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A new approach to control coordinated voltage in radial distribution feeders

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ABSTRACT: This paper deals with various aspects of coordinated voltage control in radial distribution feeders that are a type of electric power systems. At first we introduce an abstract of the paper and tutorials on voltage control and the search methods. Then we deal with the coordination of cascaded tap changers in radial distribution feeders. Unnecessary operations of the tap changers and consequently unnecessary wear as well as poor voltage quality are the result of poor coordination. A tuning rule for the local controllers as well as two new centralized schemes is proposed. We implement some simulation and result based on load patterns recorded during different seasons show that when tuned according to our recommendation, tap changers perform some 13 % fewer operations compared to when the present tuning is in use.

Keywords: controlling, coordinated voltage, radial distribution feeders, power electronic systems

INTRODUCTION

Several large-scale disturbances emphasized that secure operation of interconnected power systems requires coordination between transmission system operators (TSOs). The hierarchical voltage control systems named Coordinated Voltage Regulation (CVR) or Secondary and Tertiary Voltage Regulations (SVR and TVR), depending on their hierarchical level. The control of voltage and reactive power is a major issue in power system operation. Because of the topological differences between distribution and transmission systems, different strategies have evolved. This paper contains contributions of novel voltage control schemes for distribution and transmission systems. Whereas the work on distribution systems is directed at the normal state operation, the work on transmission systems mainly concerns the emergency state. The overall theme of the paper is to explore and demonstrate how communication and centralized measurements can be used to improve existing voltage control. A particular interest is taken to the development of control schemes to avoid so-called voltage collapse, which can result in widespread outages. The total cost of a widespread outage can be hundreds of millions, or even billions, of (US) dollars (Balanathan R al, 1998) and (Berizzi A al, 1998).

On the other hand, where the consolidation of control areas has not occurred, new strategies to coordinate the actions of those entities have been studied and implemented. The purpose of voltage control in distribution networks is to compensate for load variations and events in the transmission system, such that customer supply voltages are kept within certain bounds. A number of on-load tap changers (OLTCs), each capable of regulating the voltage of the secondary side of a transformer at one point in the network, are available in the distribution systems for this purpose. The control is discrete-valued, typically with steps of 1-3 %. The systems are most often radial, with tap changers cascaded in up to three levels.

Therefore, interaction among OLTCs at different voltage levels is possible. OLTC control is presently based on a local voltage measurement in each substation .There is normally no coordination of OLTCs on different voltage levels or in different branches of the network. Figure 1 shows a voltage measurement recorded in an early study (Borghetti A al, 1997) at a 10 kV substation with the conventional voltage control in operation .The substation is supplied through three cascaded tap changing transformers .There were 24 voltage steps1 during the 150-minute recording. Nine of the steps are due to local tap operations in the substation (marked ±1), and the rest are due to tap operations and the connection of capacitor banks higher up in the network. Most of the tap operations made in the substation counteract the effect of tap changers higher up in the network. These operations are preceded by"spikes" in the voltage. The figure clearly shows that there are oscillation and interaction phenomena between OLTCs at different voltage levels (Breuker D, 1998) and (Ca˜n´ızares CA al, 1996).

With coordinated control of tap changers it should be possible to completely eliminate, or at least reduce the number of, counteracting tap operations. Consequently, the total number of operations and the number of voltage spikes due to OLTC interaction would decrease. Wear on the tap changer mechanism is the most common reason for transformer maintenance and therefore a reduction of the number of tap operations is highly desirable. Poor coordination of cascaded tap changers can also be dangerous from a voltage stability point of view. A sudden voltage drop in the feeding network may result in voltage overshoot at the load level due to OLTC interaction (Calovi´c MS, 1984) and (CIGRE, 1998). Since loads are voltage sensitive, this will increase the loading of the feeding transmission system. Step disturbances are likely to arise during voltage instability incidents as a result of tripped lines or generation units in the transmission system (CIGRE, 2000).

During such incidents the transmission system is already operating close to its transfer limits and increased loading is highly undesirable. Referring to the role of OLTCs in voltage instability incidents, the new control schemes presented in this paper can prevent voltage overshoot due to voltage drops in the feeding system (Cooke GH al, 1992). With coordinated OLTC control, it would also be possible to use alternative control strategies during voltage instability incidents.

