# 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 $\mathrm{RTU}_n$ bus to $\mathrm{RTU_{n+1}}$ 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 $\mathrm{RTU_n}$ bus to $\mathrm{RTU_{n+1}}$ 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. |
| $\mathrm{Losses\text{-}index_{Qc}}$ | 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.

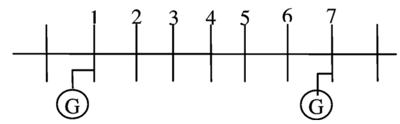


Fig. 1. Part of a distribution system.

## 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,

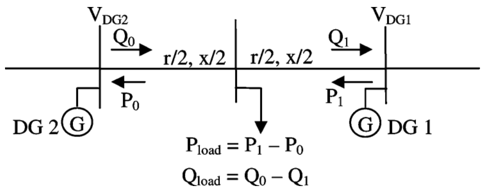


Fig. 2. A part of distribution system.

based on this assumption, the value of the minimum voltage point between the DG1 and DG2, if exists, as calculated by $\mathrm{DG}_1$ can be given as

$$V_{\min,DG1} = V_{DG1} - \left(P_1\frac{r}{2} - Q_1\frac{x}{2}\right). \tag{1}$$

Also, the value of the assumed minimum voltage point calculated by $\mathrm{DG}_2$ is given by

$$V_{\min,DG2} = V_{DG2} - \left(-P_0\frac{r}{2} - Q_0 + \frac{x}{2}\right). \tag{2}$$

Then we can take the average of these two values to get a better estimation, so

$$V_{\min} = \frac{V_{\min,DG1} + V_{\min,DG2}}{2}. \tag{3}$$

Finally substitute (1) and (2) in (3) we get

$$V_{\min} = \frac{V_{DG1} + V_{DG2}}{2} - \frac{r}{4}(P_1 - P_0) - \frac{x}{2}(Q_0 - Q_1). \tag{4}$$

Equation (4) gives an estimation for the value of the minimum voltage point, if exist, between two elements using the data measured at elements' buses only.

It is worthy to mention that, different loading schemes could have been assumed between the two elements, e.g., uniformly distributed. The choice of the assumed loading scheme should be network-specific.

## IV. Estimation of Voltage Profile Change Due to the Injection of Reactive Power

In order to develop a decentralized reactive power control scheme, it is imperative to propose a decentralized way to estimate the change in the voltage profile due to the injection of reactive power at the capacitor connecting bus.

Due to the connection of the capacitor to the feeder, the reactive power flow from station bus will be reduced by the amount of the reactive power injected at the capacitor bus, assuming the losses are negligible Also, all reactive power flows between any two buses upstream of the capacitor bus will be reduced by the amount of the reactive power injected at the capacitor bus. On the other hand, the reactive power flow downstream of the capacitor will not be affected. Hence, the injected $Q_C$ can be looked at, in a superposition fashion, as if it is flowing towards the supply.

Based on this concept we can analyze the voltage profile of any feeder as follows; the voltage difference between any two buses $n$ and $n-1$, upstream of the capacitor bus with the capacitor out of service, can be written as

$$V_{(n-1)old} - V_{(n)old} = P_{n-1,n}R_{n-1,n} + Q_{(n-1,n)old}X_{n-1,n}. \tag{5}$$

After connecting the capacitor, (5) can be written as

$$V_{(n-1)new} - V_{(n)new} = P_{n-1,n}R_{n-1,n} + (Q_{(n-1,n)old} - Q_c)X_{n-1,n}. \tag{6}$$

Subtracting (5) from (6) and rearranging, we get

$$V_{(n)new} - V_{(n)old} = V_{(n-1)new} - V_{(n-1)old} + Q_C X_{n,n-1}. \tag{7}$$

Similarly,

$$V_{(n-1)new} - V_{(n-1)old} = V_{(n-2)new} - V_{(n-2)old} + Q_C X_{n-1,n-2}. \tag{8}$$

