

Active Voltage Level Management of Distribution Networks with Distributed Generation using On Load Tap Changing Transformers

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Abstract—In this paper, time domain performance of active voltage level management based on co-ordinated control of substation voltage is studied. A control algorithm that controls the set point of the automatic voltage control (AVC) relay at the substation is proposed and its operation in an example network is tested using PSCAD simulations. The study network is a real distribution network located in south-west Finland which will experience voltage rise problems if a planned wind park is constructed.

Index Terms— Distributed generation, Active voltage level management, AVC relay, Time domain simulations

I. INTRODUCTION

CONNECTIONS of distributed generation (DG) to weak distribution networks often experience voltage rise problems. The voltage rise caused by DG can be reduced with passive methods such as increasing the conductor size but this can be quite expensive and make the connection of DG uneconomical. Active management of distribution networks can allow connection of more DG into existing distribution networks and, consequently, reduce the connection costs of DG. Voltage rise can be actively mitigated for instance by controlling the active and reactive power of distributed generators or by reducing the substation voltage. [1], [2]

In this paper, co-ordinated control of the substation voltage is studied using time domain simulations. The studied voltage control algorithm controls the automatic voltage control (AVC) relay target voltage and is based on [3] and [4]. Some modifications to the algorithm have, however, been made to prevent adverse interactions that can cause continuous tapping (hunting) of the tap changer. Also, a control with stricter voltage limits is added to restore the network voltages to a normal level after for instance disconnection of the power plant. The time domain performance of the modified control algorithm is tested on an example distribution network using PSCAD simulations.

The paper will firstly introduce some active voltage level

management methods for distribution networks. Thereafter, the proposed control algorithm is described in detail and selection of control parameters is discussed. The study system is introduced and simulation results are represented. Finally, the operation of the proposed control algorithm is assessed based on the simulation results.

II. ACTIVE VOLTAGE LEVEL MANAGEMENT

The simplest active voltage level management methods are based only on local measurements and do not require additional data transfer between distribution network nodes. On the other hand, the voltage of distribution networks could be controlled using a sophisticated distribution network management system (DMS) which controls all components capable of voltage control and requires a lot of data transfer between network nodes. The DMS can control for instance tap changers at substations, voltage regulators, power plants, compensators and loads. [5]

Some active voltage control methods are introduced in the following chapters. The first two methods are based on local measurements. The third chapter discusses co-ordinated voltage control methods. In this paper, methods that require data transfer between network nodes are referred to as co-ordinated.

A. Local reactive power control

Voltage rise caused by DG can be decreased by allowing the generator to absorb reactive power. At present, DG is usually operated with unity power factor and is not allowed to participate in distribution network voltage control. However, if DG controlled its reactive power based on its terminal voltage (in other words operated in voltage control mode) the distribution network voltage level would vary less between different loading conditions and more DG could be allowed to connect to the network as the voltage rise would be decreased. If power factor control is preferred, the controller could operate in power factor control mode when the terminal voltage is within determined limits and switch to voltage control mode when the limits are overstepped. [6], [7]

The reactive power control capability of DG depends on its network interface. Power plants with synchronous generator

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or modern power electronic interface are capable of controlling their active and reactive power independently as long as their operational limits are not exceeded. When induction generators are used the reactive power is dependent on the active power and can not be controlled unless some kind of controllable reactive power compensation device is used. As these plants usually contain power factor correction (PFC) capacitors, the reactive power consumption could be at simplest controlled by disconnecting the capacitors when the terminal voltage rises excessively. If continuous control of reactive power is needed a reactive power compensator based on power electronics (e.g. STATCOM) could be connected at the machine terminals. [1]

If local reactive power control is used its effect on network losses has to be considered. Also, the adequacy of reactive power compensation capacitors at the substation has to be reviewed. [8]

B. Production curtailment

Voltage rise can be decreased also by reducing the active power output of DG. If the voltage limit is exceeded only rarely the DG owner might find it beneficial to curtail some of its generation at times of high voltage if allowed to connect a larger generator to the network. This kind of control would be particularly suitable for DG whose output depends on some external factor such as the wind speed. [2], [8]

