ONLINE CLOSED-LOOP OPTIMIZATION OF DISTRIBUTION NETWORKS

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ABSTRACT

Distribution system operators are seeing more and more distributed generation installations being connected to medium voltage networks. This forces the system operator to operate a secure, reliable, and economic network closer to technical limits and quality limits as well as meeting requirements from transmission system operators at the point of power delivery. This paper presents an optimization algorithm for distribution networks when used as part of a distribution management system to support the operators to meet all these constraints. Experience has shown that there is actually sufficient controllable equipment in distribution networks to allow for optimization algorithms to be used. The actual implementation meets the performance requirements of an online distribution management system. Currently, open-loop mode is in operation in a large distribution system and closed-loop mode is presently being brought to service.

INTRODUCTION

Distribution networks are more frequently being operated close to their limits, which is mainly due to rapid expansion of distributed energy generation. These limits include technical constraints such as equipment ratings as well as quality requirements such as voltage limits and requirements from transmission system operators. This might be the specification of a minimum power factor, limits for reactive power demand and injection with penalties in case of limit violation, or a maximum active power demand at the point of power delivery with the right to request load shedding from the distribution system operator to avoid or clear limit violations. Additionally, distribution system operators are interested in economical operations within regulatory frameworks, which include avoiding unnecessary losses.

In order to ensure secure, reliable, and economic network operations, distribution management systems as part of the control centre software are widely used by distribution system operators. This paper presents an optimization algorithm called Volt-Var-Control (VVC) as a part of a distribution management system which is capable of addressing the constraints mentioned above.

Optimal power flow applications are well known for remotely controllable ultra-high voltage and high voltage networks. To apply similar algorithms to distribution networks, the first step is to analyze if the network is sufficiently observable and controllable.

Usually the number of remote measurements in distribution systems is not sufficient to ensure observability. It is common practice to use the available partial information and additionally utilize the statistical information relevant to distribution transformer loads which is supplied by utilities [1]. Based on the available remote monitored information (switching status, measurements), manually entered data as well as system internally derived information (pseudo measurements) the function Distribution State Estimation creates a consistent network representation.

Then, constraints and an appropriate optimization algorithm are modelled. Memory and performance requirements are important implementation issues for online distribution management systems. They are considered appropriately in the software development phase and are verified using the complete DMS data model. The control actions suggested by VVC are evaluated together with the customer using his operational experience and the study mode of the DMS before they are applied to the real-life distribution system.

DMS NETWORK MODEL

The network considered belongs to a DSO in Southeast Asia supplying rural areas. The network extends to a large area and is characterized by comparatively long medium voltage feeders with frequent voltage stability issues. For these reasons, the network features not only a high degree of remote controllable switches in the grid but also remote controllable equipment (in particular, capacitor banks and line boosters) addressing voltage issues.

The power system is divided up into several regions that are controlled by separate DMS. The DMS data model usually starts at the HV-side of the HV/MV transformers where electrical energy is drawn from the upstream transmission network and extends to the HV side of the distribution transformers which are modelled as electrical loads. The network model of a typical DMS includes about 24,000 nodes. In normal switching state the distribution system is operated radially without interconnections between the areas supplied by any of the HV/MV transformers. As a consequence for network calculations there are usually several contiguous networks; in this paper the term “network” refers to such a contiguous network. These networks are not defined statically, but depend on the actual switching state. The topological evaluation and the setup of the networks have to be done prior to each calculation.

The considered DMS data model splits up into about 25 networks in normal switching state. The largest one includes about 3,000 nodes

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FORMULATION OF THE OPTIMIZATION PROBLEM

The optimization problem is described mathematically by constraints, control variables and the objective function. Constraints are equipment ratings, load voltage requirements and requirements of the transmission system operator at the point of power delivery. Control variables are all remote controllable equipment with adequate influence on the constraints.

