Decentralized Reactive Power Control for Advanced Distribution Automation Systems

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***Abstract*—In this paper a decentralized reactive power control scheme is proposed to optimally control the switched capacitor in the system in order to minimize system losses and maintain acceptable voltage profile. The proposed technique is based on placing a remote terminal unit (RTUs) at each DG and each at line capacitor. These RTUs being coordinated together through communication protocols form a multiagent system. Novel decentralized algorithm is proposed to estimate the voltage profile change as a result of injecting reactive power at the capacitor bus. Simulation results are presented to show the validity and the effectiveness of the proposed technique.**

***Index Terms*—Distribution generation, distribution systems, multiagent system, reactive power control.**

I. Nomenclature

$P_{\mathrm{n,n+1}}$	Active power flow from RTU_n bus to $\mathrm{RTU}_{\mathrm{n+1}}$ bus. In our equations, if active power flows from downstream to upstream, it is considered positive. Otherwise it is negative.
$Q_{n,\mathrm{n+1}}$	Reactive power flow from $\mathrm{RTU}_{\mathrm{n}}$ bus to $\mathrm{RTU}_{\mathrm{n+1}}$ bus. In our equations, if reactive power flows from upstream to downstream, it is considered positive. Otherwise, it is negative.
$V_{(n)old}$	Voltage of bus n prior to the connection of the capacitor.
$X_{n-1,n}$	Reactance of the line segment between bus $n-1$ and bus n.
$R_{n-1,n}$	is the resistance of the line segment between bus $n-1$ and bus n.
$Q_{(n-1,n)old}$	Reactive power flow from bus $n-1$ to bus n prior to the connection of the capacitor.
$P_{(n-1,n)old}$	Active power flow from bus $n-1$ to bus n prior to the connection of the capacitor.
$V_{(n)new}$	Voltage of bus n after connecting the capacitor.
$\text{Losses-index}_{\mathrm{Qc}}$	Losses index corresponding to a reactive power injection at the capacitor bus equals Q_c.

Manuscript received October 15, 2011; revised March 25, 2012; accepted April 05, 2012. Date of publication June 26, 2012; date of current version August 20, 2012. Paper no. TSG-00577-2011.

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Digital Object Identifier 10.1109/TSG.2012.2197833

II. Introduction

CURRENTLY, the power network is undergoing a complete reconstruction. Motivated by technical, economic and environmental factors, this reconstruction will lead to the new concept of smart grid. In [1], advanced distribution automation (ADA) is described as the "heart of the smart power delivery system." Generally speaking, ADA is a concept that will make the distribution system fully controllable and flexible. In ADA all controllable equipment and control functions are to be automated to achieve the optimal operation of the system. Incorporating advanced control strategies, new technologies and communication schemes, ADA will result in higher reliability, minimal losses, optimal utilization of distribution system assets, and integration of larger amounts of renewable energy into the existing distribution systems.

In order to achieve the ADA concept, it is essential for many distribution system equipment to become intelligent. These devices will range from power quality management devices and monitoring devices to voltage and Var control equipment. Hence, the ADA concept, in part of it, will evolve as a large distributed intelligence platform in which the distribution system operation functions will be achieved. As a result, there is a need for advanced control techniques to utilize the distributed intelligence in the system in order to carry out the system operation in an optimal manner.

For decades the Var control has been identified as one of the crucial operation functions of the distribution system. Efficient Var control reduces system losses, improves voltage profile, and hence enhances the delivered power quality and overall system reliability.

As a matter of fact, the increasing penetration of distribution generation (DG) in distribution systems in recent years makes it even more crucial to have efficient reactive power operation schemes. In reality, the presence of DG in distribution feeders change its voltage profile greatly and hence interrupt the voltage sensing capabilities of capacitor banks which, basically, depends on ever-decreasing feeder's voltage profile. On top of that, efficient coordination between feeder's capacitors and DGs can allow for the integration of more DGs in the system.

Most of the research in Var control area was concerned with the planning of the reactive power. The optimal capacitor sizing and allocation problem has been studied extensively in the literature [2]–[4].

On the other hand, the operation of the reactive power control equipment had received little attention. It has been the usual practice in utilities to operate capacitor banks based on local signals such as time of day or current magnitude with the aim to have the capacitors connected at maximum load and disconnected at minimum load.

Currently, there is a need to adopt a more efficient reactive power control schemes in order to achieve the goals of the smart grid by having a more efficient and reliable distribution system.

