Coordinated Voltage and Reactive Power Control in the Presence of Distributed Generation

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Abstract— **This paper presents voltage and reactive power control methods in distribution systems in the presence of distributed generation (DG). Both uncoordinated and coordinated voltage control, without and with DG involved in the voltage control, are investigated. The uncoordinated voltage control means that all voltage and reactive power control equipment operate locally. The coordinated voltage control means that, in addition to the local operation, the voltage and reactive power control equipment will be adjusted remotely, based on wide area coordination, in order to obtain an optimum voltage profile and reactive power flow for a one-day-ahead load forecast and DG output planning. The result indicates that involving DG in the voltage control will result in a reduction of the losses, the number of OLTC operations and the reduction of the voltage fluctuation in the distribution system. Further, the results also indicate that the coordinated voltage and reactive power control, the losses can be decreased more,**

Index Terms—**Distributed generation, voltage control, reactive power control, voltage stability, on-load tap-changer, capacitor.**

I. Introduction

VOLTAGE and reactive power control (voltage control) in transmission systems have for many years been decomposed into three hierarchical levels, the primary, secondary and tertiary levels. The primary control is performed by automatic voltage regulators (AVR) installed on synchronous generators and the secondary control by locally operated on-load tap-changers (OLTCs) and reactive power compensation devices. Meanwhile, in the tertiary control, a short time operation planning is developed to coordinate the action of the primary and secondary control devices according to the secured operation and economic criteria based on load and generation forecast [1].

On the other hand, the voltage control in distribution systems is normally achieved by incorporating on-load tap-changer (OLTC) and switched shunt capacitors [1]-[3] only. In most distribution systems, such equipment operates locally without wide coordination (communication) with the others.

The voltage and reactive power equipment in distribution systems are mostly operated based on an assumption that the voltage decreases along the feeder. On the other hand, connection of distributed generation (DG) will fundamentally alters the feeder voltage profiles, which will obviously affect the voltage control in distribution systems [4]. A range of options have traditionally been used to mitigate adverse impacts, such as decreasing of OLTC set point voltage, altering the capacitor control or limiting the DG size according to the worst case operating scenarios [5]-[6].

The consequence of the local (uncoordinated) voltage control operation in the distribution systems is that the voltage profile and reactive power flow can be far from optimum. The optimum voltage profile and reactive power flow should be achieved if the voltage and reactive power equipment are coordinated, similar to the one in the transmission system [7].

In line with the modernization of electricity distribution recently, coordinated voltage control adopted into distribution systems have been emerging. Different methods of short term operation planning for distribution system voltage control have been proposed [8]-[11].

A synchronous DG has an inherent feature to regulate the generator terminal voltage by adjusting their reactive power output. Involving DG in the distribution system voltage control will result in positive impacts, which have also been presented in some papers. For example, it is indicated in [12] that operating DG in automatic voltage control results in a decrease of the number of OLTC operations and the distribution system voltage variation. Involving DG in the distribution system coordinated voltage control is shown in [7] and [13] to increase the maximum DG penetration limit. However, distribution network operators (DNOs) have hitherto been reluctant to allow DGs to perform automatic voltage control, as it may destabilize the OLTCs of some distribution transformers [7].

This paper presents a comparative analysis of different voltage control methods in distribution systems in the presence of DG. Two cases are investigated; without DG involved in the voltage control (DG operates at unity pf, *case-1*) and with DG involved in the voltage control (DG operates at a constant voltage, *case-2*). For each cases, both local voltage and reactive power control (*uncoordinated*) and coordinated voltage and reactive power control (*coordinated*) are analyzed. The uncoordinated voltage control means that all voltage and reactive power control equipment operate locally. The coordinated voltage control means that, in addition to the local operation, the voltage and reactive power control equipment will be adjusted remotely, based on wide area coordination. DG does not involve in the voltage control means that the DG is operated at a constant pf, meanwhile DG involves in the voltage control means that the DG is operated at a constant voltage.

The remote adjustment based on wide area coordination is intended to obtain an optimum voltage profile and reactive power flow, according to the given objective function, for a one-day-ahead load forecast and DG output planning. The DG, OLTC and substation capacitors (switched capacitors located

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at the substation secondary bus) are assumed remotely controllable, meanwhile the feeder capacitors (switched capacitors located anywhere on the feeder) are not.

II. Local Voltage and Reactive Power Control in Distribution Systems

The example of voltage and reactive power control can simply be explained by using the one-line diagram shown in Fig. 1. The voltage drop along the feeder can be approximated as

$$U_2 - U_3 \approx \frac{RP_{\mathrm{L}} + X(Q_{\mathrm{L}} - Q_{\mathrm{CF}})}{U_3} \qquad (1)$$

with R and X the resistance and reactance of the feeder, respectively. Hence, the reactive power injected by feeder capacitor Q_{CF} decreases the voltage drop by compensating the reactive power drawn by the load, which will in turn decrease the active power losses on the feeder.