Constraints

Following constraints are considered by VVC:

Table 1: Constraints

Element	Constraint
Transformers	Maximum current
Power Lines	Maximum current
Nodes	Maximum voltage
	Minimum voltage
External Injections	Minimum power factor
	Maximum active power flow
	Maximum reactive power flow
Outgoing Feeder	Maximum active power flow
	Maximum reactive power flow

For all constraints two values are provided. A less restrictive value called soft constraint and a more restrictive one called hard constraint. The optimization algorithm is allowed to violate soft constraints if otherwise no solution can be found. In contrast, hard constraints must always be fulfilled.
The values of the maximum current constraint of transformer elements is calculated from the rated data of the transformer and two system global factors, one for the soft and one for the hard constraint.
For the power lines the maximum current constraints are calculated by their limiting thermal current and two system global factors, one for the soft and one for the hard constraint
For the node voltage constraints four system global factors are defined. Two factors are used for the soft and hard limit of the maximum node voltage and two for the soft and hard limit of the minimum node voltage. The constraint value is obtained by multiplying the appropriate factor with the nominal voltage of the node. In order to reduce the number of constraints node voltage constraints are only considered for nodes with a busbar, an electrical load or an external injection connected to.
The minimum power factor constraint and the maximum active and reactive power flow constraints for external injections are intended to model the requirements of the transmission system operator at the point of power delivery. The soft and hard limit can be defined by the user for every individual external injection element. If no individual power factor constraint is defined system global default values for the soft and hard constraint will be used.
For each outgoing feeder in the HV/MV substations additional constraints for the maximum active and reactive power flow can be defined by the user. They are intended to limit the power flow for the individual feeders. This allows for a more fine-grained control over the area affected by active power demand reduction than using the constraints of the feeding external injection.

Control variables

A major prerequisite to optimization is that there are sufficient control variables, i. e. remote controllable equipment in the network with adequate influence on the constraints. Besides the on-load tap changers of the HV/MV transformers the considered network features remote controllable capacitors in HV/MV substations and in the grid as well as autotransformers with on-load tap changers (line boosters), usually equipped with voltage regulators. Thus, following control variables are available:

Table 2: Control Variables

Elements	No. of
Shunt capacitor banks in HV/MV substations	~30
Shunt capacitors in the MV feeders	~280
HV/MV transformer tap positions	~80
Line booster tap positions	~2
Automatic voltage regulator setpoints	~40

In the HV/MV substations there are usually three individually remote controllable capacitors connected to the MV busbar (capacitor bank). In the feeder there is usually a single remote controlled capacitor. All capacitors can only be switched on and off by corresponding circuit breakers or load break switches. A continuous regulation of the reactive power is not available. To determine if a capacitor bank or a single capacitor in the feeder is allowed to be used as a control variable, several remote controllable selector switches and indications, which state if a command can be issued to the corresponding switch, have to be evaluated dynamically. Otherwise, it might not be possible to set up the network according to the optimization results. For all remote controllable equipment there are LOCAL/REMOTE selector switches to prohibit or allow remote operation. A capacitor may only be used as control variable if the corresponding selector switch is in REMOTE position. Furthermore, there is an AUTO/MANUAL selector switch to allow or prohibit automatic switching of the capacitors depending e. g. on the power factor of the connection point. If this switch is in AUTO mode the capacitor must not be used as control variable. If the operator has set an Inhibit of Command tag then the capacitor must not be used as control variable as well. To avoid too frequent

switching actions on the same switch, a minimum delay time between subsequent switching actions is defined. As long as this delay time has not elapsed the capacitor must not be considered as a control variable.
The on-load tap changers of HV/MV transformers may be used as control variables if their LOCAL/REMOTE selector switch is in REMOTE position and, if present, the automatic voltage regulation is switched off and no Inhibit of Command tag is set.
For the line boosters the same checks for LOCAL/REMOTE and Inhibit of Command tags are performed. The difference to the HV/MV transformers is that line boosters are allowed to be used as control variables if their automatic voltage regulation is switched on. In this case, the optimization has to provide a voltage setpoint as a result. Otherwise the optimal tap position has to be provided.
Voltage setpoints for automatic voltage controllers are continuous control variables; whereas on/off states of the capacitors and tap positions are discrete control variables. The optimization algorithm has to deal properly with both kinds of control variables.
All control variables mentioned above have a major influence on voltage and the reactive power balance. There are only minor effects to the active power demand. The main influence on the active power demand is achieved by properly modelling the loads' voltage dependency. Reducing the voltage profile across the feeders correspondingly reduces the load demand. As long as the node voltages are kept within acceptable limits, this effect can be used by the optimization to reduce the active power demand.