The simplest method to implement production curtailment is to disconnect a required number of generating units when the voltage exceeds its limit. If active power of DG can be controlled for instance by blade angle control of wind generators, disconnection is not required as the active power of DG can be controlled continuously. [8]

C. Co-ordinated voltage level management

Co-ordinated voltage control methods determine their control actions based on information about the whole distribution network and therefore data transfer between network nodes is required. Typically, co-ordinated voltage control methods regulate the substation voltage and reactive power of DG but also other components capable of voltage control could be included in the control [5]. Control is usually based on network voltages that can be either measured or estimated. At present, measurements on distribution networks are usually restricted to the substation and precise information about the state of the network is not normally available. However, measurements in distribution networks are likely to increase in future which makes the use of co-ordinated voltage control methods more attractive. In Finland, some distribution network operators have already installed automatic meter reading (AMR) devices to all their customers.

Usually, co-ordinated voltage control methods alter the set points of lower level controllers such as AVC relays at the substations [3], [4] and power factor controllers of the DGs [9]. Also implementations that alter the lower level controllers or control the actuating devices directly have been suggested [10], [11]. The benefit of the first approach is that the lower

level controllers do not need to be replaced and only the upper level controller and data transmission network have to be installed.

The simplest co-ordinated voltage control methods determine their control actions according to simple rules (e.g. reduce AVC relay set point when distribution network maximum voltage exceeds its limit). This type of control is most suitable for use in simple networks with only few measurements and control possibilities such as typical Finnish distribution networks. Co-ordinated control can also use an optimization algorithm to determine the control actions. Optimization algorithms should be used if determining simple control rules is difficult due to complexity of the network or multitude of controllable components. [12]

The simplest and most studied method of co-ordinated voltage level management controls the substation voltage based on maximum and minimum voltages in the distribution network. These maximum and minimum voltages can be measured [4] or estimated [3]. The control principle is simple: The substation voltage is decreased, when maximum voltage is too high, and increased, when minimum voltage is too low. If both maximum and minimum voltages are outside the feeder voltage limits it is not possible to normalize the voltages by controlling the substation voltage and, therefore, nothing is done. The substation voltage is controlled through changing the set point of the AVC relay which controls the tap changer of the main transformer. [3], [4]

When co-ordinated control of substation voltage is used, the number of tap-change operations is increased which increases the need for maintenance of the tap changer. However, the maintenance costs are likely to be smaller than network reinforcement costs.

III. THE PROPOSED CONTROL ALGORITHM

The proposed control algorithm controls the AVC relay target voltage and is based on the control algorithm presented in [3] and [4]. Some modifications to the algorithm have, however, been made to prevent unnecessary tapping of the tap changer and to restore the voltages to a normal level after for instance disconnection of DG. The functional diagram of the algorithm is shown in Fig. 1. The inputs to the algorithm are distribution network maximum and minimum voltages and the purpose of the algorithm is to keep both the voltages between the feeder limits. The voltages can be measured or estimated.

If both maximum and minimum voltages are within the feeder limits, the AVC relay set point is not changed as all distribution network voltages are at an acceptable level with the current setting. If maximum voltage exceeds the feeder voltage upper limit and minimum voltage falls below the feeder voltage lower limit, it is not possible to restore all voltages to an acceptable level by controlling the substation voltage and, therefore, the AVC relay set point is not changed in this case either. If only one of the input voltages is outside its limit, the set point is changed if certain other conditions are fulfilled.

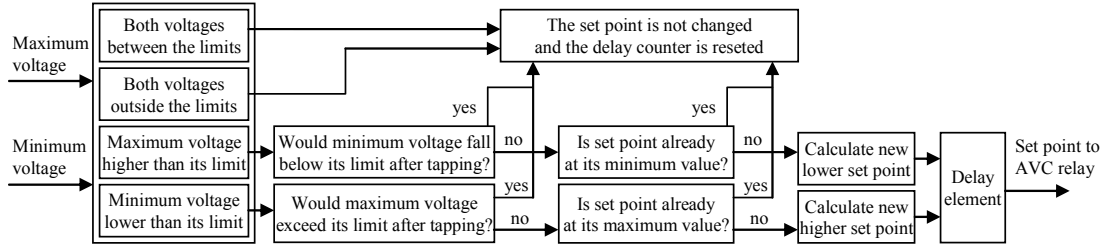


Fig. 1. The functional diagram of the proposed control algorithm.