Ultimately,

$$V_{(1)new} - V_{(1)old} = V_{(0)new} - V_{(0)old} + Q_C X_{0,1}. \tag{9}$$

However, bus 0 is the station bus, which we will assume to be stiff, then

$$V_{(1)new} - V_{(1)old} = Q_C X_{0,1}. \tag{10}$$

Applying (10) recursively in (7) we can write

$$V_{(2)new} - V_{(2)old} = Q_C X_{0,1} + Q_C X_{1,2}. \tag{11}$$

Generalizing (11), we get

$$V_{(n)new} - V_{(n)old} = Q_C X_{0,1} + Q_C X_{1,2} + Q_C X_{2,3} + \cdots + Q_C X_{n-2,n-1} + Q_C X_{n-1,n}. \tag{12}$$

Put in compact form,

$$V_{(n)new} = V_{(n)old} + Q_C \sum_{k=1}^{k=n} X_{k-1,k}. \tag{13}$$

Equation (13) gives the change in the voltage of any bus upstream of the capacitor in terms of the amount of reactive power injected at the capacitor bus and feeder reactance.

On the other hand, the voltage change at any bus downstream of the capacitor bus is the same as the voltage change at the capacitor bus itself. This result follows directly from the fact that the reactive power flow downstream of the capacitor will not be changed due to the connection of the capacitor.

In the light of (13), we will propose the structure of the decentralized reactive power control scheme, in Section V, to be able to calculate the new voltage at any bus due to the injection of reactive power at the capacitor bus.

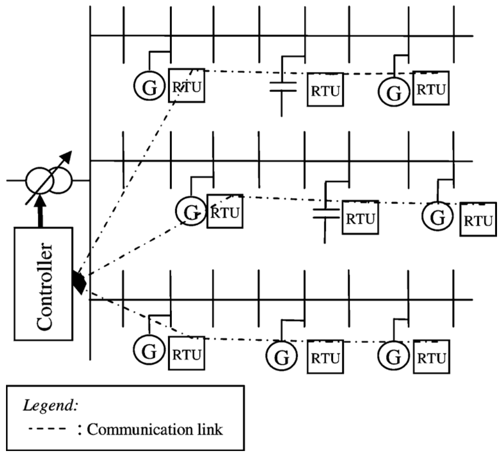


Fig. 3. Proposed system structure.

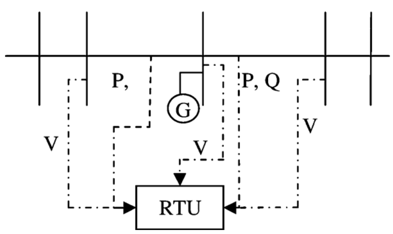


Fig. 4. Details of RTU measurements.

## V. Proposed System Structure

Based on the results of Sections III and IV, we propose the system structure depicted in Fig. 3. The system consists of an RTU at each DG and each capacitor and a communication link between each two RTU that have a power line connection between their elements (DGs or capacitors). Each RTU is responsible for taking local measurements at its element, perform calculations, execute some logical statements and communicate with its neighbor RTU or the station. Fig. 4 shows a detailed view for parameters measured by each RTU.

Namely, each RTU measures the voltage of its element bus, active and reactive power flow in lines connected to its element bus, and the voltages of the immediate neighbor buses of its element bus. Note that the voltage of the immediate neighbor buses is needed only in order for the RTU to get the trend of the voltage profile, increasing or decreasing, thus, measuring a point on the feeder adjacent to the RTU could be sufficient.

Based on the measurements of each RTU, it will be able to:

1. Measure a maximum voltage point of the voltage profile; the DG or the capacitor bus voltage.
2. Check one part of the condition for the possibility of the existence of a minimum voltage point of the voltage profile between its element and any neighbor element.
3. Estimate the value of the minimum voltage point on each side of its element, if it exists.

The communication structure between the RTU can be represented by the graph of Fig. 5. This communication structure represents a tree in which the station is the root of the tree, each feeder segment is a branch and each RTU is a node.

In a previous work by the authors, the same structure was used to achieve a decentralized voltage control for multiple feeders [11].

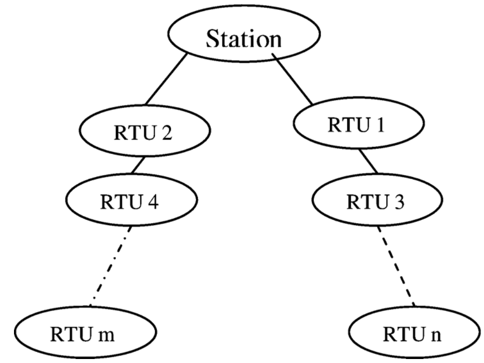


Fig. 5. A graph representing the communication structure between the RTUs.

