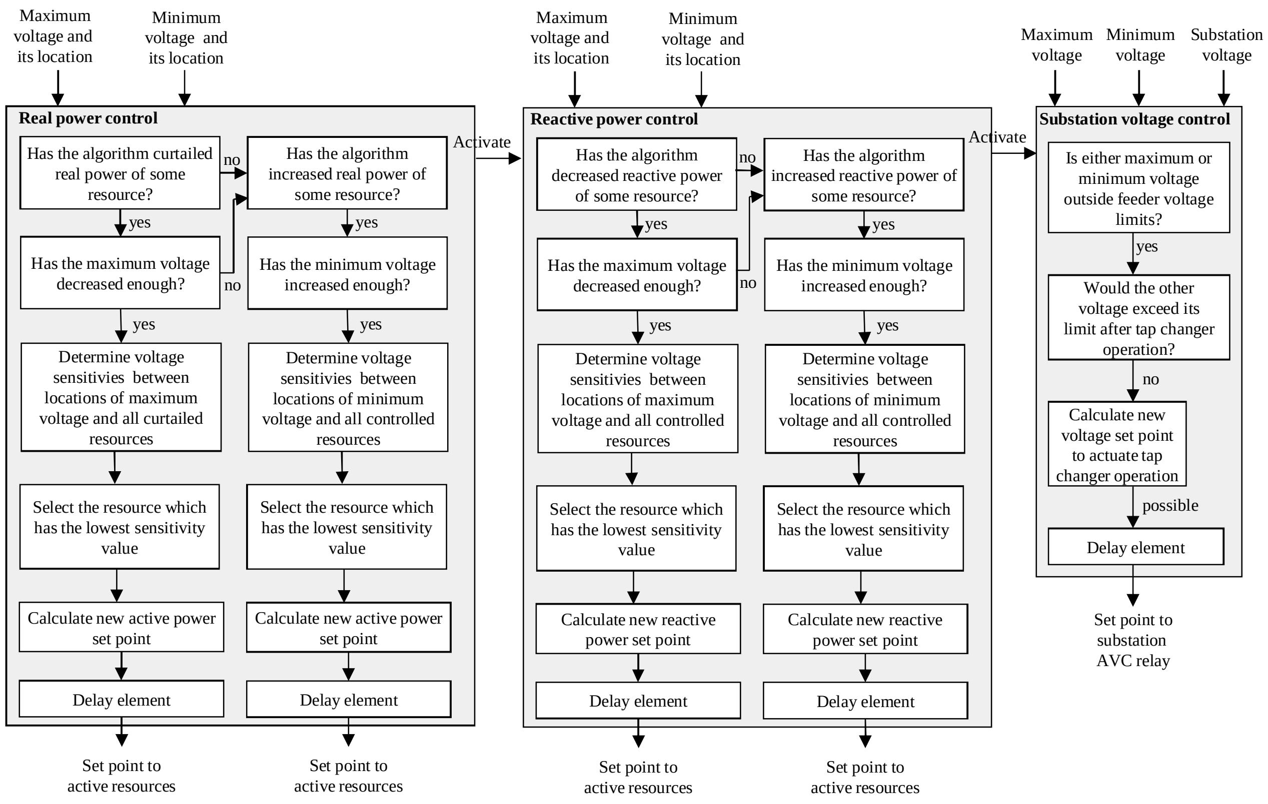

Figure 5. The operational principle of restoring control.

2.2.1 Restoring real power control

A detailed flow chart of restoring real power control is represented in Figure 6. At first (Part 1), the algorithm determines whether restoring real power control is needed i.e. has the real power of some active resource been decreased or increased. If controlled resources exist, the algorithm determines if the network state is such that restoring actions can be allowed. It is determined that the real power of some resource can be increased if the maximum voltage has decreased enough i.e. is below the value V_{upper}-*marg*. Correspondingly, the real power of some resource can be lowered if the minimum voltage has increased enough. If there is no need for restoring real power control or the network state does not allow it, the restoring reactive power control is activated.