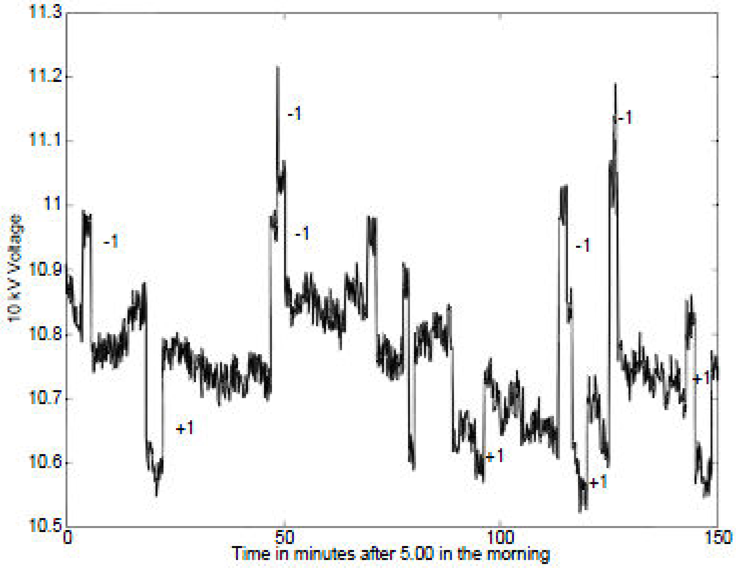


Figure 1.Field measurement of the voltage in the 10 kV substations during load pickup. The tap operations made locally are marked with +/-1 [11]. The large number of voltage spikes is an indication of OLTC interaction.

Related Work

Different approaches have been taken to the problem of extending maintenance intervals for tap changers. New designs where the mechanical switches, which are the critical part from a maintenance perspective, are totally replaced by power-electronics have been proposed (Elmqvist H al, 2000) and (Pal MK, 1992). Such tap changers can be used also for rapid compensation of voltage dips and continuous regulation of the voltage. However they are more expensive, less robust to fault currents and have higher power losses than mechanical tap changers. Thyristor-assisted tap changers, which retain the mechanical switches but divert the current through the switches using power-electronics during tap changing, have also been proposed (Pal MK, 1995) and (Pessi E al, 1990). There is no current through the tap changer during switching and consequently no arcing and the wear on the tap changer is therefore reduced. Since the current is flowing through the mechanical tap changer between tap changes, no extra power losses are added by the power electronics in between tap changes. Ref. (Plaat A, 1996) employs combinatorial optimization to coordinate tap changer and capacitor bank control based on the full nonlinear power flow formulation. Their approach is similar to the volt/var control problem formulated by (Romero Navar, 1999) but with the aspiration of real-time implementation. Results from field tests of the actual implementation are given in (Roytelman I al, 2000). Furthermore, ref (Roytelman I al, 1995) discusses modifications of the scheme to account for the effects of remaining local controllers in the controlled distribution system. Another approach by (Schaeffer J al, 2000) employs variable-structure control, a successively linearized system model, and centralized information for the coordination of tap changers.

The large-disturbance stability properties of a system representation with continuous approximations of the OLTC dynamics are investigated using Lyapunov theory (Shannon CE, 1950).Ref. (Shuttle worth R al, 1996) examine the effect of different load characteristics on the existence of the studied limit cycles and shows that for some load characteristics, it is indeed possible to avoid limit cycles by retuning the OLTC control system. This paper also extends some of the results to the multi-tap/multi-load case.

The work on emergency control schemes can be divided into approaches using only local measurements and those that rely on centralized measurements. The main advantages of the local schemes are the low installation cost, fast control response and reliability that can be achieved since they do not rely on communication. Fast response is necessary if the system aims at arresting short-term voltage instability. For emergency controllers with the purpose of arresting long-term voltage collapse, response times of up to a minute or so is acceptable.