When maximum voltage exceeds feeder voltage upper limit, the AVC target voltage is lowered. However, if the minimum voltage would fall below feeder voltage lower limit after tapping, the set point is not changed as this could lead to continuous set point changing and tapping of the tap changer. In [13] the target voltage is not changed if the minimum voltage is within the target voltage adjustment step of feeder voltage lower limit. In the algorithm proposed here, the minimum voltage has to be more than a tap step away from the lower limit to allow the set point change.

When minimum voltage falls below feeder voltage lower limit, the AVC relay target voltage is increased. Otherwise the operation of the algorithm is similar to that introduced in the preceding paragraph.

After determining whether the set point should be changed the algorithm checks if the set point is already at its limit. The set point limits are adjusted to keep the substation voltage within feeder voltage limits and, therefore, the AVC relay target voltage has to be between limits of $V_{upper}-DB \geq V_{ref} \geq V_{lower}+DB$, where V_{upper} and V_{lower} are the feeder voltage upper and lower limits, V_{ref} is the target voltage and DB is the AVC relay deadband setting. The AVC relay set point is changed in user-defined steps. However, if the calculated new set point would exceed the voltage reference limits the target voltage is set to its extreme value. This change might be so small that it will not initiate a tap-change operation but, on the other hand, the whole control range of the set point is used and tapping initiated always when possible. A delay element is also included in the algorithm as short-time voltage variations should not initiate a set point change.

If only the above described algorithm would be used the network voltages could remain at an unusually high or low level after a change in the operating conditions. Therefore, a control with stricter voltage limits (restoring control) is added to the algorithm. The operation of the control is similar to the basic control depicted in Fig. 1, only the control parameters are different. The purpose of the basic control is to restore the network voltages to an acceptable level when voltage rise or drop at some network node becomes excessive whereas the purpose of the restoring control is to restore the voltages to a normal level when the voltage level of the whole network remains unusually high or low after for instance disconnection of DG.

A. Selecting the parameters of the control algorithm

The control algorithm uses the parameters shown in Table I

when determining the AVC relay set point. Some of the parameters are determined by the network's operating limits or parameters of other components in the network whereas some can be more freely selected. The parameters should be such that continuous tapping of the tap changer does not occur in any circumstances and that the set point is not changed if the AVC relay or the tap changer is operating. If target voltage adjustment step (the set point change at a time) and the delays are correctly selected these conditions can be fulfilled.

TABLE I
CONTROL ALGORITHM PARAMETERS

Parameter	Selection criteria
AVC relay deadband	Directly from AVC relay parameters
Main transformer tap step	Directly from main transformer characteristics
Feeder voltage upper limit	All customer voltages have to be kept in an acceptable level
Feeder voltage lower limit	
Target voltage adjustment step	One set point change should initiate only one tap-change operation
Delay in basic control	The set point should not be changed before the AVC relay has completed its operation
Delay in restoring control	
Voltage upper limit in restoring control	Network voltage level should not remain in an unusually high or low level
Voltage lower limit in restoring control	

The set point of the AVC relay is lowered (increased) only if minimum (maximum) voltage is more than a tap step away from the feeder voltage limit. Hence, one set point change should initiate one tap-change operation but never more. If multiple tap steps are initiated, oscillations between the AVC relay and the voltage control algorithm might occur. On the other hand, the target voltage adjustment step should be selected to be as large as possible to ensure that one tap-change operation is initiated as often as possible when the set point of the AVC relay is changed as the delay will naturally be longer if multiple set point changes are needed. If the target voltage adjustment step is selected to be a bit smaller than the tap step the preceding conditions are fulfilled.

If the delay of the control algorithm is too small the algorithm might change the AVC relay set point also in situations where no change is needed. For instance, a change in the supply system voltage might initiate a set point change even if the normal operation of the AVC relay would be sufficient in this situation. On the other hand, the control algorithm should be able to restore the voltages between

feeder voltage limits before DG is disconnected from the network by its over/undervoltage protection and, hence, the delay should not be too long.