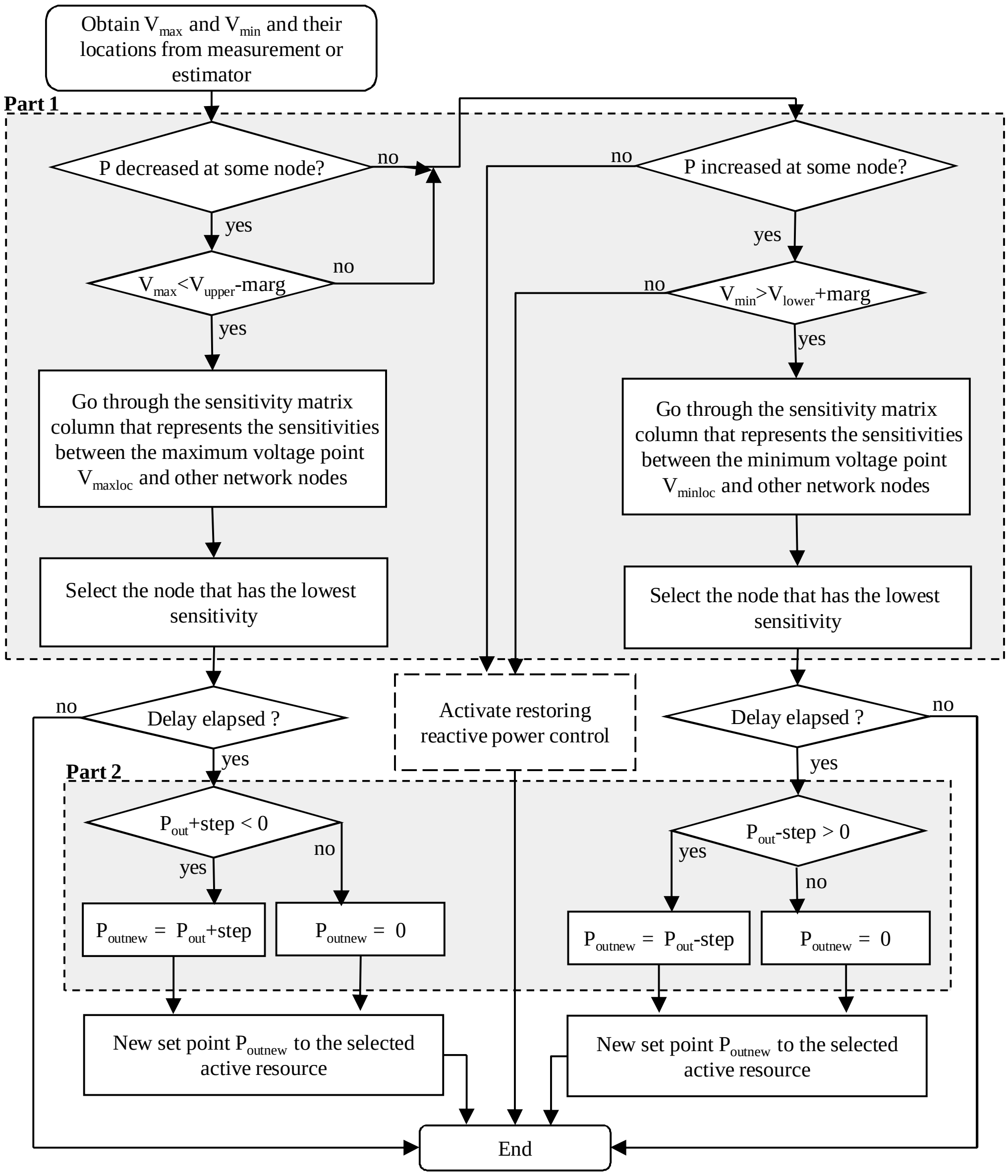

Figure 6. The flow chart of restoring real power control.

When it has been decided whether the real power of some resource should be increased or lowered, the active resource whose real power is controlled will be selected. Sensitivity factors are used also here to select the controlled resource. If the real power of some resource has been previously lowered and the maximum voltage is low enough, the algorithm selects the controllable resource that has the lowest voltage sensitivity value in proportion to the location of network maximum voltage. Correspondingly, if the real power of some resource is to be lowered, the algorithm selects the controllable resource that has the lowest voltage sensitivity value in proportion to the location of network minimum voltage.

A new set point is calculated for the selected resource only after a predefined delay. The conditions for set point change have to be fulfilled for the whole delay time and the delay counter is reseted when the control action is taken.

The second part of the algorithm (Part 2) calculates the new real power set point for the selected active resource. The objective is to set all components of vector P_{out} to zero. In Figure 6 the real power set point is changed in predefined steps. If state estimation is available, it can also be utilized in determining the new set point.