The main drawback of the local schemes is the difficulty of tuning such schemes, and that coordination of emergency controls in different locations is difficult to facilitate using only local measurements. Emergency control schemes can also be classified as being either of a rule based or of an algorithmic type. Rule-based schemes are technologically simple to implement but require engineering judgment and specific knowledge of the system in which the system will be installed. The efficiency of a rule-based system may be limited for disturbances that were not foreseen during the design of the system. On the other hand, algorithmic approaches are often theoretically more complicated but do not require specific knowledge about the system, and are applicable to any system as long as a system model is available. Since the algorithmic approaches make their decisions based on a system model, they are better equipped to handle disturbances of kinds not foreseen during the design stage and to coordinate emergency controls of different types and in different locations.

The use of centralized measurements mainly enables better coordination of actuators in different geographic locations compared to schemes using only local measurements. Compared to the rule-based schemes, algorithmic schemes can better assess the effect of emergency controls and also enable better coordination of actuators of different types.

It should be noted that a centralized scheme can coexist with and complement a local scheme. The main task of the centralized scheme is then to steer the system trajectories away from operating points where the local scheme or other protection systems are activated. Since the centralized scheme offers better coordination, this can hopefully be achieved with less drastic emergency controls than would be executed by a standalone local scheme. Because of the longer response time of the centralized systems, they are presently better suited for protection in the long-term time frame than the short-term. Note, however, that fast wide-area communication systems (WAMS) are becoming available (Taylor CW, 2000), which will make the use of centralized strategies feasible also for schemes aimed at short-term voltage collapse. Which contains a significant amount of heating loads, the risk of long-term voltage collapse is considered greater than that of its short-term counterpart.

MATERIAL AND METHODS

The basic assumption when using search methods is that all decision variables can be represented in a discrete state space (normally a graph), and that a solution can be given as a sequence of state transitions. Take for example the classic problem of route-finding (Taylor CW, 2000). The problem statement is as follows: A person is at present in Lund and wants to reach using the shortest possible route. Distances are indicated on the lines drawn between the towns. In the search problem formulation, each town is represented by a state (or node) in a graph and the available state transitions by arcs in the graph. Such transitions are referred to as actions. In the literature on game tree search, the equivalent term move is most often used for the transitions. Each transition has an associated cost, which in the example is taken as the length of the road to the next town. The initial state is Lund, the goal state is and the available actions are given by the road network in the region. A sequence of actions is called a path, and finding a solution to the problem is thus equivalent to finding a path that terminates in the goal state. Such paths are called solution paths. The path cost is the sum of the costs of each individual action in a path.

Uninformed Search

Many different methods for exploration of a search state space have been proposed. Some examples are depth-first, random-walk and breadth-first. We will concentrate on the depth-first2 method, which is an example of an uninformed search method. Uninformed search methods explore the state space in a blind Solving Problems by Search manner without knowledge of the environment–only the available actions in each node are known. This method always expands the first node given by the success or function until it reaches a dead-end node where no more transitions are available. Then it retraces its steps until it reaches a node with success or that were ignored at the first visit, and expands the first of those.

The search continues in this way until a solution path is found or until all possible paths in the state space have been expanded. In this way, the state space is organized in a tree structure where the initial state corresponds to the root of the tree. Since the uninformed search has no preference between different actions, the successor function may return nodes in an arbitrary order. Assume for the sake of presentation that the successor function returns the available actions in alphabetical order. A depth-first search would then expand the sequence, in an infinite cycle. The sensitivity to cycling paths is an inherent property of depth first search for problems where the state space is a graph, which in this case prevents the search from finding a solution. A simple, although partial, solution is to introduce a maximum search depth corresponding to the maximum length of any explored path and consequently to the number of actions necessary to reach the goal state.

Search Enhancements

From the uninformed search example, we see that there is much room for improvement of the basic depth-first search. It is sensitive to cyclic paths, it spends much time in fruitless parts of the search tree and it cannot guarantee optimality3.1. Short Introduction to Search 65of a solution path unless the complete state space is searched. These drawbacks make the basic depth-first method inadequate for most practical problems, since the search effort would be huge when all possible paths have to be explored. However, many enhancements to the basic algorithm have been suggested. A more complete survey of such enhancements is given in (Tuan T al, 1994).

