Abstract—In weak distribution networks the amount of distributed generation (DG) is usually limited by the voltage rise effect. The voltage rise can be mitigated using passive methods such as increasing the conductor size which can, however, be quite expensive. Also active voltage control methods can be used to reduce the maximum voltage in the network. In many cases active voltage control can increase the capacity of connectable DG substantially which can lead to significantly lower connection costs.

In this paper, operation of an active voltage control algorithm is viewed. The algorithm controls the substation voltage and DG reactive power and determines its control actions based on the state of the whole network. The algorithm is implemented as a Matlab program and communication between Matlab and SCADA is realized using OPC Data Access. Correct operation of the algorithm is verified using Real Time Digital Simulator (RTDS). The same algorithm could also be implemented as a part of the distribution management system (DMS).

Index Terms—Active voltage control, coordinated voltage control, distributed generation, real time simulations

I. INTRODUCTION

The amount of distributed generation (DG) is constantly increasing. The European Union has set ambitious targets of 20 % share of energy from renewable sources by 2020 [1] to reduce gaseous emissions, diversify the energy supply and reduce dependency on fossil fuel markets. To meet the overall renewable energy target a substantial increase in the share of renewable energy sources in electricity production is needed. Renewable electricity is often produced in relatively small power plants whose location is determined by external factors such as wind and solar resources. Hence, power plants using renewable energy sources are often connected to distribution networks. Also, deregulation of energy markets has made distribution network access available to all energy producers and the prices of small generating plants have reduced. [2]

The existing distribution networks are designed based on the assumption of unidirectional power flows. When the penetration level of DG increases, this assumption is no longer valid and the operation and planning principles of distribution networks need to be revised. [2]

DG can have both positive and negative impacts on network operation. It changes the power flows and fault currents in the network and can, therefore, cause problems related to voltage quality, protection and increasing faults levels. In weak distribution networks, the maximum capacity of DG is usually limited by the voltage rise effect. Also the transient voltage variation at generator connection or disconnection can in some cases turn out to be the limiting factor. [2]

At present, voltage rise is usually mitigated by reinforcing the network (increasing the conductor size or connecting to a dedicated feeder) and the operational principle of the network is not changed. This can, however, be quite expensive. Also active voltage control methods can be used to reduce the maximum voltage in the network. Active voltage control can increase the allowed penetration of DG substantially and, therefore, lower the connection costs. [3]

Several active voltage control methods of different complexity and data transfer needs have been proposed in publications. The simplest active voltage control methods are based only on local measurements and do not require additional data transfer between distribution network nodes. When only local measurements are used the voltage rise caused by DG can be mitigated by allowing the DG unit to absorb reactive power or by limiting the active power output of DG when the terminal voltage exceeds its limit (production curtailment). [3]

Coordinated voltage control methods use information about the whole distribution network when determining their control actions and, therefore, data transfer between network nodes is needed. The methods can determine their control operations based on simple rules [4]-[9] or use some kind of optimization algorithm [10]-[16]. The simplest control algorithms control the substation voltage based on network maximum and minimum voltages whereas network voltages can also be controlled using an advanced distribution network management system which controls all components capable of voltage control (e.g. tap changers at substations, power plants, compensators and loads). The most suitable control method is selected based on the structure of the network and the number of components participating in the control.

In this paper, correct operation of a coordinated voltage control implementation is verified using Real Time Digital
The coordinated voltage control algorithm controls the substation voltage and DG reactive power by changing the set points of substation automatic voltage control (AVC) relay and DG automatic voltage regulator (AVR). The algorithm is a slightly modified version of the algorithm presented in [9] and its purpose is to keep all distribution network voltages between acceptable limits.

The algorithm comprises two functions: Basic control is used to restore the network voltages to an acceptable level when network maximum or minimum voltage exceeds its limit. Restoring control is used to restore DG power factor to unity when network state allows it and to normalize network voltages if the voltages in the whole distribution network have remained in an unusually high or low level. Both control functions consist of two parts: the first part controls the substation voltage and the second one DG reactive power.

