Combined Local and Remote Voltage and Reactive Power Control in the Presence of Induction Machine Distributed Generation

Ferry A. Viawan, *Student Member, IEEE*, and Daniel Karlsson, *Senior Member, IEEE*

***Abstract*—This paper first investigates a local voltage and reactive power control (local control) in a distribution system based on local control of on-load tap-changer (OLTC), substation capacitors, and feeder capacitors, and how the presence of induction machine based distributed generation (DG) affects it. A proper coordination among those available voltage and reactive power control equipment to minimize losses in the distribution system, with and without DG, is formulated. Secondly, a combined local and remote voltage and reactive power control (local-remote control), which is based on automated remote adjustment to the local control in order to minimize the losses even more, is proposed. The automated remote adjustment in the local-remote control is also intended to keep the operating constraints fulfilled all the time, which cannot be achieved by using the local control when DG is present in the system. The OLTC and substation capacitors are assumed to be remotely controllable, while the feeder capacitors are not. DG with both constant power and varying power are investigated.**

***Index Terms*—Capacitor, distributed generation, distribution system, induction machine, losses, on-load tap-changer, reactive power control, voltage control.**

I. Introduction

VOLTAGE and reactive power control in conventional distribution systems is normally achieved by incorporating on-load tap-changers (OLTC) and switched shunt capacitors. The OLTC keeps the substation secondary bus voltage constant by adjusting the tap position. The switched shunt capacitor is used to compensate the reactive power demand and thereby decrease the voltage drop [1], [2].

Many distribution network operators (DNOs) operate OLTC and shunt capacitors locally by using conventional controllers, i.e., voltage controller for the OLTC and either voltage, reactive power or time controller for the capacitors, in order to maintain the voltages in the distribution system within the acceptable range and to minimize power losses. The drawback of this method is that the power losses may not always be minimized. Interventions to the locally controlled OLTC and capacitors operations may be needed. In an extreme case, the local control operation of the OLTC and capacitor operations are fully replaced with a remote control, for example in [3] and [4] where the OLTC and capacitors are remotely dispatched every hour, by using an automated schedule, which is defined based on a one-day-ahead load forecast. However, even though the OLTC tap position and capacitors on/off configuration are optimum at their dispatching times, loads will continuously ramp, and the OLTC tap position and capacitors on/off configuration might no longer be optimal until the next dispatch is executed. On the other hand, more frequent remote OLTC and capacitor dispatch, every 15 min for instance, seems to be impractical. Further, by fully omitting the local control function, the OLTC and the capacitor will lose their capability to react to load changes that deviate from the ones forecasted. Other obstacle of the implementation of this method is its dependency on communication links to all capacitors in the feeders.

The introduction of distributed generation (DG) affects the power flows, which in turn alters feeder voltage profiles and influences the voltage and reactive power control in the distribution system [5]. Hence, the connection of DG into a distribution system needs coordination with available voltage and reactive power control equipment in the system in order to ensure that the distribution system will not lose the proper voltage regulation. The reduction of the OLTC set-point is shown in [6] to be necessary to increase DG power output. In [7], it is shown that capacitor control set-points need to be changed with the presence of DG. However, besides coordination between DG and single equipment that is investigated in those references, it is also necessary to investigate how DG should be coordinated with all available voltage and reactive power control equipment simultaneously and how the need to adjust the control set-point of one equipment will be affected by adjustment of other equipment.

This paper first investigates voltage and reactive power control in conventional distribution systems based on coordination of OLTC, substation capacitors (the shunt capacitors installed at substation secondary bus) and feeder capacitors (the shunt capacitors located somewhere along the feeder) by using combined local and remote control to minimize distribution system losses. Local control means that the equipment is kept to operate based on their own local controllers and predetermined control set-points. Remote control means that the local control will be adjusted remotely if required in order to obtain the optimum voltage and reactive power control. Secondly, the impact of DG on both conventional and proposed voltage and reactive power control, and how the control strategy should be changed with the presence of DG, are presented.

Manuscript received January 16, 2007. Paper no. TPWRS-00019-2007.

F. A. Viawan is with the Division of Electric Power Engineering, Department of Energy and Environment, Chalmers University of Technology, Gothenburg 41296, Sweden (e-mail: ferry.viawan@chalmers.se).

D. Karlsson is with Gothia Power, Gothenburg, Sweden, and also with the Division of Electric Power Engineering, Department of Energy and Environment, Chalmers University of Technology, Gothenburg 41296, Sweden.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRS.2007.907362

Fig. 1. One-line diagram of a simple two-bus system.