Transposition tables are often used to store such directing knowledge about sub trees already evaluated. By storing knowledge about evaluated states or sub trees in a table along with some additional information about the status of the search, a transposition table may reduce the search tree considerably without sacrificing completeness of the search, since redundant searches are eliminated. Generally, the potential reduction depends on the application. A detailed study on the implementation of transposition tables and their average effect on the size of the search tree in chess can be found in (Taylor CW, 2000), who reports about a 40 % reduction of the search tree. Transposition tables can reduce the search tree for all search problems where the state space is a graph, even if no application-specific knowledge is used. Their implementation, most often as hash tables, are however often application specific since different applications use hash keys of different lengths.

In the uninformed example, nodes were expanded in alphabetical order. The purpose of move ordering is to organize the search such that the search space is explored in an order where the goal node is most quickly reached. Consider for example how such domain-specific knowledge can help reduce search complexity by move ordering: Assume in our example that it is known that the goal node is north of the initial state (Lund). If moves leading north are expanded first, the search will explore the nodes, thus visiting only the four nodes in the optimal solution path.

Using more formal definitions, the strategy described above minimizes an estimate $h(s)$ of the remaining distance $h*(s)$ to the goal node from the last node in the path s. Typically, the exact distance $h*(s)$ is hard to compute, but approximations can often be found using domain-specific knowledge. The estimator function $h(s)$ is often referred to as a search heuristic.

In the example, nodes with lesser estimate of the remaining distance are expanded first.3.1. Short Introduction to Search strategies, which aim to minimize the remaining distance to the goal $h(s)$, are called Greedy strategies. Another widely used strategy is to expand nodes in the order minimizing $f(s) = g(s) + h(s)$, aiming to account for the cost of the next segment in the candidate path as well as the goal distance. Such move ordering is used for example by the A∗-method. The construction of search heuristics requires sound domain knowledge.

A poorly designed search heuristic can often do more harm than good since it systematically leads the search off track. A desired property of search heuristics is that they are admissible, meaning that they never overestimate the effort of reaching a goal node, that is, $h(s) \leq h*(s)$.

The heuristic devised here illustrates one of the pitfalls in designing such functions–it only works when travelling north. The straight-line distance between two towns is a more robust and also admissible heuristic, which works when travelling between any two towns.

If all action costs are non-negative, the accumulated action cost $g(s)$ always increases as the search progresses deeper into the tree. Therefore, for the path s, $LB(s) = g(s)$ can be used as a lower bound on the cost of any solution path via node s. If we have an admissible search heuristic $h(s)$, the stronger criteria $LB(s) = g(s) + h(s)$ can be used as a lower bound. Consequently, once a solution path $s*$ with $g(s*) = b$ has been found, all sub trees originating from the last node in the path s where LB(s) ≥ b can be pruned without risk of ignoring better solutions than the one already found.

Lower bound pruning can have a dramatic effect on search complexity, especially when used in conjunction with good move ordering criteria so that good solution nodes are found early in the search.

Combinatorial Optimization using Search

The idea of using search methods to solve combinatorial optimization problems is not new. Well-known methods such as hill-climbing, tab u-search and branch-and-bound methods are all variations on this theme
Hill-climbing is a special case of best-first search where the search tree is not retained during the search. Tab u-search is a type of best-first search where a special table, similar to a transposition table, is used to store states that must not be revisited. Branch-and-bound search uses a mechanism similar to lower bound cut-off to prune sub trees that cannot contain solutions better than one already found. Optimization by genetic algorithms can be seen as a random-walk search method, which uses a random mechanism to overcome local minima. A fitness criterion in terms of a cost function is used to facilitate successor generation and thereby concentrate the search on promising parts of the search space. The approach taken in this paper uses a more traditional search formulation in order to benefit from the many search enhancements developed and analyzed in the research on game tree and single agent search. A combinatorial optimization problem
Minimize J(x)
Subject to x ∈ S(x0)
X integer
G(x) ≤ 0

Can be solved by search as follows: the search state space is given by the integer constraint and the limits on the optimization variables given in S(**x0**), and **G**(**x**) defines a goal test. The optimization problem is equivalent to searching the state space for the node that has the minimum value of the cost function among all nodes that pass the goal test. The vector of optimization variables is denoted **x** and **x0** is the initial state. In case the problem contains a mix of continuous and discrete optimization variables, each evaluation of the cost function involves the solution of a reduced (continuous) optimization problem where the discrete optimization variables are fixed.
An important advantage over conventional optimization methods when applied to the voltage control application studied in this paper is that the search method can provide not only the optimal control state **x**∗ but also a switching sequence to reach **x**∗ from the initial state.