## VI. Optimal Operation of Switched Capacitor Banks in Distribution Feeders Algorithm: Single Capacitor Case

The main goal of the algorithm executed by the RTU is to enable the capacitor to determine the optimal reactive power injection based on system conditions. The optimal reactive power is defined as the value that:

1. will minimize the losses of the feeder.
2. does not cause a violation of the voltage profile along the feeder.

Firstly, we have to introduce a measure for the losses corresponding to each reactive power injection at the capacitor bus. In this work, as we do not measure the voltage at every node of the system, we cannot measure or calculate the exact amount of losses. However, knowing which reactive power will minimize the losses is enough for our sake. In this work we will consider the voltage difference between the buses as an approximate measure for the losses in the lines. As the difference between buses' voltages is reduced, the losses will be reduced. Hence, in the following algorithms, we are looking for the reactive power injection at the capacitor that will minimize the voltage difference between the buses. In other words, the optimal reactive power injection at the capacitor is the one that will minimize the losses-index defined as

$$losses\_index = \sum_{n=1}^{N-1} (V_n - V_{n+1})^2 \tag{14}$$

where N is the total number of minimum and maximum voltage points of the voltage profile of the feeder.

Secondly, for the capacitor's RTU to determine the optimal reactive power injection that will not violate the voltage profile, it has to know the maximum and the minimum value of the voltage profile corresponding to each possible reactive power injected at the capacitor's bus.

In summary, the goal of the proposed algorithm is to enable the capacitor to determine three main values corresponding to each possible reactive power injection; the maximum voltage of the feeder, the minimum voltage of the feeder and the value of the losses-index.

The algorithm starts off at the farthest RTU from the station. There are five different types of RTU according to their locations relative to the capacitor. These types are: End of feeder RTU; RTU located downstream of the capacitor; Capacitor RTU; RTU located upstream of the capacitor; and the station's RTU. In the following, the algorithm executed by each RTU type is described.

*1) End of Feeder RTU Will:*

1. read and store its bus voltage;
2. check for minimum voltage point between itself and its upstream RTU, using result 2 of Section III, then it will estimate this minimum point, if exists;
3. send to its upstream RTU its own voltage and the estimated voltage of the minimum point accompanied with a flag indicating the possibility of the existence of a minimum voltage point.

*2) RTU Downstream of the Capacitor Will:*

1. read and store its bus voltage;
2. if the minimum voltage flag received from the downstream RTU is high, check the condition for the existence of a minimum voltage point from its own side and calculate an estimate for the minimum voltage value and hence, update the voltage of the minimum point between itself and the RTU downstream of it using (3);
3. check for minimum voltage point between itself and its upstream RTU then estimate this minimum voltage point, if it exists;
4. send to its upstream RTU the following: the value of its voltage, the values of the voltages received from any downstream RTU, and the estimated voltage of the minimum point between itself and the upstream RTU accompanied with a flag indicating the possibility of the existence of a minimum voltage point.

Following the above procedure, the capacitor's RTU will receive all the maximum and minimum points of the voltage profile of the part of the feeder downstream of the capacitor.

*3) The Capacitor's RTU Will:*

1. Carry out the first three tasks same as the RTU downstream of the capacitor as described above.
2. Create a variable called the overall maximum feeder voltage corresponding to each of the possible capacitor's reactive power injection;
3. Create a variable called the overall minimum feeder voltage corresponding to each of the possible capacitor's reactive power injection;
4. Calculate the new capacitor's bus voltage corresponding to each possible reactive power injection utilizing (13);
5. As noted in Section IV, voltage change for the points downstream of the capacitor is the same as voltage change of the capacitor bus. So the capacitor can update the voltages of the points downstream of its bus based on the data it has received from its downstream RTU.
6. Having the new voltages corresponding to the possible reactive power injection for the part of the feeder downstream of the capacitor, the capacitor's RTU can update the overall maximum and the overall minimum feeder voltage variables.
7. Having the new voltages corresponding to the possible reactive power injections for the part of the feeder downstream of the capacitor, the capacitor's RTU can calculate the losses-index for that part using (14).
8. Send to its upstream RTU the following: overall maximum feeder voltage, overall minimum feeder voltage, the losses-index, list of all the possible reactive power injections at its bus, the voltage of the capacitor bus.