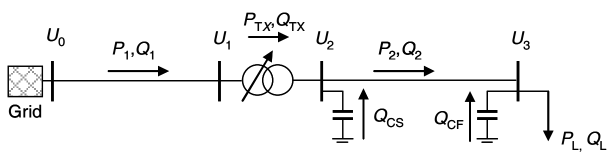

Fig. 1. One-line diagram to illustrate the local voltage and reactive power control.

Reactive power injected by the substation capacitor Q_{CS} compensates the reactive power flow through transformer Q_{TX} and thereby boosts the voltage U_1 and decreases the active power losses in the transformer. If the voltage drop causes the voltage U_2 lower than the OLTC lower boundary voltage, the OLTC will operate to bring U_2 back within the range specified by

$$U_{\mathrm{LB}} \leq U_2 \leq U_{\mathrm{UB}} \qquad (2)$$

where

$U_{LB} = U_{\mathrm{set}} - 0.5\,DB$ is the lower boundary voltage
$U_{UB} = U_{\mathrm{set}} + 0.5\,DB$ is the upper boundary voltage
U_{set} is the set point voltage
DB is deadband.

By replacing the shunt capacitor at the load bus in Fig. 1 with a DG generating active power P_{G} and reactive power Q_{G}, the voltage drop on the feeder can be written as

$$U_2 - U_3 \approx \frac{R(P_{\mathrm{L}} - P_{\mathrm{G}}) + X(Q_{\mathrm{L}} - Q_{\mathrm{G}})}{U_3} \qquad (3)$$

which indicates that the presence of DG will increase the voltage at its connection point. Depending on the size of the DG relative to the size of the load, this increase may cause a general voltage rise in the feeder.

III. Description of the System Under Study

The system for the study is shown in Fig. 2. A 10 kV distribution system fed from a 70 kV transmission system, shown in Fig. 2 with the daily load profile shown in Fig. 3, which is taken from [12]. In all cases, each DG generates a constant power $P_{\mathrm{DG}} = 2.97$ MW.

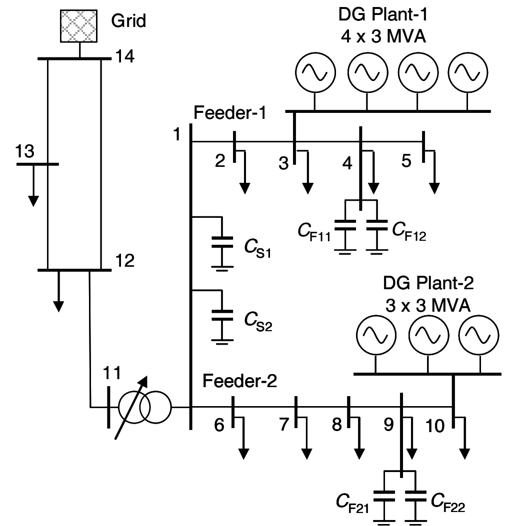

Fig. 2. One-line diagram of the system under study.

Voltage control with loss minimization as the objective function is investigated in this paper. The load characteristics affect the optimum distribution system operating voltage (in order to minimize losses). On a system with a constant power load, the losses will decrease with the increase of the operating voltage; on a system with a constant current load, the losses will not change with the change of operating voltage; meanwhile for a system with a constant impedance load, the losses will increase with the increase of the operating voltage due to the increase of the load consumption. For a simplification, loads with constant power model are used.

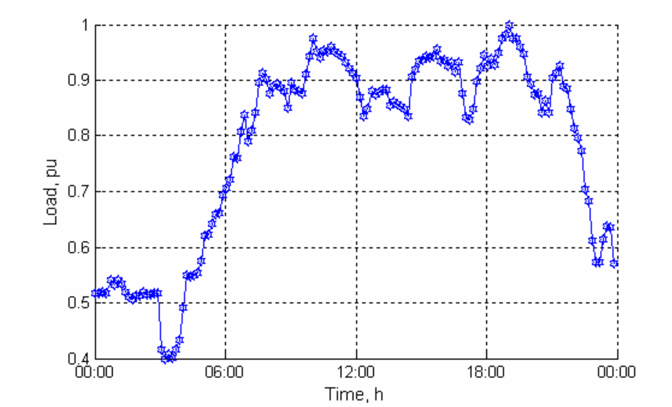

Fig. 3. Daily load profile of the system under study.

IV. Problem Formulation

The OLTC and shunt capacitors in distribution systems normally operate by using their local controllers based on pre-determined control set points (*local voltage and reactive power control*). Hence, the OLTC and capacitors are set in a conservative way in order to keep the voltage at all buses in