Network Model

Throughout the simulations a single-line equivalent of the power system has been used. Transformers are modeled by an ideal transformer in series with a short-circuit impedance and the distribution lines as simple series impedances. Tap operations are modeled by changes in the transformer ratio. A constant frequency model of the network with the feeding network as a venin source is used.

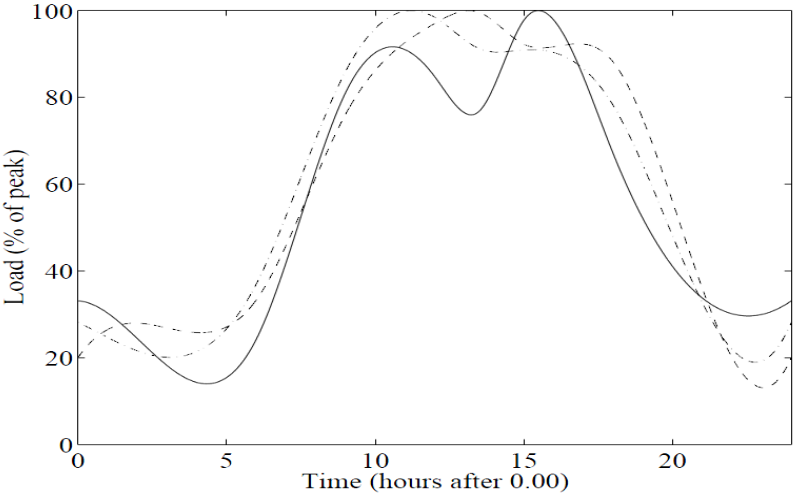


Figure 2. The load curves used for the 50 kV (solid line), 20 kV (dashed) and10 kV (dash-dotted) loads.

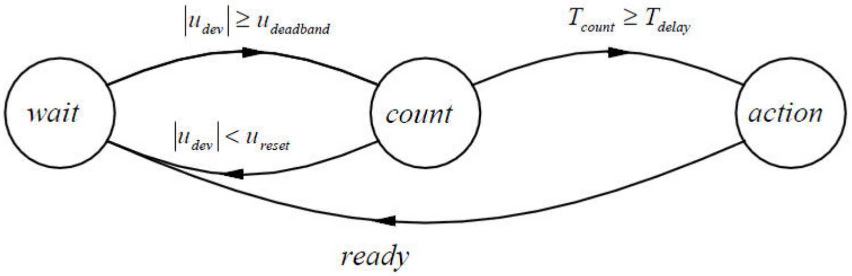


Figure 3. State graph illustrating function of local OLTC control systems.

If the limit is exceeded, there is a transition to state count. When entering count a timer is started and is kept running until either it reaches the delay time, firing a transition to the state action, or the voltage deviation is less than the reset voltage, firing a transition to the state wait and reset of the timer. In the state action a control pulse to operate the tap changer is given. When the operation is done, the control system gets a ready signal from the tap changer and returns to state wait.

The aim of this paper is to show that the number of tap operations can be reduced without increasing the voltage deviations. Therefore, the dead bands have been fixed at the present settings (1.5 %) in the simulations and field measurements.

A.3.1 Response to Voltage Disturbance in Feeding Network It is a common observation in Sydkraft's distribution networks that the delay times of cascaded tap changers are tuned to the same value. Figures 4–5show excerpts from simulations with different sets of time delays. There are three voltage steps at the 132 kV-level (solid line) due to the connection of three capacitor banks at bus 1 at simulation time 330, 345 and 360 min. In Figure 4, the same delay time is used for all the OLTCs. After the second and third step voltage steps, more than one of the OLTCs compensate for the voltage deviation at the same time. Since the voltage disturbance already has been compensated for at the highest level, the lower level tap changers have to make reverse tap changes. In Figure 5, the OLTCs are tuned according to the rule derived, with longer delay time for lower level OLTCs. Four tap operations are avoided with the new tuning.