Two versions of the algorithm have been implemented. In the first one, substation voltage is the primary control variable and DG power factor is changed only if substation voltage control is not able to restore the network voltages to an acceptable level. In the second version, DG reactive power is primarily controlled. Both approaches have advantages and disadvantages: When DG reactive power is the primary control variable, the additional reactive power flow often increases losses. On the other hand, when substation voltage is primarily controlled the number of tap changer operations is increased which increases the maintenance need of the tap changer and causes transient voltage variations to the whole distribution network. Hence, depending on the network and planning principles either one could be more advantageous.

A. Operational principle

The inputs to the algorithm are distribution network maximum and minimum voltages, substation voltage and generator connection point voltage. In the implementation discussed in this paper, substation and generator connection point voltages are measured. Maximum voltage is always located at either one of these and a state estimator is used to obtain network minimum voltage.

In [9] the origin of the coordinated voltage control algorithm input data was not defined and, therefore, existence of a state estimator was not assumed when the control algorithm was defined. In this implementation a state estimator described in [18] is available and some minor modifications that require state estimation are done. In [9] only one tap changer operation was initiated at a time and DG reactive power set point was changed in user-defined steps. In this paper, the calculation of new set points is modified in such a way that only one set point change is needed to restore the voltages to an acceptable level. In substation voltage control the algorithm determines the number of tap operations needed and uses this information to determine the new AVC relay set point. In power factor control state estimation is used to determine the new set point of DG power factor. In power factor control the algorithm uses state estimation also to determine whether DG’s reactive power capability is adequate to lower network maximum voltage sufficiently.

The functional diagram of the basic control when substation voltage is primarily controlled is depicted in Fig. 1. Fig. 2 represents the operation of basic control when DG reactive power is the primary control variable. In the control algorithm it is assumed that network maximum voltage is always located either at the substation or at the generator connection point. It is also assumed that the network is such that there is no need to use DG reactive power control to increase network minimum voltage and, therefore, no part that increases DG reactive power production is included in basic control. The functional diagram of restoring control is depicted in Fig. 3. More detailed flow charts of each control block can be found in [9].

When substation voltage is primarily controlled (Fig. 1) the control operates as follows: If network maximum or minimum voltage exceeds feeder voltage limits, basic substation voltage control is activated. At first, the control determines the number of tap changer operations to be done based on two conditions: Firstly, the other voltage should not exceed its limit after the tap changer operation because this can lead to continuous set point changes and operations of the tap changer (hunting). Secondly, the voltage that exceeds its limit should be restored between acceptable limits if this is possible. The control algorithm assumes that a tap changer operation changes all network voltages by an amount equal to the tap step. So, the number of tap changer operations \( n \) is set such that 1) the other voltage (i.e. voltage not exceeding its limit) is more than \( n \) tap steps away from its limit and 2) the exceeding voltage is less than \( n \) tap steps away from its limit. If the latter condition can not be fulfilled, the largest \( n \) that fulfills the first condition is selected.

After the number of needed tap changer operations is determined, the new substation AVC relay target voltage is determined. The target voltage is set such that after the tap changer operations the substation voltage is near its setting value. Also the set point limits are taken into account at this point.

If basic substation voltage control is activated but is unable to improve network state (determined number of tap changer operations is zero or tap changer operation can not be
initialized because of set point limits), basic power factor control is activated. Basic power factor control reduces the power factor set point of DG AVR (and increases DG reactive power consumption) if this would either lower network maximum voltage or enable basic substation voltage control. The new power factor set point is calculated using state estimation.

When DG reactive power is primarily controlled (Fig. 2) the two control blocks (substation voltage control and DG reactive power control) change places. DG power factor is decreased (and DG reactive power consumption increased) if this would either reduce network maximum voltage when it exceeds feeder voltage upper limit or enable the operation of substation voltage control when minimum voltage is lower than the feeder voltage lower limit.