The delay can be selected using similar principles as with cascaded tap changers in radial networks: The number of tap operations needed to compensate for the worst case voltage disturbance at the supply system is computed. The delay of the proposed control algorithm is selected to be longer than the time needed to complete these tap operations. [14] This ensures that the set point is not changed when the AVC relay or the tap changer is still operating. After determining the delay it is checked that the voltage control operates faster than DG protection to prevent unnecessary disconnection of DG. In many cases the delay of the AVC relay has to be shortened from the delays used nowadays to be able to fulfill these requirements.

IV. DESCRIPTION OF THE STUDY SYSTEM

The operation of the proposed control algorithm is studied in an example distribution network located in south-west Finland. The examined network consists of two medium voltage feeders which are fed from the same substation and its structure is depicted in Fig. 2. The network is relatively weak and contains a long sea cable and will therefore experience voltage rise problems when a planned wind park depicted in Fig. 2 is connected to the network. Voltage control in the example network has been previously studied in [8] using load-flow calculations but time domain simulations have not been carried out. In this paper, the operation of the proposed control algorithm is examined using PSCAD simulations. Simulations are conducted in maximum and minimum loading conditions of the example network. As the effect of DG on network voltage depends also on its ability to control its reactive power, simulations are performed with two kinds of network interfaces. When induction generators are used the reactive power is dependent on the active power and can not be controlled. When synchronous generators are used the reactive power can be controlled through excitation control. Network protection is not modeled.

The network model includes a representation of an AVC relay and tap changer mechanism [15]. The AVC relay measures the substation voltage and compares it with its target voltage V_{ref} . If the measured voltage differs more than the AVC relay deadband DB from the target voltage a delay counter is started. This counter remains active as long as the measured voltage is outside the hysteresis limits of the relay and a tap-change operation is initiated when the counter reaches its setting value T_{AVC} . In these simulations, the deadband DB is 1 %, the hysteresis limit 90 % of the operating value and the delay T_{AVC} 5 s. Line drop compensation is not used. The tap changer mechanism is modeled simply as a delay. The tap step is 1.67 % and the delay 1 s.

The target voltage of the AVC relay is determined by the control algorithm depicted in Fig. 1. The feeder voltage lower

and upper limits used in the basic control are 0.95 and 1.05 pu whereas the restoring control tries to keep the network voltages between 0.98-1.03 pu. The target voltage adjustment step is 1.5 % which is a bit smaller than the tap step and the delay is 10 s in both the basic and the restoring controls. The minimum and maximum voltages are supposed to be measured.

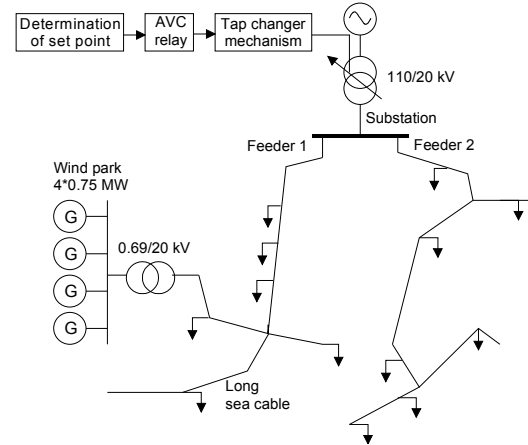


Fig. 2. The structure of the example network.

The wind park consists of four 0.75 MW induction or synchronous generators and a generator transformer. When induction generators are used a 200 kVAr PFC capacitor, which compensates for nearly all of the no-load reactive power demand of the generator, is connected to the terminals of each generator. Simulations are carried out with and without the capacitors.

When synchronous generators are used the reactive power of the wind park is controlled through excitation control of the generator. The automatic voltage regulators (AVR's) of synchronous generators can be operated either in voltage control or power factor control mode. The excitation system is of type IEEE AC8B and it contains also an underexcitation limiter of type IEEE UEL2 [16]. Power factor control is implemented as cascade control where the power factor controller determines the set point of the voltage controller. The power factor controller is of type IEEE Var Controller Type 2 [16]. Simulations are conducted in three different situations: voltage control with set point of 1.0 pu and power factor control with set points of 1.0 and 0.92_{ind}.