2.2.2 Restoring reactive power control

A detailed flow chart of restoring reactive power control is represented in Figure 7. The algorithm is very similar to restoring real power control. At first, it determines whether restoring reactive power control is needed and whether the network state is such that it can be executed. After that it selects the controlled resource using voltage sensitivity values. New reactive power set point is calculated only after a predefined delay and in Figure 7 the set point is changed in predefined steps. State estimation can be utilized also here if it is available.

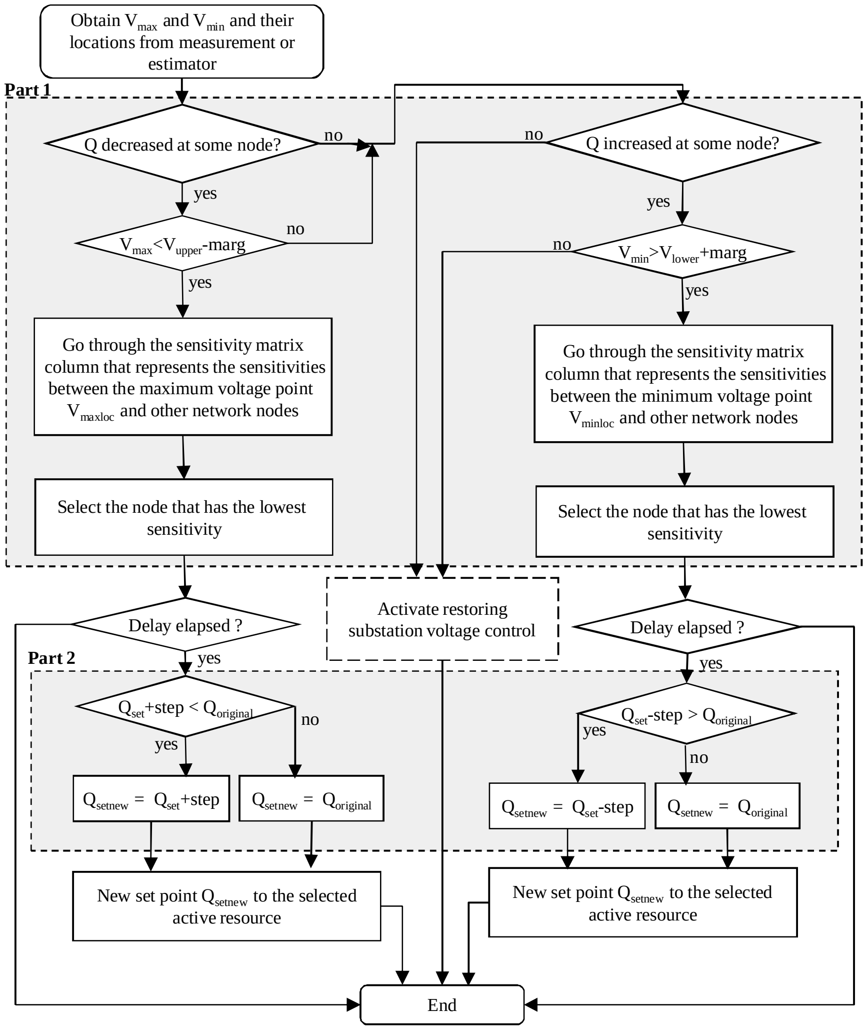

Figure 7. The flow chart of restoring reactive power control.

2.2.3 Restoring substation voltage control

The restoring substation voltage control is similar to basic substation voltage control depicted in Figure 2. The only difference is that different parameters are used.

2.3 Interactions between control blocks and implementation of the rule based algorithm

If the control blocks described in chapters 2.1 and 2.2 would be operating independently, several control blocks would try to execute control actions at the same time and hunting or other adverse interactions might occur. To avoid these adverse interactions, communication between the control blocks is needed. The inputs and outputs and the connections between control blocks are depicted in Figure 8.