Several solutions have been reported in literature to achieve the optimal reactive power control in the presence of DG. Forming the reactive power control as a centralized optimization problem has been proposed in different works [5]–[8]. In these techniques, a central point monitors the status of the reactive power control equipment, perform a load forecast for a certain horizon, solve a reactive power optimization problem based on the forecasted conditions and finally determine the optimal settings for the reactive power control equipment. The problems with this approach are, first, for large systems, the centralized approach will be too cumbersome. Second, given that this approach is based on load forecasting, there is no guarantee for the accuracy of the solution especially in the presence of renewable-based DG with varying output power.

Another emerging approach is solving the problem in a decentralized manner. In [9], a multiagent decentralized reactive power DG dispatch for the support of the system voltage was proposed. The problem with that approach is that it assumes the existence of a moderator point which takes bids from DGs and calculates the optimal overall solution which is, more or less, a centralized way of solving the problem. In another work [10], a decentralized approach for the control of DG reactive power output was proposed to mitigate the voltage rise due to the connection of the DG. This work is not applicable for the control of other reactive power control equipment of the system such as capacitors.

In this paper, we propose a decentralized optimal reactive power control scheme. The proposed scheme controls the switched capacitor banks, and possibly other reactive power control devices, in real time. This approach is based on the existing loading conditions to minimize the system losses while maintaining acceptable voltage profile for the feeder. The proposed scheme is based on the coordination between RTU located at each DG and at each shunt capacitor of the feeder to form a multiagent system.

This paper is structured as follows; Section III details the voltage profile estimation technique based on the readings of the RTU located at the DG buses and the capacitors buses. Following that, the estimation of the change of the voltage profile due to the injection of the reactive power at the capacitor bus is discussed in Section IV. Based on the results of Sections III and IV, the proposed system structure for the reactive power control is presented in Section V. The reactive power control algorithm is presented in Section VI for the case of single capacitors and is generalized in Section VII. Simulation study is provided in Section VIII to validate the proposed technique. The paper's conclusions are drawn in Section IX.

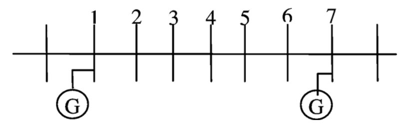

Fig. 1. Part of a distribution system.

III. Voltage Profile Estimation

In this section two important results will be proved regarding the estimation of the maximum and the minimum voltage points of the voltage profile along the feeder. It is worthy to note here that the knowledge of the maximum and the minimum points of the voltage profile is enough to achieve voltage regulation and reactive power control for the feeder.

We will start by maximum voltage points. The next result shows that maximum points of the voltage profile can only happen at the DG connecting buses or at a capacitor connecting buses. The proof of this result can be found in [3]

1) Result 1: For the voltage profile of a feeder, maximum voltage can happen only at the DG connecting buses, capacitors connecting buses, and the substation bus, provided that the R/X ratio of the feeder is constant along the whole feeder.

Now we turn to the minimum voltage points. In general, minimum voltage points can occur only at the end of the feeder as well as in between any DG connecting buses. The voltage of the end points can be read using RTU or alternatively it can be estimated the same way as minimum points in between the DG units.

For the minimum points in between the DG or capacitor connecting buses, the following result gives the necessary and sufficient condition for the existence of these points. The proof of this result can be found in [3]

2) Result 2: There exists a minimum voltage point in between two DG connecting buses if and only if, for both DGs, the voltage of the DG neighboring bus, in the direction of the other DG, is less than the voltage of the DG bus. In other words, for Fig. 1 and based on this result, there will be a minimum voltage point at one of the buses 2, 3, 4, 5, or 6, if and only if, the voltage of bus 1 is greater than the voltage of bus 2 and that the voltage of bus 7 is greater than the voltage of bus 6.

Similarly, the same result will apply to the points in between two capacitors as well as between one capacitor and one DG.

Note that it is not important, from the point of view of voltage regulation, to know the exact location of the minimum voltage point. The importance of the above results is that it provides a guaranteed method to check for the existence of a minimum voltage point. In fact, knowing the mere existence of minimum voltage points is not enough. We need to know the value of the minimum voltage point as well.

We propose to estimate the value of the minimum voltage point using the readings available at the DG or the capacitor bus only. In fact, this part of the proposed method can be tailor-designed for each network based on whatever available information about its loading characteristics. Nevertheless, we will use an estimation which gives the worst case value for the minimum voltage point thus it could be considered as a good lower bound for the minimum voltage point.

We will assume that the load between the two elements (DG or capacitor) is concentrated halfway between them. For Fig. 2,