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

$$U_2 - U_3 \approx \frac{RP_L + X(Q_L - Q_{CF})}{U_3} \qquad (1)$$

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.
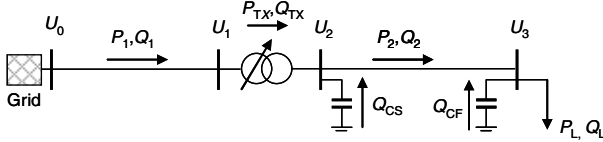

Fig. 1. One-line diagram to illustrate the local voltage and reactive power control.

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

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

where

$U_{LB} = U_{set} - 0.5\,DB$ is the lower boundary voltage
$U_{UB} = U_{set} + 0.5\,DB$ 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

$$U_2 - U_3 \approx \frac{R(P_L - P_G) + X(Q_L - Q_G)}{U_3} \qquad (3)$$

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 $P_{DG} = 2.97$ MW.
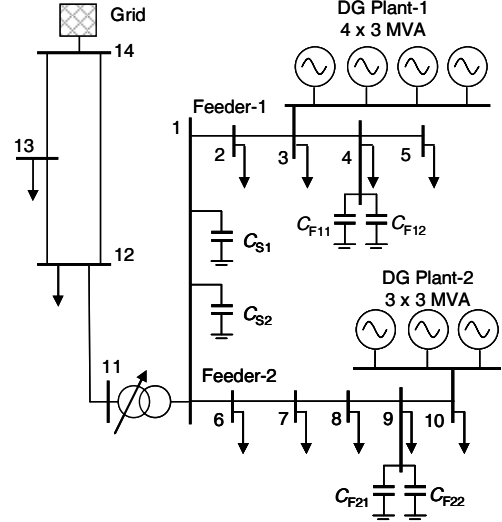

Fig. 2. One-line diagram of the system under study.

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.
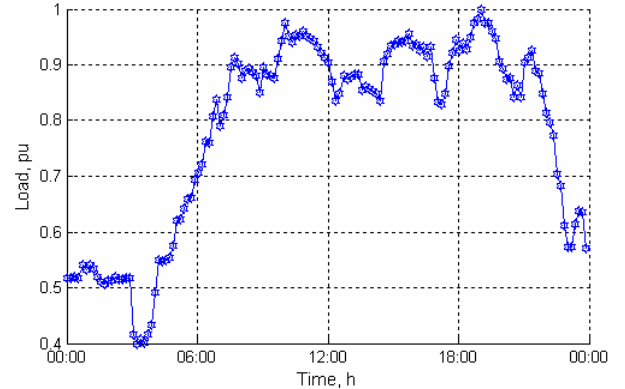

Fig. 3. Daily load profile of the system under study.
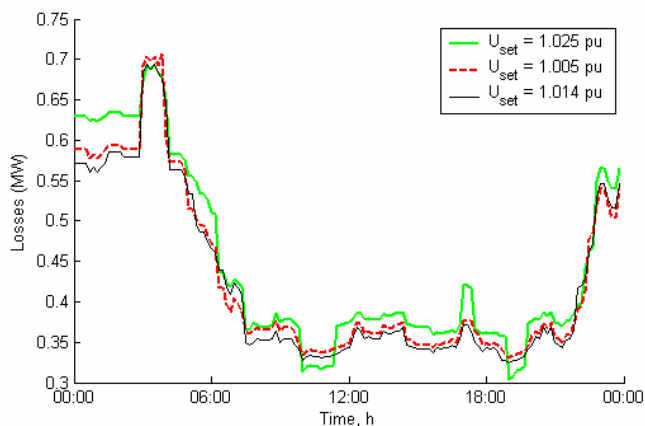
IV. PROBLEM FORMULATION

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

the system within the allowed range for all possible load variation in a considerably long period, as frequent alteration of the OLTC and capacitor controllers is not practical in many cases.

On a distribution system with only load, where the load is of constant power type, the minimization of the losses can be achieved by operating the feeder close to the maximum allowed voltage while keeping the shunt capacitors to properly compensate the reactive power demand [12]. However, this condition will change with DG present in the system, as the feeder capacitors can be switched off when the reactive power demand is still considerably high. Hence, the losses will not always be minimized with the local voltage and reactive power control.

For example, the daily losses of the system under study, with DG operated at a constant pf, are shown in Fig. 4. The results indicate that lowest daily losses will be achieved if the OLTC set point voltage U_{set} is set as 1.014 pu. However, the figure shows that the losses can be decreased if, for example, the OLTC set point is changed to 1.025 pu on two peak hours, e.g., around 11 and 19 o'clock (see also Fig. 3), by using a remote automated schedule (short term operation planning).