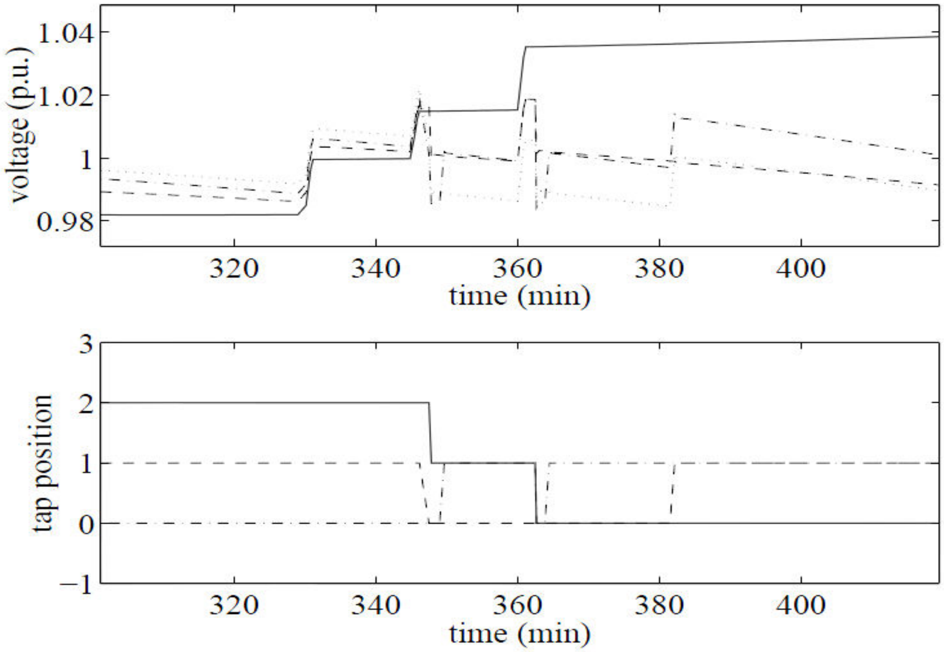


Figure 4. Simulation, connection of capacitor banks. Conventional control with delay times 110 s. Top, node voltages-132 kV (solid line),50 kV (dashed), 20 kV (dotted) and 10 kV (dash-dotted).Bottom,132/50 kV (solid), 50/20 kV (dashed) and 20/10 kV (dash-dotted).

In the simulations, unnecessary tap operations are avoided by adjusting the time delays. Based on these simulations the following tuning rule for cascaded OLTCs in radial networks, giving gradually longer delay times for lower level units, is therefore proposed:

Set the delay time (T1) of the top level OLTC adequately long to filter out fast transients. For a worst case voltage disturbance at the top level, compute the number of tap operations needed (N1) for the top level OLTC to compensate for the disturbance. For lower level OLTCs, make Tk+1 > NkTk. Check that the delay time of the lowest level OLTC provides fast enough customer voltage restoration.