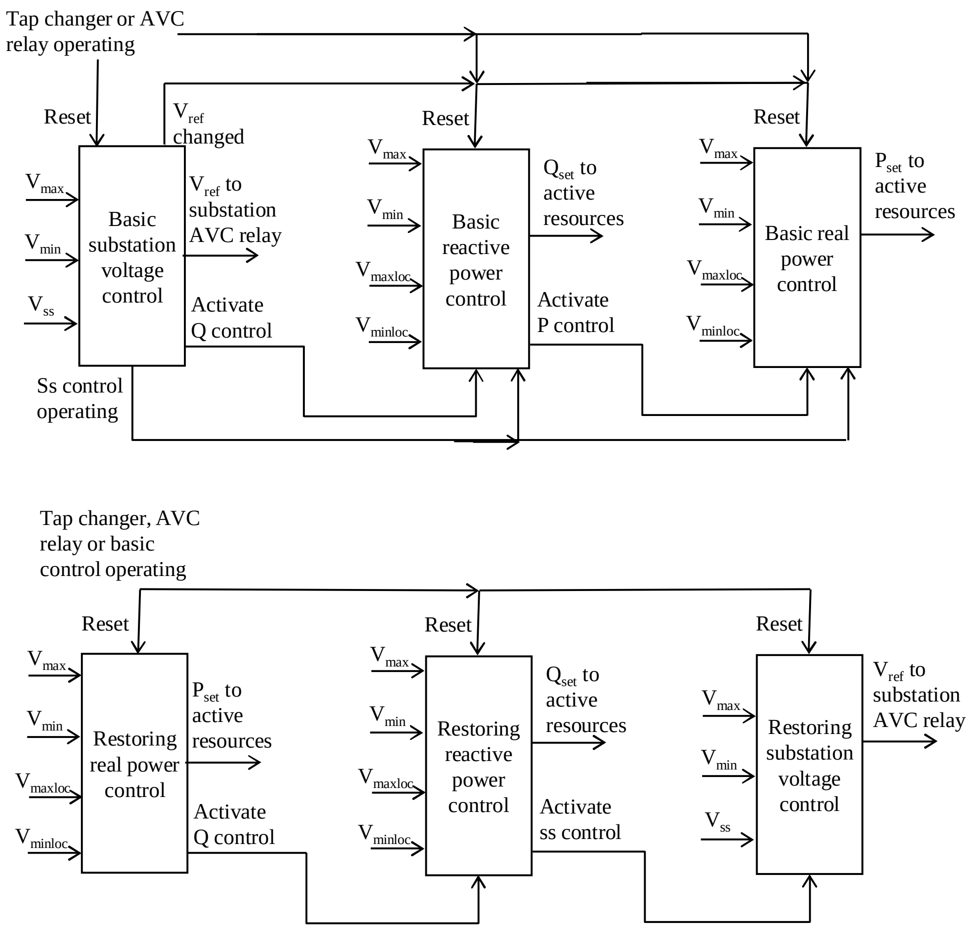

Figure 8. The inputs and outputs and the connections between control blocks.

In addition to the inputs introduced in the previous chapters, all control blocks have also a reset-input. This input is used to reset the delay counter(s) of the control block and to block its operation. The operation of the whole CVC algorithm is blocked if the tap changer or substation AVC relay is operating. Basic reactive and real power controls are reseted also when basic substation voltage control changes the AVC relay set point. Restoring control is blocked if any of the basic control blocks is operating.

The generation of the activation signals is described in the previous chapters 2.1 and 2.2. Also the purpose of signal “ss control operating” is explained in those chapters.

The above described control algorithm is implemented as a Matlab program that consists of a main function and several subfunctions. Each control block is programmed as its own subfunction and the main function calls these functions in the correct order and realizes the connections depicted in Figure 8.

2.4 Optimizing control

The optimization of distribution network voltage control is a mixed-integer nonlinear programming problem (MINLP)

$$\min f(\mathbf{x},\mathbf{u_d},\mathbf{u_c}) \tag{1}$$

$$g(\mathbf{x},\mathbf{u_d},\mathbf{u_c}) = 0 \tag{2}$$

$$h(\mathbf{x},\mathbf{u_d},\mathbf{u_c}) \leq 0 \tag{3}$$

where $\mathbf{x}$ is the vector of dependent (only indirectly controllable) variables, $\mathbf{u_d}$ is the vector of discrete control variables and $\mathbf{u_c}$ is the vector of continuous control variables. To be able to solve the optimization problem, the vectors $\mathbf{x}$, $\mathbf{u_d}$ and $\mathbf{u_c}$ need to be defined. Also the objective function $f(\mathbf{x},\mathbf{u_d},\mathbf{u_c})$, the equality constraints $g(\mathbf{x},\mathbf{u_d},\mathbf{u_c}) = 0$ and inequality constraints $h(\mathbf{x},\mathbf{u_d},\mathbf{u_c}) \leq 0$ need to be defined.