Different methods of short term operation planning for the voltage and reactive power in distribution systems have been proposed. For example, in [8]-[9], OLTC and all capacitors (both substation capacitors and feeder capacitors) are automatically dispatched in hourly basis, which is defined based on a one-day-ahead load forecast. This method fully replaces the local control with remote control. The drawback of full remote control method is that the OLTC and the capacitor will lose their capability to respond to load changes that deviate from the ones forecasted. In [10], the OLTC is controlled by considering the dispatch schedule of all capacitors in order to reduce the number of OLTC operations. Firstly, a dispatch schedule of capacitors is determined based on a one-day-ahead load forecast. The capacitor schedule is then used as the basis for the change of OLTC set point voltage, which is controlled in real time to cover the difference between the actual and the forecasted load.

Fig. 4. Losses in the distribution system with DGs operated at unity pf and different OLTC set point voltages.

The methods in [8]-[10] depend on communication links to all capacitors in the feeders. A short term operation planning without communication to the feeder capacitors is presented in

[11]. Firstly, a set of daily OLTC tap position and status of all capacitors for a load forecast, based on their local control operation, can be found. By using dynamic programming, the optimum OLTC tap position and status of all capacitors in a day can be obtained. A remote dispatch schedule of OLTC and capacitors in the substation can then be defined. In practice, the difference between the actual and the forecasted load, as long the difference is not significant, will be covered by the local operation of the OLTC and capacitors. The implementation of the proposed method to the system with induction machine based DG, where the DG does not take part in the voltage regulation, has also been investigated.

DG is normally not involved in the voltage control in the distribution system, though synchronous DGs have an inherent feature to perform automatic voltage control, with a rapid operation that is much faster than the operation of the OLTC and mechanically switched shunt capacitors. By involving DG in the voltage control, the DG will be the first equipment that responses to the voltage fluctuation due to the load change. Further, DG in voltage control mode will continuously keep its terminal voltage constant; meanwhile the OLTC and voltage-controlled-capacitor will only operate if the voltage at the controlled bus goes beyond a certain range. Hence, it can be expected that involving DG in the distribution system voltage control will result in a reduction of the number of OLTC operations and voltage fluctuation in the distribution system.

By involving DG in the coordinated voltage control, the voltage control in the distribution systems will be similar to the coordinated voltage control in transmission systems, where the voltage control is deployed into three hierarchical levels. The primary control is performed by DG. The secondary control is performed by locally operated OLTCs and switched capacitors. Meanwhile, the tertiary control is performed by remotely adjusting DG, OLTC and substation capacitors, if required, in order to obtain an optimum voltage profile and reactive power flow. The method proposed in [11] can be extended, by involving DG in the control process, to perform the tertiary control.

When the DG is operated at voltage control mode and the feeder capacitor is controlled by a voltage controller, the capacitor will not operate except when the DG has reached its limit, as the DG operate faster than the capacitor. Hence, the capacitor reactive power is not maximally used. On the other hand, the capacitor reactive power is considerably cheaper than the DG reactive power (by assuming that the capacitor has already been available in the distribution system). Further, as DG has a fast dynamic characteristic and the mechanically switched capacitor does not, the unused DG reactive power will be the reactive power reserve during a grid fault, meanwhile the de-energized capacitor will not. Therefore, coordinated voltage control involving DG will have a potential benefit in increasing reactive power reserve for emergency purpose.

V. The Coordinated Three-Level-Voltage Control with DG

The coordinated three-level-voltage controls that will be investigated here will be emphasized on minimization of losses and maximization of the usage of shunt capacitor as the objective function. The conceptual diagram of the proposed voltage control is shown in Fig. 5. The DG performs the primary voltage control by keeping its terminal voltage equal to the DG reference voltage U_{DG}. The secondary voltage control is performed by the capacitors and the OLTC. The feeder capacitors are controlled by, and will maintain, their local bus voltage U_{CF}. The DGs and the feeder capacitors will also affect the reactive power flow on the corresponding feeders Q_F. The substation capacitors are controlled by the transformer reactive power flow Q_{TX} and will maintain Q_{TX} and the substation primary bus voltage U_0. The OLTC is controlled by, and will maintain, the substation secondary bus voltage U_1 within a certain range. The tertiary control is performed by developing a short term operation planning, in order to remotely adjust the DG, OLTC and substation capacitors, based on a specified objective function and constraints for a one-day-ahead forecasted load and planned DG power output.
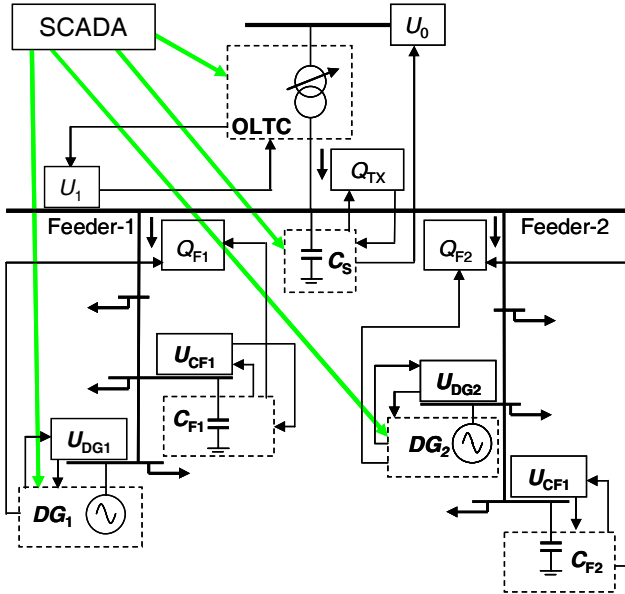