DG power factor is not, however, reduced if DG’s reactive power capability is insufficient to restore the voltages between acceptable limits. If the adequacy of DG’s reactive power capability is not checked the following operation is possible: At first DG power factor is lowered to its minimum value but maximum voltage still remains above its limit. Basic substation voltage control is activated and the tap changer operates and the voltages are restored between acceptable limits. At this point, the generator voltage becomes lower than the limit of restoring power factor control and the power factor is increased. So, unnecessary controls of DG reactive power are made when controlling only the substation voltage would have restored the voltages to an acceptable level.

If DG power factor control is not needed or is not able to operate, substation voltage control is activated. Substation voltage control operates similarly as in Fig. 1 except for the fact that only one tap changer operation at a time is initialized. This is done to avoid the situation where the tap changer operates multiple times when one operation followed by DG reactive power control would have been sufficient.

Fig. 1. The functional diagram of basic control when substation voltage is primarily controlled.

Fig. 2. The functional diagram of basic control when DG reactive power is primarily controlled.

Restoring control (Fig. 3) consists of two control blocks that are always executed in the same order. Restoring power factor control is intended to restore the DG power factor to unity when network state allows it. DG power factor can be increased if generator voltage has decreased enough. The new power factor set point is calculated using state estimation. If substation voltage is the primary control variable in basic
control, also a part that reacts when minimum voltage has increased enough is included. This part activates basic substation voltage control that in turn lowers the voltage level of the whole distribution network. After tap changer operation also the generator voltage has decreased and the first part of the restoring DG power factor control is able to increase the power factor set point.

The coordinated voltage control prototype software is implemented using the Matlab programming language and it is run on a Matlab environment. It consists of a main program and several function subprograms and realizes state estimation, coordinated voltage control and data transmission between Matlab and SCADA.

The main function reads measurements from SCADA, executes state estimation and coordinated voltage control, sends possible commands to SCADA and saves data for later examination. The state estimation algorithm estimates network voltages using network information obtained from the network information system, load information obtained from the load curves and measurements obtained from the SCADA [18]. The coordinated voltage control algorithm uses the outputs of state estimation as inputs and determines the set points of substation AVC relay and DG AVR. Data transfer between Matlab and SCADA is realized via OPC Data Access.

The coordinated voltage control function realizes the functionality introduced in chapter II. A. If network voltages can not be restored to an acceptable level by controlling substation voltage and DG reactive power, a warning is outputted for the operator and the operator can take actions to improve the network state.

C. Discussion of the algorithm

The coordinated voltage control algorithm is designed such that it can be easily implemented as a part of distribution management system (DMS). In Finland, the DMS includes a state estimator and, therefore, only the voltage control algorithm needs to be implemented.

The voltage control algorithm is simple. Therefore, its operation can be easily understood and its implementation does not require extensive work. The algorithm requires only little computational time and the interval in which the algorithm can be executed in real DMS is mainly dependent on the execution time of state estimation. Although the algorithm is simple it is still able to utilize the whole control range of the controllable variables to restore the network voltages to an acceptable level.

The algorithm is also modular which has advantages both at the implementation phase and if changes to the algorithm are needed. The substation voltage control algorithm is suitable for distribution networks in general whereas the reactive power control algorithm is suitable only for traditional radial distribution networks where only few DGs exist [9]. If the reactive power control algorithm needs to be modified, the substation voltage control algorithm can still remain unchanged.

III. RTDS SIMULATION ARRANGEMENT

RTDS simulations are used to verify the correct operation of the coordinated voltage control prototype software. They are also used to test the algorithm in situations that can not be realized in real distribution network tests.

RTDS is a power system simulator for real time studies. The simulator environment consists of hardware and software. The hardware is used to solve electromagnetic transient simulations in real time and is installed in rack(s). The software RSCAD is run on an external computer and is used to construct the power system models and to control the simulations. Real external devices can be connected to the system. [17]

The connection used in the RTDS simulations of this paper is depicted in Fig. 4. In the simulations, RTDS emulates a real distribution network that is controlled using real SCADA (ABB MicroSCADA Pro SYS 600). Measurement signals are extracted from the simulated network similarly as from a real distribution network and control commands are transferred to the simulation through SCADA.