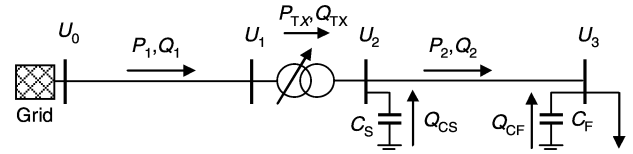

Fig. 2. One-line diagram to illustrate the voltage and reactive power control.

DGs are assumed to be induction generators, the commonly used generator type for small hydro and wind power applications [8]. Both dispatchable DG power output, representing the power output of small hydro power, and variable power output representing the power output of wind power, are examined. The optimum control set-point and remote adjustment schedules are obtained based on a one-day-ahead load forecast and a three-hour-ahead wind power forecast. It is assumed that the OLTC and the substation capacitors can be monitored and controlled remotely, whereas the feeder capacitors cannot.

II. Voltage and Reactive Power Control in Conventional Distribution Systems

A. *On-Load Tap-Changer and Shunt Capacitors for Voltage and Reactive Power Control*

On-load tap-changer (OLTC) is a transformer with adjustable taps, which is part of most of HV/MV power transformers [1], [2]. The OLTC keeps the HV/MV substation secondary bus voltage U_1 constant within the range

$$U_{\rm LB} \le U_1 \le U_{\rm UB} \tag{1}$$

where

$U_{\rm LB} = U_{\rm set} - 0.5$ DB	lower boundary voltage;
$U_{\rm UB} = U_{\rm set} + 0.5$ DB	upper boundary voltage;
$U_{\rm set}$	set-point voltage;
DB	deadband.

Reactive power can be controlled by using shunt capacitors that inject reactive power to the system. The reactive power injected by the capacitor compensates the reactive power demand and thereby boosts the voltage, according to the following voltage drop ΔU approximation for a two-bus system shown in Fig. 1

$$\Delta U = U_0 - U_1 \approx \frac{RP_{\rm L} + X(Q_{\rm L} - Q_{\rm C})}{U_1} \tag{2}$$

with R and X resistance and reactance of the line, respectively.

Voltage and reactive power control involves a proper coordination among the OLTC and all capacitors in the distribution system according to the objective function, such as loss minimization that will be investigated in this paper, and operating constraints, such as voltage limits, line thermal capacity, and transformer rating. The voltage and reactive power control can simply be explained by using the one-line diagram shown in Fig. 2. The OLTC maintains the substation secondary voltage U_2 constant within a certain range according to (1). Reactive power injected by feeder capacitor $Q_{\rm CF}$ compensates the reactive power drawn by the load and thereby boosts the voltage U_3 and decreases the active power losses on the feeder. Reactive power injected by the substation capacitor $Q_{\rm CS}$ compensates the reactive power flow through transformer $Q_{\rm TX}$ and thereby boosts the voltage U_1 and decreases the active power losses in the transformer.

B. *Problem Formulation*

In practice, OLTC and capacitors are mostly operated locally by using conventional controllers. The control set-points alteration can be very rare, on seasonal basis for instance. This local control method reduces the effectiveness of the control function in minimizing the losses. By searching the optimum OLTC tap position and capacitor on/off configuration in the system for a certain load profile, and then adjusting the OLTC and capacitor operation according to the obtained optimum OLTC and capacitor configuration, further loss reduction can be obtained.

The OLTC and the substation capacitors can be adjusted remotely in most high voltage/medium voltage (HV/MV) substations, where the OLTC and the substation capacitors are connected to the SCADA system. On the other hand, many distribution utilities do not have communication links downstream to the feeder capacitors locations. However, the voltage at the feeder capacitor connection point can be altered by dispatching the OLTC and the substation capacitors to force the feeder capacitors on or off by their own local controller.

The OLTC and capacitor dispatches can be scheduled one day in advance based on a one-day-ahead load forecast. Although there is a random fluctuation in the load variation, the major component of load variations are related to weather conditions and deterministic pattern during the hours of the day due to social activities [9]. Therefore, load profile is very estimateable. It can be forecasted one-day-ahead with an average error less than 2% [9], [10].

C. *Proposed Method*

The proposed method emphasizes on voltage and reactive power control for loss minimization in the distribution system based on load forecast, off-line simulation and combined local and remote control. The conceptual diagram of the proposed voltage and reactive power control is shown in Fig. 3. The OLTC is controlled by, and will maintain, the substation secondary bus voltage U_1 within a certain range. The substation capacitors are controlled by the transformer reactive power flow $Q_{\rm TX}$ and will maintain $Q_{\rm TX}$ and the substation primary bus U_0. The feeder capacitors are controlled by, and will maintain, their local bus voltage $U_{\rm CF1}$ and $U_{\rm CF2}$, and they will also affect the reactive