*4) RTU Upstream of the Capacitor Will:*

1. Carry out the first three tasks same as the RTU downstream of the capacitor as described above.
2. Calculate its new voltages corresponding to the possible reactive power injections at the capacitor using (13).
3. If there is a minimum voltage point downstream of the subject RTU, the subject RTU will calculate the new voltages of the minimum point corresponding to the possible reactive power injection at the capacitor using (13).
4. Update the overall maximum and overall minimum feeder voltages variables according to its calculations of the new voltages at its bus and at the minimum point downstream of it.
5. If there is a minimum point downstream of the subject RTU, the subject RTU will calculate the losses-index between that minimum point and the downstream RTU in addition to the losses-index between itself and that minimum point. Otherwise, it will calculate the losses-index between itself and the downstream RTU. In any case, it will update the losses-index received from the downstream RTU accordingly.
6. Send to its upstream RTU the following: overall maximum feeder voltage, overall minimum feeder voltage, the losses-index, list of all the possible reactive power injections at its bus, the voltage of its own bus.

*5) The Station RTU Will:*

1. Carry out the first three tasks same as the RTU downstream of the capacitor as described above.
2. If there is a minimum voltage point downstream of the subject RTU, the subject RTU will calculate the new voltages of the minimum point corresponding to the possible reactive power injection at the capacitor using (13).
3. Update the overall maximum and overall minimum feeder voltages variables according to its calculations of the new voltages at its bus and at the minimum point downstream of it.
4. If there is a minimum point downstream of the subject RTU, the subject RTU will calculate the losses-index between that minimum point and the downstream RTU in addition to the losses-index between itself and that minimum point. Otherwise, it will calculate the losses-index between itself and the downstream RTU. In any case, it will update the losses-index received from the downstream RTU accordingly.
5. At this point the station RTU will have the overall maximum feeder voltage, overall minimum feeder voltage, the losses-index for the whole feeder. So the station's RTU will determine the optimal reactive power injection which corresponds to the minimum losses and, at the same time, does not violate the voltage profile.
6. Send to the downstream RTU the optimal reactive power injection to pass it to the capacitor.

*6) Comments:*

1. Limiting the number of switching operations of the capacitor to meet the practical operation practice can be incorporated easily in the proposed algorithm. Simply, there could be a counter at the capacitor RTU to count how many switching operations took place in a certain predetermined period. If the number of allowable switching operations is reached the capacitor will convert to the idle status.
2. It is not necessary to predefine the RTU as upstream or downstream of the capacitor. In fact, that can be done dynamically. One way of doing that is to have a capacitor-flag that indicates that the capacitor is downstream. The only RTU that is allowed to set this flag high is the capacitor's RTU. As messages propagate from the end of feeder, each RTU will decide its location as follows: As long as the capacitor flag is low, then the location is downstream of the capacitor.

## VII. Optimal Operation of Switched Capacitor Banks in Distribution Feeders Algorithm: General Case

In this section a generalized algorithm is presented to tackle the case where more than one capacitor exists on the feeder.

Following the same analysis of Section IV, one can notice that (7) is a general equation that gives the voltage change at a certain bus in terms of the voltage change at its upstream bus. This equation can be used to estimate the voltage change at a certain bus given the reactive power flow between this bus and its upstream bus.

In order to calculate the voltage change due to the reactive power injections at a certain RTU using (7), it is necessary to know the voltage change at the RTU upstream of the subject RTU. Therefore, this proposed algorithm is carried out in two phases; Forward phase and backward phase. These two phases are described below:

*1) Forward Phase:* This phase can be described in the following points:

1. RTUs will estimate the voltage profile of the feeder in the same manner as was discussed in Section VI. More details about the voltage profile estimation algorithm can be found in [11].
2. In addition, each capacitor will send a list of its possible reactive power injection to its upstream RTU.
3. Each RTU will store the received reactive power injections list to be used in the backward phase.
4. When a capacitor's RTU receives a list of possible reactive power injections from the downstream RTU, it will combine the received list with a list of the possible reactive power injections of its own capacitor and forward the combined list to the upstream RTU.