Fig. 5. Conceptual diagram of the proposed coordinated voltage and reactive power control.

Mathematically, the coordinated voltage control can be expressed with the following objective function and inequality constraints:

Min

$$J = \sum_{i=1}^{N} \left(C_1 P_{Loss,i} - C_2 \sum_{j=1}^{NC} SC_{j,i} \right) \tag{4}$$

subject to

$$U_{min} \leq U_{k,i} \leq U_{max}, \; \forall \text{ buses} \tag{5}$$

$$I_{L,p,i} \leq I_{L,p,rat}, \; \forall \text{ lines} \tag{6}$$

$$S_{TX,i} \leq S_{TX,rat} \tag{7}$$

$$Q_{DG,j}\big|_{min} \leq Q_{DG,j,i} \leq Q_{DG,j}\big|_{max}, \; \forall \text{ DGs} \tag{8}$$

where

N	number of stages in a day, which is 144 for 10 minutes interval between i and $i + 1$
C_1, C_2	coefficient factor for losses and DG reactive power, respectively
$P_{Loss,i}$	total feeders and transformer losses at time i
$SC_{j,i}$	status of capacitor-j at time i , 1 if the capacitor is on and 0 if the capacitor is off
NC	number of capacitors in the system
$U_{k,i}$	voltage at bus-k at time i
U_{min}	minimum allowed voltage, i.e. 0.95 pu
U_{max}	maximum allowed voltage, i.e. 1.05 pu
$I_{L,p,i}$	current flowing on line-p at time i
$I_{L,p,rat}$	line thermal capacity of line-p
$S_{TX,i}$	apparent power flow on substation transformer at time i
$S_{TX,rat}$	substation transformer rating
$Q_{DG,j}\big|_{min}$	minimum reactive power output of DG-j
$Q_{DG,j}\big|_{max}$	maximum reactive power output of DG-j

Besides the objective function and operating constraints, the number of daily OLTC operations and the following bus voltage fluctuation index, given by the following equations, will also be examined

$$DT = \sum_{i=1}^{N} |TAP_i - TAP_{i-1}| \tag{9}$$

$$UF = \frac{1}{NB} \sum_{k=1}^{NB} \sum_{i=1}^{N} \frac{|U_{k,i} - U_{k,i-1}|}{N} \times 100\% \tag{10}$$

where

TAP_i	OLTC tap position at time i
DT	daily number of OLTC operations
UF_k	voltage fluctuation index
NB	number of buses in the distribution system

VI. Simulation Results

The local controller used in the simulation is indicated in **Error! Reference source not found.**, are shown in **Error! Reference source not found.**. The set points for the local operation of the OLTC and capacitors in **Error! Reference source not found.** are obtained based on an optimization with loss minimization as the objective while meeting the constraints in Eqs. (5)-(8) for a given daily load profile and DG output. Steps for this optimization are presented in [12].

TABLE I
SETTING OF THE OLTC AND CAPACITORS

	OLTC [pu]		C_{F11}, C_{F12} [pu]		C_{F21}, C_{F22} [pu]		C_{S1}, C_{S2} [Mvar]	
	U_{set}	U_{DB}	U_{OFF}	U_{ON}	U_{OFF}	U_{ON}	Q_{ON}	Q_{OFF}
Case-1	1.014	0.02	1.048	1.005	1.042	1.00	2	-2
Case-2	1.045	0.01	1.048	1.038	1.047	1.041		

The remote dispatch schedule is presented in Table II. The losses for different cases with local control and with coordinated control are presented in **Error! Reference source not found.**. For case-1, in principle more loss reduction can be gained by executing more dispatch actions than the actions in **Error! Reference source not found.**. However, this will result in an enormous increase of the number of OLTC operations.