2.4.1 State variable vectors

The vector of dependent variables contains the voltage magnitudes V and voltage angles δ of all n distribution network nodes

$$\mathbf{x} = [V_1,\ldots,V_n,\delta_1,\ldots,\delta_n] \tag{4}$$

The vector of discrete variables contains the switched control variables such as positions of tap changers, network switches and switched capacitors and reactors. In this case it is assumed that the distribution network includes one tap changer at the substation main transformer and switched capacitors can be connected on the feeders. Hence, the vector of discrete variables becomes

$$\mathbf{u_d} = [m, B_1,\ldots,B_i] \tag{5}$$

where m is the main transformer tap ratio and B_i is the susceptance of the ith capacitor that is dependent on its switching state.

The vector of continuous control variables contains variables such as set points of real and reactive powers or terminal voltages of active resources. In this case the controllable variables are the real and reactive powers of active resources. Hence, the vector of continuous control variables becomes

$$\mathbf{u_c} = [P_1,\ldots,P_i,Q_1,\ldots,Q_i] \tag{6}$$

where P_i is the real power set point and Q_i the reactive power set point of the ith active resource.

2.4.2 Objective function

The objective function is defined such that it will minimize the total costs of network losses and generation curtailment

$$f(\mathbf{x},\mathbf{u_d},\mathbf{u_c}) = C_{\text{losses}}*P_{\text{losses}}+C_{\text{cur}}*\Sigma P_{\text{cur}} \quad (7)$$

The price of losses C_{losses} is assumed to be 44.6 €/MWh which is an average value of Nordpool Finland spot price in years 2006-2010. The price of curtailed energy is assumed to be 83.5 €/MWh which is the feed-in tariff for wind generators in Finland and the distribution charge is assumed to be 0.7 €/MWh which is the maximum allowed distribution charge for production units in Finland. The lost income due to curtailment C_{cur} is, hence, 82.8 (83.5-0.7) €/MWh. [9]

The losses can be calculated as the sum of real powers of all network nodes

$$P_{\text{losses}} = \Sigma P_{\text{i}} \quad (8)$$

The bus power injections can be computed from the following equation

$$\mathbf{P_i}+\mathbf{Q_i} = \text{diag}(\mathbf{V})(\mathbf{Y_{bus}}\mathbf{V})^* \quad (9)$$

where $\mathbf{V}$ is the node voltage vector $[V_1 e^{j\delta 1},\ldots,V_n e^{j\delta n}]$ and $\mathbf{Y_{bus}}$ the bus admittance matrix [10]. It should be noted that the variables $B_1,\ldots,B_i$ in the vector $\mathbf{x_d}$ affect the bus admittance matrix.

Also other components could be added to the objective function. The objective function could include also for instance the costs of reactive power generation and consumption, the amount of tap changer operations and quantities related to voltage quality such as average voltage deviation and maximum voltage deviation. Adding the costs of reactive power consumption and generation to the objective function of equation 7 would be quite straightforward. Determining the costs for tap changer operations or voltage quality issues would be more complicated. In these cases multiobjective optimization might be an attractive option.

2.4.3 Equality constraints

The voltagemagnitudes, voltage angles and injected real and reactive powers have to fulfill the power flow equations in all distribution network nodes. In power flow calculations each network node is modeled as a slack node (constant voltage magnitude and angle), as a PV node (constant active power and voltage magnitude) or as a PQ node (constant active and reactive powers). At each node there are 4 variables of which two are now fixed and the remaining two can be calculated using the power flow equations for real and reactive power injections (equation 9). [10]

In the optimization problem the power flow equations are represented as equality constraints. In this case the substation (node 1) is defined to be the slack node and the following equality constraints have to be fulfilled there

$$V_1 - \frac{V_{orig}}{m} = 0 \quad (10)$$

$$\delta_1 = 0 \quad (11)$$

where V_{orig} is the substation voltage with a tap ratio of 1.0.

All other network nodes are defined to be PQ nodes because all active resources operate on reactive power control mode instead of voltage control mode. At the PQ nodes the following in equality constraints have to be fulfilled

$$P_i - P_{geni} + P_{loadi} = 0 \quad (12)$$

$$Q_i - Q_{geni} + Q_{loadi} = 0 \quad (13)$$

where injected powers P_i and Q_i can be calculated from equation 9, P_{geni} is the generated real power at the ith node, P_{loadi} the consumed real power at the ith node, Q_{geni} the generated reactive power at the ith node and Q_{loadi} the consumed reactive power at the ith node.

The total number of equality constraints is 2**n* where *n* is the total number of distribution network nodes.