V. SIMULATION RESULTS

The simulation sequence is similar in all the simulations: At the beginning of the simulation the wind power plant is not connected to the network. At time 10 s all the generators are connected to the network. The mechanical moment T_m of the generators is at this time 0.0 pu. At time 30 s T_m is raised to 0.5 pu which raises the active power output of the plant to approximately 1.5 MW. At time 90 s T_m is raised to 1.0 pu which raises the active power to approximately 3.0 MW. At time 150 s two of the four generators are disconnected from the network and at time 180 s also the remaining units are

disconnected.

In the simulations the reactive power of the generators is controlled based on local voltage measurement whereas the substation voltage is controlled using the control algorithm illustrated in Fig. 1. The reactive power control is much faster than the co-ordinated control and the substation voltage will, therefore, be changed only if the reactive power control does not restore the voltages to an acceptable level.

A. Wind park with induction generators

When the 3 MW wind park depicted in Fig. 2 is connected to the network using induction generators the proposed control algorithm is able to restore the network voltages to an acceptable level in both maximum and minimum loading conditions irrespective of the state of the PFC capacitors. However, when the capacitors are in use and the network load at its minimum value the substation voltage is lowered to a value of approximately 0.96 pu and the minimum voltage in the network is almost at its limit. Hence, if the load of feeder 2 would in this situation increase even slightly the minimum voltage would fall below its limit. If the PFC capacitors are not used the voltage rise caused by the wind park is smaller and the substation voltage need not be lowered as much as with the capacitors connected.

If only the voltage level of the network is considered, no PFC capacitors should be installed to the wind park using induction generators as the voltage level of the network varies in this case less between different loading conditions and fewer control actions of the proposed control algorithm are needed to keep the network voltages within acceptable limits. However, the absorption of reactive power might increase the network losses significantly and, therefore, controlling the capacitors based on the terminal voltage might prove to be

more profitable.

The operation of the proposed control algorithm is illustrated in Fig. 3 in an example case. In this situation the network voltages remain in an acceptable level when the wind park generates 1.5 MW of active power but when the active power increases to 3.0 MW the voltage rise at the generator terminals becomes excessive and the proposed control algorithm lowers the AVC relay target voltage after a delay of 10 s. The tap changer operates after the AVC relay and tap changer delays (5+1 s) and the maximum voltage is restored below the feeder voltage upper limit. After disconnection of two generator units the network voltage level is below the restoring control limits and, therefore, the AVC relay target voltage is increased and the tap changer operates to increase the network voltages. The disconnection of the remaining generators does not initiate any control actions.

B. Wind park with synchronous generators

When the 3 MW wind park is connected to the network using synchronous generators the reactive power of the park is not dependent on the active power of the park but can be controlled through excitation control of the generators. Hence, the wind park can either absorb or generate reactive power whereas with induction generators the park absorbs reactive power in all situations. Traditionally these kinds of distributed power plants have been operated with unity power factor. In the example case studied, the unity power factor approach can not be used without network reinforcements because the proposed control algorithm is not able to restore the maximum voltage at an acceptable level when the wind park is producing 3 MW in network maximum loading conditions. In minimum loading conditions the substation voltage has to be lowered to approximately 0.96 pu and both the maximum and minimum voltages are almost at their limits. Hence, if a 3 MW wind park is connected to the example network, the network voltages can not be restored to an acceptable level only by controlling the substation voltage but also either the active or the reactive power of the plant has to be controlled. When synchronous generators are used the absorption of reactive power can be accomplished by using the AVR in voltage control mode or in power factor control mode with an inductive set point. Operation in voltage control mode is preferable as in this case the network voltages vary less between different loading and production conditions and also the losses are likely to be smaller because reactive power is absorbed only when necessary.