Data transfer between RSCAD and SCADA is realized using shared files. RSCAD writes the measurement signals
from the power system to a file. Matlab located at another computer reads the file and transfers the data to SCADA using OPC standard. Similarly, the commands given by the coordinated voltage control algorithm are firstly transferred from SCADA to Matlab and, thereafter, Matlab writes the values to a file that is read by RSCAD.

The coordinated voltage control algorithm executed in another Matlab communicates with the SCADA via OPC. The coordinated voltage control algorithm is executed once every second.

A. The simulation network

The simulation network is a real Finnish distribution network. The network consists of two medium voltage feeders and contains one relatively large hydro power plant. The network will experience voltage rise problems if no actions are taken to diminish the effect of DG. The structure of the study network is represented in Fig. 5.

The distribution lines are modelled using a π-connection and the loads are modelled as static constant power loads. A representation of substation AVC relay and tap changer mechanism is also included [19]. The hydro power plant is connected to the network using a synchronous generator and its reactive power can be controlled through excitation control of the generator. The excitation system is of type IEEE AC8B [20] and the power factor control is realized as cascade control where a power factor controller of type IEEE VAr controller Type 2 [20] determines the set point of the voltage controller (PID control used instead of PI control). The coordinated voltage control algorithm outputs a power factor set point that is converted to reactive power set point before sending to the DG AVR.

B. Control parameters

The parameters used in the simulations are the following: AVC relay deadband $DB$ is 1.5 %, hysteresis limit 90 % of the operating value and delay 10 s. Line drop compensation is not used. The main transformer tap step is 1.67 % and its delay is 2 s.

The feeder voltage lower and upper limits used in basic substation voltage control are 0.95 and 1.045 pu whereas the restoring substation voltage control tries to keep the network voltages between 1.00-1.045 pu. The voltage reference limits are set equal to the feeder voltage limits. In basic substation voltage control the delay is 20 s and in restoring substation voltage control 30 s.

Minimum power factor set point is 0.98 and the delay in basic power factor control 10 s. In restoring power factor control, the generator voltage has to be at least 0.01 pu below the feeder voltage upper limit to enable increase of the DG power factor. The delay in this control is 20 s. In the other part of restoring power factor control, the minimum voltage has to exceed the feeder voltage lower limit by at least 0.02 pu to

Fig. 4. The connection used in RTDS simulations.

Fig. 5. The structure of the study network.
activate basic substation voltage control. The delay in this control is 30 s.

IV. SIMULATION RESULTS

The operation of the coordinated voltage control prototype software is studied quite extensively in RTDS simulation environment. Simulations are conducted in three loading conditions (maximum, minimum and middle) and different kinds of simulation sequences are used. Changes in the real power of DG and loading changes are used to disturb the network state to make the coordinated voltage control algorithm active.

A. Example simulations

Results of two example simulations are represented here. Both simulations are conducted in minimum loading conditions and have similar simulation sequences. The simulation sequence is following: At 10 s the DG unit is connected to the network with output power of 0.0 MW. At time 50 s, the real power of DG is raised to 2.0 MW and at 150 s lowered to 1.0 MW. At 250 s the unit is disconnected from the network.

In the first simulation depicted in Fig. 6 substation voltage is primarily controlled and in the second one represented in Fig. 7 DG reactive power is the primary control variable.

In Fig. 6 network maximum voltage exceeds its limit when DG output power is raised to 2.0 MW. Basic substation voltage control is activated and AVC relay set point changed in such a way that two tap operations are initiated because maximum voltage would remain over its limit after one tap operation. After the tap operations, network voltages are restored between acceptable limits. When DG output power is lowered to 1.0 MW, all voltages still remain within feeder voltage limits both in basic and restoring controls and, hence, nothing is done. When the DG unit is disconnected at 250 s, network minimum voltage falls below feeder voltage lower limit in restoring substation voltage control and AVC relay set point is increased after the delay. In this simulation, DG power factor control is not needed at all.