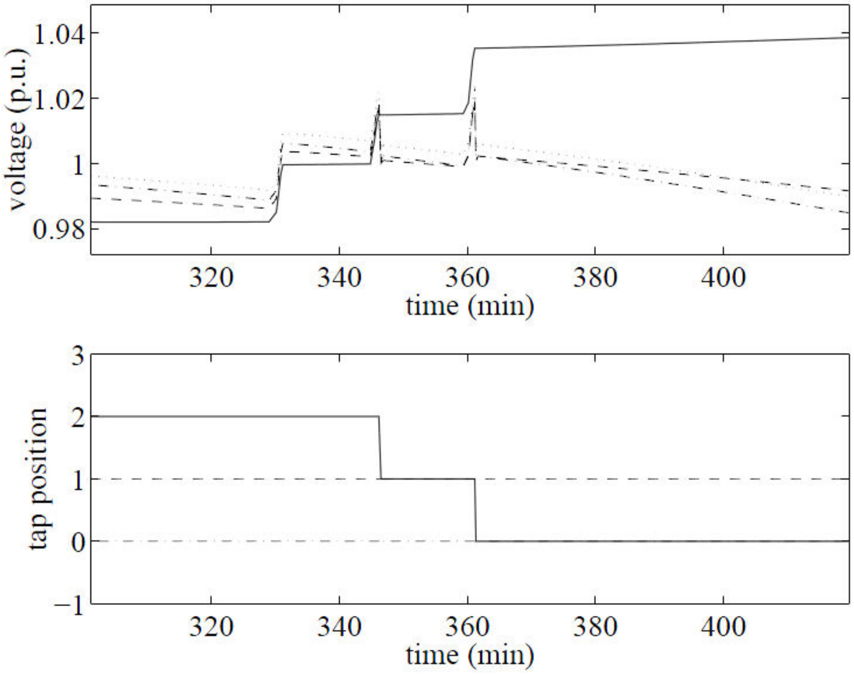


Figure 5. Simulation, connection of capacitor banks. Conventional control with delay times [30, 70, 160] s. Compared to Figure 3, four tap operations are avoided with the new tuning. Load and feeding network disturbances. This type of tuning was initially suggested, but not confirmed.

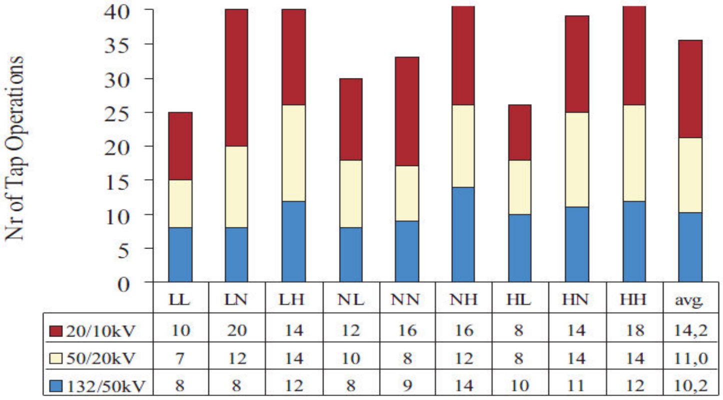
RESULT AND DISCUSSION

The purpose of the simulation is to verify the tuning rule under different load patterns. Nine cases with permutations of low (33 %), normal (66 %) and high (100 %) active and reactive load have been studied. For the case of high active and reactive loading, all transformers are loaded to rated load. Figure 6 shows a bar chart of the number of required tap operations for the different load patterns for the conventional control with the old tuning. The labeling of the bars is made as first active then reactive power with L,N,H for the low, normal and high load level. Thus, the load pattern NH means normal active load and high reactive load. The corresponding bar chart for the new tuning is shown in Figure 7.We can conclude that for all of the load cases, the new tuning reduces the number of tap operations required.

The tap changer operations have been recorded for about two weeks to verify the impact of the OLTC delay times on the number of tap operations. The recordings have been performed for maximum delay time on each control unit (120 s) and for 30 s (132/50 kV), 60 s (50/20 kV) and 120 s (20/10 kV) corresponding to the proposed tuning rule From the recordings it can be concluded that the total number of tap operations has been reduced, from 69 operations/ day to 49 (Figure 8). This corresponds to a 28 % reduction. It is clear that the largest reduction is achieved at the lowest voltage level. A.3.