Operating modes

The optimization algorithm provides three operating modes called Volt Control, Var Control and Integrated Volt/Var Control. The objective of Volt Control is to reduce the area's active power demand, whereas the objective of Var Control is to ensure that the power factors at the points of power delivery are maintained above acceptable limits. Integrated Volt/Var Control combines both of them in a single optimization. The desired operating mode can be set by the user for the whole network and can additionally be altered for individual outgoing feeders of the HV/MV substation. This allows to execute Var Control for the whole network as a default operating mode and to enable Volt Control for an individual feeder only, e. g. under peak load conditions.
The operation modes differ in the sets of constraints and control variables that are included in the mathematical formulation of the optimization problem. Table 3 shows a summary of the constraints used for the different operating modes.

Table 3: Constraints according to operating mode

Element	Constraint	Volt	Var	Int.
Transformers	Max. current	X	X	X
Power Lines	Max. current	X	X	X
Nodes	Max. voltage	X	X	X
	Min. voltage	X	X	X
External Inj.	Min. power factor		X	X
	Max. active power	X		X
	Max. reactive power	X		X
Feeder	Max. active power	X		X
	Max. reactive power	X		X

The equipment ratings modelled as maximum current constraints of power transformers and power lines are considered in all operating modes. The same holds for the node voltage constraints. For Volt Control the maximum power flow constraints for external injections and outgoing feeders are taken into account, but the minimum power factor constraints of the external injections are ignored. If the optimization is set to Var Control mode the minimum power factor constraints are considered, but the power flow constraints are not. For the Integrated Volt/Var Control mode all defined constraints are used by the optimization algorithm.
The control variables for the different operating modes are selected according to their main influence on the operating mode's objective. In order to reduce the area's active power demand by Volt Control the HV/MV transformer on-load tap changers and the line boosters are used to reduce the voltage level along the feeders within acceptable limits and, as a consequence, reduce the active power demand of the electrical loads according to their load-to-voltage dependency. In Var Control mode the shunt capacitors in the HV/MV substations and in the feeders are used to maintain the power factor at the point of power delivery above an acceptable limit. The Integrated Volt/Var control uses all available control variables. Table 4 gives a summary of the control variables used in the different operating modes.

Table 4: Control variables acc. to operating mode

Control variable	Volt	Var	Int.
Shunt capacitor banks in HV/MV substations		X	X
Shunt capacitors in the MV feeders		X	X
HV/MV transformer tap positions	X		X
Line booster tap positions	X		X
Automatic voltage regulator setpoints	X		X

Figure 1 presents a simplified schematic diagram showing the placement of the remote controlled equipment used as control variables in the MV grid.

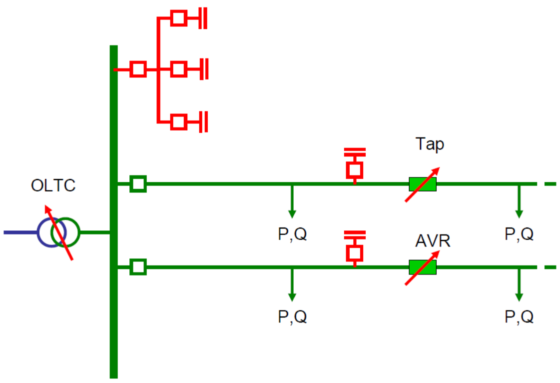

Figure 1: Schematic Diagram of Control Variables

The active control variables are gathered dynamically depending on the actual switching state. For each potential control variable in the MV grid the corresponding outgoing feeder is figured out by topological search. Depending on the operating mode of this feeder, either inherited from the setting of the whole network or explicitly entered by the user, the element is included as control variable. The operating mode of the network determines if the on-load tap changers of the HV/MV transformers are included as control variables.

Objective Function and Solver

The mathematical description of the optimization problem does not depend on the operating mode. All VVC modes are described as a problem of quadratic programming (QP) [2] with the objective function of minimizing network losses. The selection of the objective function is secondary, because the main objective of VVC is to find a network state that meets all of the constraints. Choosing the minimization of the network losses as objective function gives additionally an economical benefit if there are several solutions that fulfil the constraints.

The input of the QP is a quadratic approximation of the objective function with respect to the control variables and a linear approximation of the constraints. The solver, based on Beale's algorithm, finds the optimal settings of the control variables which are all treated as continuous control variables. To account for the discrete values of control variables describing the on/off state of capacitors and tap positions, they are fixed to their possible discrete values by a branch-and-cut algorithm.