Effectively, at the end of the forward phase each RTU will have stored its voltage and a list of the combined reactive power injections from capacitors downstream of it. Hence, for each RTU to calculate the change in its voltage due to the reactive power injections using (7), it only needs to have the change in the upstream RTU voltage. The forward phase will end at the station.

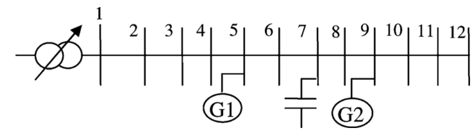


Fig. 6. System used for simulations.

TABLE I
Active and Reactive Power Values at Each Bus of the System

| Bus # | P(kW) | Q(kVar) |
|---|---|---|
| 2 | 26 | 60 |
| 3 | 40 | 30 |
| 4 | 55 | 55 |
| 5 | -80 | 0 |
| 6 | 60 | 15 |
| 7 | 55 | 0 |
| 8 | 45 | 45 |
| 9 | -250 | 0 |
| 10 | 35 | 30 |
| 11 | 40 | 30 |
| 12 | 30 | 15 |

*2) Backward Phase:* The backward phase starts at the station and propagates in the downstream direction. This phase can be described as follows:

1. Each RTU will receive the voltage change of its upstream RTU. Note that as the station bus is assumed to be stiff, the change in its voltage is zero.
2. After receiving the change of the upstream RTU voltage, each RTU will be able to calculate the change in its own voltage corresponding to the list of the reactive power injection stored at the forward phase using (7).
3. The RTUs will be able to calculate the losses index in the same way described in Section VI.
4. Ultimately, the most downstream capacitor will have the maximum and the minimum voltages, in addition to, the losses index of the feeder corresponding to each possible combination of the reactive power injections from feeder's capacitors.
5. Therefore, the downstream capacitor will be able to determine which combination of the reactive power injections of the all the capacitors is optimal and hence it will send its decision back to the upstream capacitors.

For a more detailed discussion of this case, the reader is referred to [12].

## VIII. Simulation Results

In this section several simulation results will be reported to validate the proposed reactive power control scheme. Fig. 6 shows the system under study; two DGs are connected to buses 5 and 9 and a capacitor is connected to bus 7. Loads connected at each bus are given in Table I. For all of the following cases we assume the following data:

- the station bus $\text{voltage} = 1.05$ pu;
- the maximum allowable $\text{voltage} = 1.06$ pu;
- the minimum allowable $\text{voltage} = 0.94$ pu.

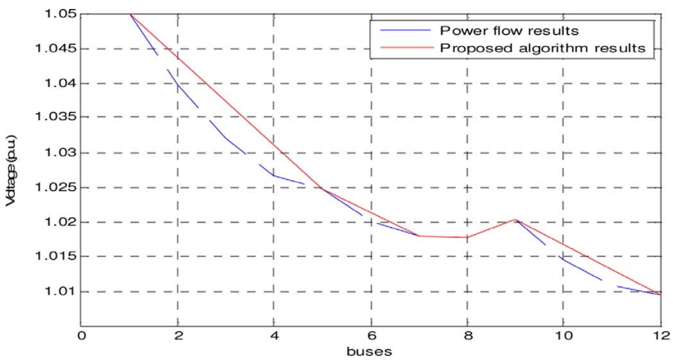


Fig. 7. Voltage profile of the test system: Capacitor reactive power $= 0$.

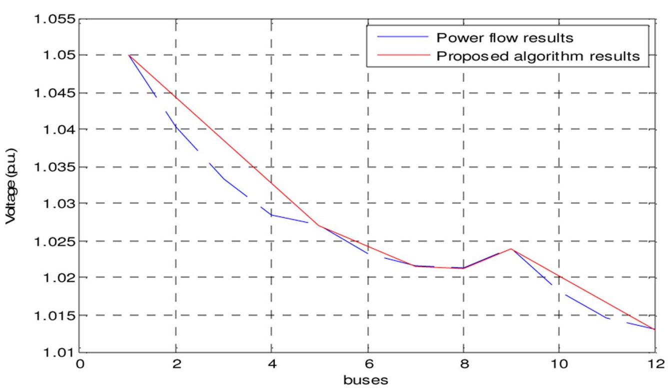


Fig. 8. Voltage profile of the test system: Capacitor reactive power $= 20$.