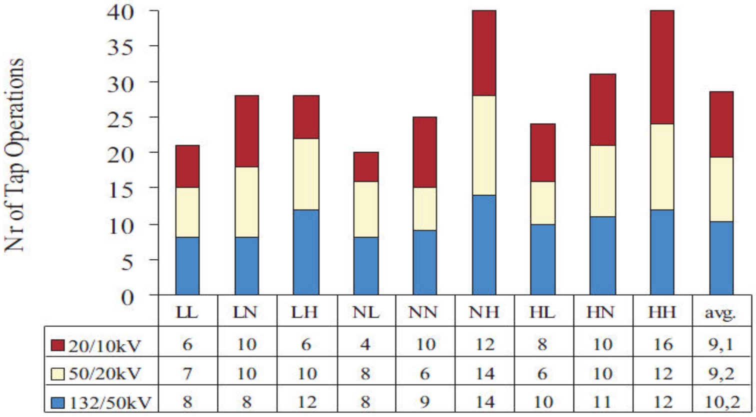
The coordinated voltage control problem is formulated as a multivariable control problem based on on-line constraint optimization. Operational limits, such as line capacity limits or tap limits are specified as inequality constraints. The optimization is dependent on network data.

In this paper the optimization is done statically, i.e., only the latest measurements and control signals are considered in the objective function, as opposed to dynamically where control signals are calculated for times up to a prediction horizon based on both present and old measurements. Using a dynamic approach would improve performance further at the cost of a more complex and computationally demanding optimization.



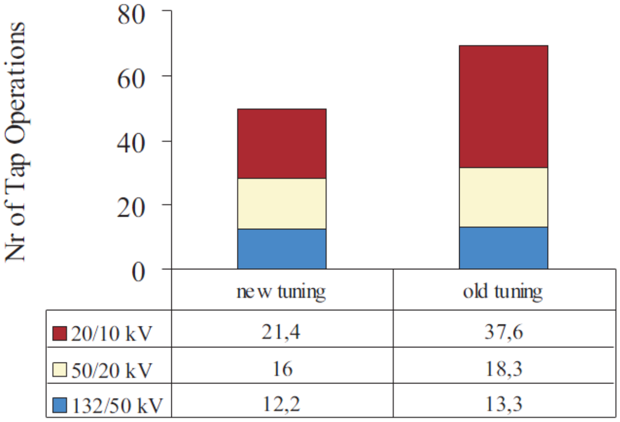
	LL	LN	LH	NL	NN	NH	HL	HN	HH	avg.
🟥 20/10kV	10	20	14	12	16	16	8	14	18	14,2
□ 50/20kV	7	12	14	10	8	12	8	14	14	11,0
🟦 132/50kV	8	8	12	8	9	14	10	11	12	10,2

Figure 6. Simulation. Number of tap operations during daily operation for the nine load patterns. Conventional control with delay times [110,110,110] s. load patterns) number of operations is 35.4 and with the new 28.5, corresponding to a 19 % reduction. The reduction is especially pronounced at the lowest voltage level. This is important since these units are the most numerous because of the structure of the network.



	LL	LN	LH	NL	NN	NH	HL	HN	HH	avg.
🟥 20/10kV	6	10	6	4	10	12	8	10	16	9,1
□ 50/20kV	7	10	10	8	6	14	6	10	12	9,2
🟦 132/50kV	8	8	12	8	9	14	10	11	12	10,2

Figure 7. Simulation. Number of tap operations during daily operation for the nine load patterns. Conventional control with delay times [30, 70, 150] s. Notice the substantial reduction of the number of tap operations made by the 20/10 kV OLTC compared to Figure 6.



	new tuning	old tuning
🟥 20/10 kV	21,4	37,6
□ 50/20 kV	16	18,3
🟦 132/50 kV	12,2	13,3

Figure 8. Chart showing the daily average number of tap operations during atwo week field measurement with the new and old tuning.

CONCLUSIONS

It is an important issue for multi-TSO system to coordinate voltage/reactive power control operations. The aim of this work was to reduce the number of unnecessary tap operations made due to lack of coordination between OLTCs in radial distribution networks. A tuning rule for the conventional OLTC control systems which gives selectivity of cascaded OLTCs in normal state operation has been presented.

The rule assigns long time delay to lower level OLTCs. The tuning rule has been verified in simulations and field measurements, and has been shown to reduce the number of tap operations by a good 20 %, compared to the tuning presently used. A more sophisticated multivariable control scheme based on on-line tap optimization is presented. In simulations, the multivariable control scheme has been shown to reduce the number of operations some further 30 %. The control schemes have been tuned to yield voltage deviations of the same average magnitudes in the simulations as well as the field measurements.

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