The operation of the proposed control algorithm with unity power factor control is depicted in Fig. 4 in network minimum loading conditions. The basic control (BC) operates three times: once when the active power is increased to 1.5 MW and twice when the active power is increased to 3 MW. When two tap-change operations are needed to restore the voltages to an acceptable level the second target voltage change takes place only 4 seconds after the first tap-change operation because the delay counter of the proposed control algorithm has been active since the preceding target voltage

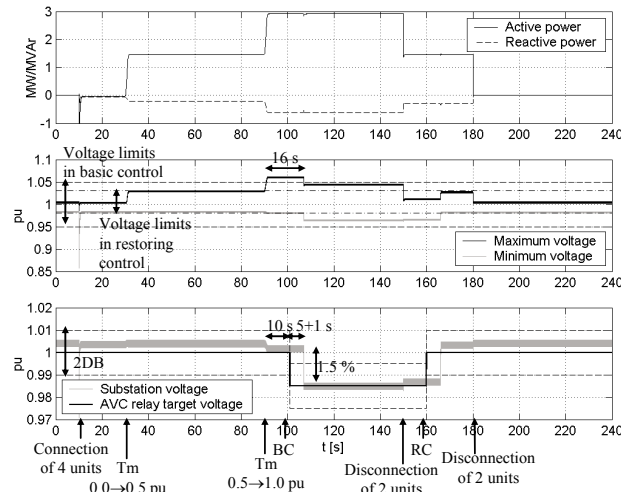


Fig. 3. The operation of the proposed control algorithm in maximum loading conditions with the PFC capacitors connected. The uppermost figure depicts the active and reactive power of the wind park measured at the 20 kV side of the generator transformer and the lower figures illustrate network maximum and minimum voltages, the substation voltage and the AVC relay target voltage. BC means basic control and RC restoring control.

change. The latter change in AVC relay target voltage is only one per cent because lowering the target voltage by 1.5 per cent would have taken it below its lower limit. In this case also a target voltage change of one per cent initiates a tap-change operation and the voltages are restored to an acceptable level after a total delay of 26 seconds. The restoring control (RC) operates in this case twice: once after the disconnection of the first two generators and once after the disconnection of the remaining units. When voltage control is used in the same loading condition the network voltages vary less between different production conditions and only one operation of the proposed control algorithm is needed.

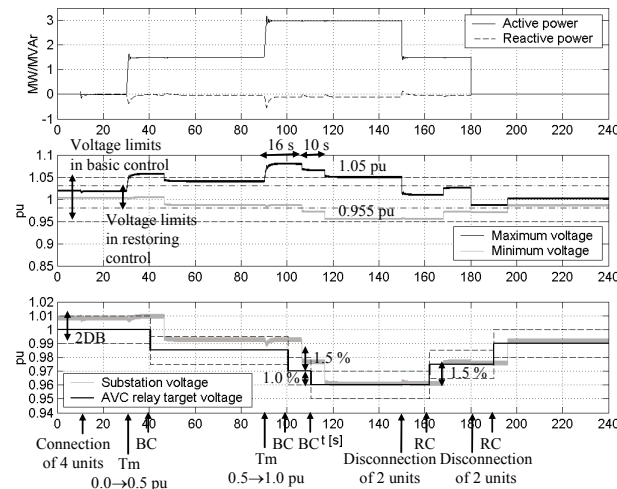


Fig. 4. The operation of the proposed control algorithm in minimum loading conditions when power factor control with set point of 1.0 is used. The notations are similar as in Fig. 3.

C. Discussion of the simulation results

The proposed control algorithm operated in the simulations as desired. The basic control restored the network voltages to an acceptable level if normalizing the network voltages by controlling the substation voltage was possible. No continuous tapping of the tap changer appeared and also the restoring control operated as desired, in other words, network voltages did not remain in an unusually high or low level after for instance disconnection of the wind park.

The proposed control algorithm regulates only the substation voltage and the reactive power of the power plant(s) is controlled based on local measurements. However, absorbing reactive power may increase the network losses and, therefore, controlling the substation voltage might be a better way to regulate the voltage. This could be accomplished by including the reactive power control as a part of the co-ordinated voltage control algorithm. In future, these kinds of studies will be conducted.

VI. CONCLUSIONS

In this paper, the operation of active voltage level management based on co-ordinated control of substation

voltage was studied. A control algorithm that controls the substation voltage based on maximum and minimum voltages in the network was introduced and the operation of the proposed control algorithm was tested using time domain simulations. The simulations were carried out using an example network which is a real distribution network located in south-west Finland.

The proposed control algorithm operated in the simulations as desired. It restored the network voltages to an acceptable level always when possible and did not cause continuous tapping of the tap changer in any situation. Also, network voltages did not remain in an unusually high or low level after a change in network operating conditions.

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