2.4.4 Inequality constraints

The inequality constraints are used to model network technical constraints and the capability limits of the controllable resources. The following constraints are used in this case:

$$V_{lower} \leq V_i \leq V_{upper} \quad (14)$$

$$P_{activeimin} \leq P_{activei} \leq P_{activeimax} \quad (15)$$

$$Q_{activeimin} \leq Q_{activei} \leq Q_{activeimax} \quad (16)$$

$$m_{min} \leq m \leq m_{max} \quad (17)$$

$$B_{cimin} \leq B_{ci} \leq B_{cimax} \quad (18)$$

$$S_{ij} \leq S_{max} \quad (19)$$

The first inequality constraint (14) states that all network voltages have to remain between feeder voltage limits. The second (15) constraint sets the limits for real powers of controllable active resources and the third constraint (16) sets the limits for reactive power of controllable active resources. These are the limits of continuous control variables in $\mathbf{u_c}$ (6). Constraint (17) limits the main transformer tap ratio and constraint (18) the susceptance of feeder capacitors. These are the limits of the discrete control variables in $\mathbf{u_d}$ (5). Constraint (19) limits the flows in all networks branches below the maximum allowed value.

2.4.5 Implementation

The optimization is realized using Matlab Optimization Toolbox. Function fmincon is used. This function realizes nonlinear programming (NLP) and treats all variables as continuous. The voltage control problem includes, however, also discrete variables such as the position of the main transformer tap changer and the switching states of capacitors and reactors. If only a small number of discrete variables exist, all possible switching combinations can be gone through. If, however, the number of discrete components increases a mixed-integer nonlinear programming (MINLP) algorithm is needed. In the literature, the discrete nature of some variables is not always taken into account at all (for instance [11]) or some heuristic method is used. In [12] the MINLP has been implemented in a two-stage manner. At first, a solution is calculated while assuming that all variables are continuous. After this solution, the discrete variables are rounded to their closest integer values and another solution is calculated with the discrete variables fixed. In [13] an iterative procedure is used to assign the discrete variables.

In Finnish distribution networks, the main transformer tap changer is usually the only discrete control variable because feeder capacitors are rare in Finnish distribution networks. Therefore, heuristic methods are adequate for assigning the discrete variables. The algorithm used in this deliverable assigns the tap changer position using a three-stage procedure. At the first round, fmincon is executed assuming that also the tap changer position is a continuous variable. After the first round, the two tap changer positions on both sides of the calculated value of the tap changer position are selected. The second and the third round execute fmincon using the two previously selected tap changer positions. The alternative with the smallest value of the objective function is selected. Another option would be to use the method used in [12] where the discrete variables are rounded to their closest integer values after the first round. In future, it will be studied whether adding the third calculation round is sensible.

It is not sensible to change the set points of control devices if the benefit of alteration is not large enough. To avoid changing the network state when the benefit is negligible, an algorithm part represented in Figure 9 is added. This algorithm part calculates the value of the objective function also using the current set points and the new set points calculated by the optimization algorithm are given to the controllable resources only if the value of the objective function decreases more than a set limit.

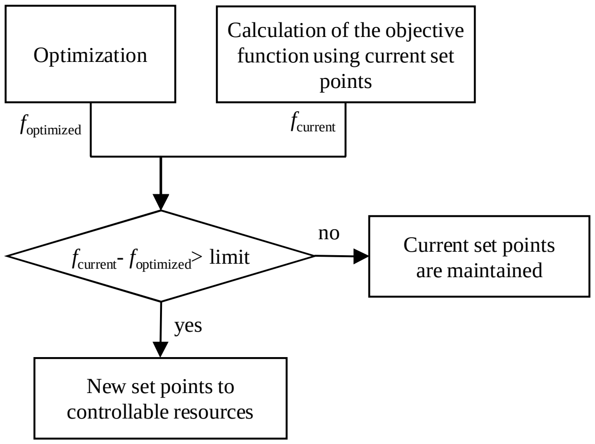

Figure 9. The algorithm part that checks whether to execute the changes suggested by the optimization algorithm.

3 Conclusions

This deliverable presents a detailed definition of one coordinated voltage control algorithm. The algorithm consists of rule based parts and optimizing parts and the parts can also be used separately. The defined control algorithms are implemented as Matlab programs but have so far been tested only using single load flow calculations. In future, also time domain simulations will be conducted and the benefits of different algorithms will be evaluated using statistical planning method.

4 References

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