In Fig. 7 network maximum voltage exceeds its limit when DG output power is raised to 2.0 MW. The primary control variable is DG power factor but the maximum voltage is so far from its limit that DG’s reactive power capability is insufficient to lower the maximum voltage below its limit. Therefore, basic substation voltage control is activated and a tap changer operation initiated. After the tap changer operation maximum voltage is still above its limit and basic power factor control is activated. DG power factor set point is lowered to 0.985 and network maximum voltage restored below its limit. When DG real power is lowered to 1.0 MW, restoring power factor control operates for the first time and when DG is disconnected, DG power factor is restored to unity.

B. Discussion of the simulations results

Simulation results show that the coordinated voltage control prototype software implemented in Matlab operates as expected and that the modifications done to the algorithm improve the operation of the algorithm. New set points are
calculated such that only one set point change is needed to reach an acceptable network state whereas in the original algorithm [9] set point changes were performed in user-defined steps. Also, no unnecessary control actions are performed when the modified control algorithm is used. When DG reactive power capability is noticed to be inadequate, substation voltage control algorithm is activated and no control actions on DG reactive power are taken.

The implemented control algorithm restores the network voltages between acceptable limits in all the cases where restoration is possible by controlling substation voltage and DG reactive power. If restoration is not possible the algorithm outputs a warning for the operator. DG power factor differs from unity only when network state demands it and network voltages do not remain in an unusually high or low level for a long period of time. No continuous or unnecessary set point changes appear. Hence, the correct operation of the algorithm is verified and the prototype is ready for testing in a real distribution network.

V. FURTHER STUDIES

The operation of the implemented coordinated voltage control algorithm will be next tested in a real distribution network. The real distribution network tests are currently in progress (project ADINE [21], [22]).

In future, coordinated voltage control methods will be further studied. Their application also in more complex networks that include a variety of components participating in voltage control will be studied. Also, methods using fuzzy logic and/or optimization algorithms will be developed and their operation will be examined.

VI. CONCLUSIONS

In this paper, the operation of a coordinated voltage control implementation was studied using RTDS simulations. In the simulations, RTDS was used to emulate a real distribution network whose voltage was controlled by the coordinated voltage control implementation. The control algorithm was implemented as a Matlab program that communicated with SCADA via OPC. The algorithm can also be implemented as a part of the distribution management system (DMS).

The RTDS simulations conducted verified the correct operation of the coordinated voltage control prototype software. The next step is to test the operation of the algorithm also in a real distribution network. The real network tests are currently in progress.

VII. REFERENCES

VIII. BIOGRAPHIES

Anna Kulmala was born in Tampere, Finland, on March 13, 1982. She received her Master’s Degree in electrical engineering from Tampere University of Technology in 2006.

At present, she is a researcher and a post-graduate student at the Department of Electrical Energy Engineering of Tampere University of Technology. Her main research interest is distributed generation. Specifically voltage level management issues are of interest to her.

Antti Mutanen was born in Tampere, Finland, on June 10, 1982. He received his Master’s Degree in electrical engineering from Tampere University of Technology in 2008.

At present, he is a researcher and a post-graduate student at the Department of Electrical Energy Engineering of Tampere University of Technology. His main research interests are load research and distribution network state estimation.

Antti Koto was born in Mustasaari, Finland, on March 4, 1984. He received his Master’s Degree in electrical engineering from Tampere University of Technology in 2010.

Currently he is a researcher and a post-graduate student at the Department of Electrical Energy Engineering of Tampere University of Technology. His main interest is the data transfer between information systems in distribution network operations.

Sami Repo received his M.Sc. and Dr.Tech. degrees in Electrical Engineering from Tampere University of Technology in 1996 and 2001 respectively.

At present he is a University Lecturer at the Department of Electrical Energy Engineering of Tampere University of Technology. His main interest is the management of active distribution network including distributed energy resources.

Pertti Järventausta received his M.Sc. and Licentiate of Technology degrees in Electrical Engineering from Tampere University of Technology in 1990 and 1992 respectively. He received the Dr.Tech. degree in Electrical Engineering from Lappeenranta University of Technology in 1995.

At present he is a professor at the Department of Electrical Energy Engineering of Tampere University of Technology. The main interest focuses on the electricity distribution and electricity market.