TABLE II
REMOTE DISPATCH SCHEDULE OF OLTC, SUBSTATION CAPACITORS AND DG

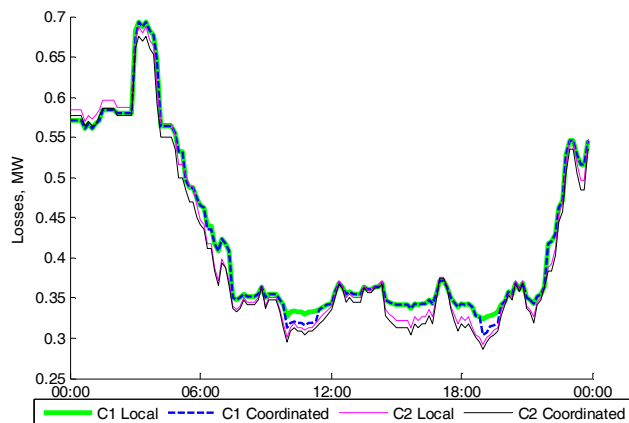|	Case-1		Case-2			
	Time	Action	Time	Action		
		U_{set} [pu]		U_{set} [pu]	U_{DG1} [pu]	U_{DG2} [pu]
1.	10.00	1.025	07.30	-	-	1.045
2.	11.20	1.014	09.50	1.05	1.05	-
3.	19.00	1.025	12.00	1.0475	-	-
4.	19.40	1.014	14.30	1.05	-	-
5.	-	-	16.50	1.0475	1.0475	-
6.	-	-	17.40	1.05	1.05	-
7.	-	-	20.00	1.0475	1.0475	-
8.	-	-	22.00	-	-	1.04

Fig. 6. Losses for different cases with local and coordinated control.
C1 and C2 mean case-1 and case-2, respectively.

It is shown in Fig. 6 that, in these cases, the loss reduction by the coordinated control is very marginal. This is because the control set points are already optimal for the given daily load. However, in practical systems, the daily load profile will change every day, meanwhile with the local voltage and reactive power control method, the local control set points are kept unchanged for a considerably long period, on a seasonal basis for instance. Hence, in principle, more significant loss reduction, as in the cases with induction DG, can be expected.

The maximization of the usage of capacitors with coordinated control in case-2 can be seen in **Error! Reference source not found.**. As has been explained, by the maximizing of the usage capacitor, the DG reactive power is expected to be reserved for emergency that will improve the voltage stability of the system.

The simulation results in Table III indicate that:
- The coordinated voltage control will decrease losses, with the increase in the number of OLTC operations as the expense.

- DG involved in the voltage control will significantly reduce the number of OLTC operations and voltage fluctuation in the distribution system.
- Changing from uncoordinated to coordinated control does not significantly change the voltage fluctuation in the system.
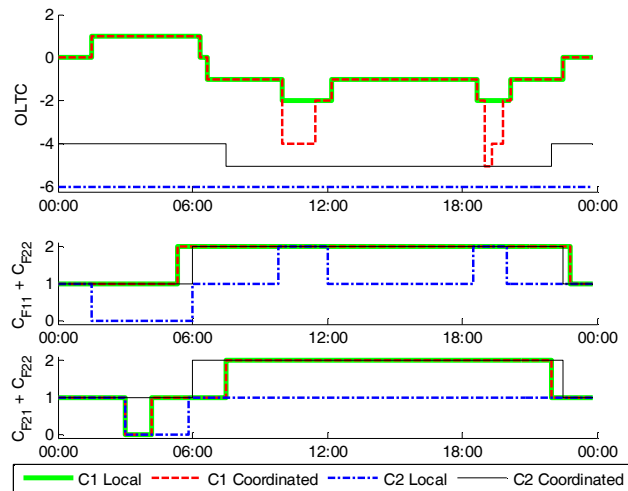

Fig. 7. OLTC and capacitor status for different cases with local and coordinated control.

TABLE III
TOTAL DISTRIBUTION SYSTEM LOSSES AND TOTAL NUMBER OF
OLTC/CAPACITOR OPERATIONS IN A DAY WITH LOCAL
AND COORDINATED CONTROL

		Losses [MWh]	Number of OLTC Operations	*UF* [%]
Case-1	Local	10.29	8	0.322
	Coordinated	10.13	18	0.328
Case-2	Local	9.96	0	0.039
	Coordinated	9.79	2	0.025

VII.   CONCLUSIONS

In this paper, a comparative analysis of different voltage and reactive power control methods in distribution systems in the presence of distributed generation (DG) has been presented. Both uncoordinated and coordinated voltage control, without and with DG involved in the voltage control, are investigated.

The coordinated voltage control presented in this paper is based on automatic remote adjustment to the local operation of the voltage and reactive power equipment in the distribution system. The adjusted equipment are the on-load tap-changer (OLTC), capacitors in the substation, and DG. The automatic adjustment is 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 number of OLTC operations and of the voltage fluctuation in the distribution system. Further, by involving DG in the coordinated voltage control, the usage of capacitor reactive power can be

minimized in such a way that the DG reactive power can be reserved for emergency (during a grid fault).

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