As a first step, the optimization algorithm tries to find a solution that meets all soft constraints. If no solution can be found, violations of soft limits are allowed, and a second run of the optimization using hard limits is executed. If there is no solution within the hard limits, the optimization problem cannot be solved.

It has turned out that the number of constraints has a major influence on both memory requirements and calculation time. Thus, a lot of effort has been put on reducing the number of constraints without counteracting the objectives of VVC. Because there are a lot of passive nodes in the network, i. e. nodes that are just connecting several power lines but without any customer connected to, the number of node voltage constraints can significantly be reduced if constraints are only included for nodes that contain a busbar, an external injection or an electrical load. Further improvements could be achieved by neglecting branch current constraints if the actual current of the branch is "far away" from the corresponding soft limit. These measures mainly improve the performance of the solver. During the last step of the optimization algorithm all current constraints are taken into account to verify that no invalid solution has been introduced by these simplifications.

RESULTS

The results of VVC are the optimal settings of the active control variables. HV/MV transformer tap positions, line booster tap positions, automatic voltage regulator setpoints and on/off states of capacitors in the feeders can directly be applied to the process. However, special attention has to be paid to the capacitor banks in the HV/MV substations.

Usually the individual capacitors of a capacitor bank have identical electrical characteristics. The result of the optimization only returns the number of capacitors that have to be connected to the MV busbar in optimal state. During the optimization there is no relationship to the actual switching state of the capacitor bank. Thus, after the optimization a result preparation is necessary to minimize the number of switching actions. The basic idea is that the capacitors should remain in their actual switching state if possible. If actually one capacitor is switched on and in the optimal state it should be two, the solution is clearly to execute one switching action to switch on another capacitor. For the optimization switching off one capacitor and switching on two different ones would be an equivalent solution, but this is not acceptable from the operation's point of view. If there is more than one capacitor that can be chosen for the necessary switching actions, the one with the lowest operation count will be selected.

The results of VVC are presented to the user by tabular displays showing the actual and the optimal value of all control variables. Active and inactive control variables can clearly be distinguished. In open-loop mode the user can optionally review the suggested control variable settings by power flow simulations. From the tabular display he can choose to apply all the suggested settings or select any subset of the control variables. After confirmation the commands are built and issued to the equipment in the grid.

In closed-loop mode the confirmation of the commands by the user is not needed. As soon as the results are available the commands are automatically build and issued without any user interaction. In closed-loop mode all of the suggested control variable settings are applied. It is not possible to select a subset.

If no solution can be found clear diagnostic messages are presented to the user, e. g. in case the calculation does not converge. Commonly there is no solution of the optimization problem because some of the constraints could not be met by solver. They are reported to the user so that he can decide to change their hard or soft limits.

OPERATIONAL EXPERIENCE

VVC is fully integrated in the distribution management system, running in the background on medium-voltage networks with typically up to 1,200 nodes. VVC is executed at regular intervals, usually every 15 minutes. Exclusive VVC memory is sized according to the expected largest network of about 8,000 nodes that occurs rarely when two galvanically isolated networks are temporarily tied together. The required memory size is 640 MB which not an issue for modern control centre workstations. The calculation time for networks of typical size is within the range of 10 to 20 seconds per network using a full three-phase unbalanced network model. The calculation performs adequately when used in an online DMS.

Actually, VVC is running in open-loop mode, so that the operator must review and approve all the suggested control actions. VVC results are verified by study mode power flow simulations and are found to be reasonable. Closed-loop mode is currently being brought into service.

CONCLUSION AND OUTLOOK

This paper shows that the application of a VVC optimization algorithm can support distribution system operators in ensuring secure, reliable, and economic network operations under consideration of technical constraints, quality constraints, and transmission system operator requirements at the points of power delivery. Already today, there are distribution networks which feature sufficient control variables and the installation of controllable equipment is continually increasing. It has been shown that the VVC algorithm can be included in an online DMS without causing performance problems or issues with insufficient memory. VVC has been tested in open-loop mode using real-life networks yielding reasonable results. Future extensions of the VVC will include active power control of dispersed generation and monetary objective functions, e. g. to account for penalties in case of reactive power limit violations.

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