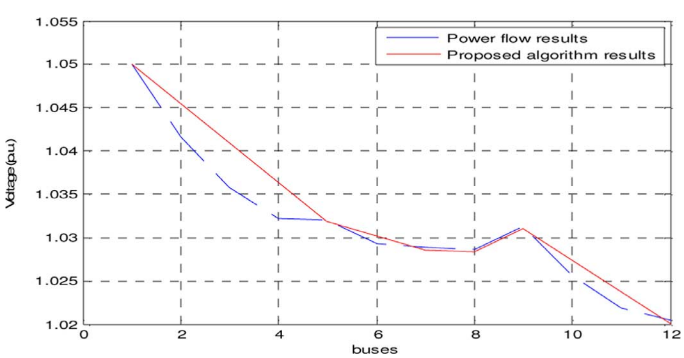


Fig. 9. Voltage profile of the test system: Capacitor reactive power $= 65$.

### A. Voltage Profile Change Due to Reactive Power Injection

In this case, we want to test the ability of the algorithm to estimate the change in the voltage profile due to the injection of reactive power at the capacitor bus. Different reactive power values are injected at the capacitor bus and the voltage profile estimated by the proposed algorithm is compared with the voltage profile obtained from a standard power flow algorithm. Figs. 7–9 show the results. It is clear from these figures that compared to the power flow solution; the proposed algorithm was able to estimate the voltage profile of the feeder efficiently given that the proposed algorithm requires much less data and acts in a decentralized manner.

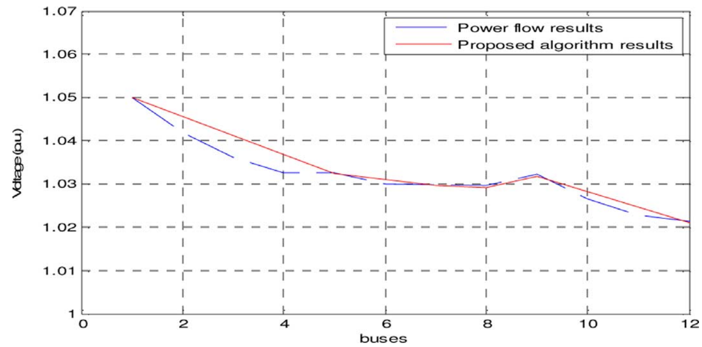


Fig. 10. Voltage profile of the test system: Capacitor reactive power $= 65$.

### B. Optimal Reactive Power Control

In this section we will test the proposed reactive power control algorithm.

*1) Case 1:* For the same system used above, the goal is to determine the optimal reactive power which will minimize the losses while maintain the voltage profile of the feeder.

After running the algorithm the capacitor's RTU will get the following data for each possible reactive power injection:

| | $\mathbf{Q} = 0$ | $\mathbf{Q} = 20$ | $\mathbf{Q} = 40$ | $\mathbf{Q} = 65$ |
|---|---|---|---|---|
| **Feeder Max Voltage** | 1.05 | 1.05 | 1.05 | 1.05 |
| **Feeder Min Voltage** | 1.0094 | 1.0130 | 1.0165 | 1.0210 |
| **Losses index** | 0.8136 | 0.6847 | 0.5698 | 0.4460 |

It is apparent that the optimal setting is $Q = 65$ kVAR. To validate this results a power flow algorithm was used to calculate the losses corresponding to each reactive power injection, the results are tabulated below:

| | $\mathbf{Q} = 0$ | $\mathbf{Q} = 20$ | $\mathbf{Q} = 40$ | $\mathbf{Q} = 65$ |
|---|---|---|---|---|
| Losses (kW) | 10.1 | 8.7 | 7.4 | 6.1 |

Fig. 10 shows the voltage profile obtained from the power flow algorithm and from the proposed voltage estimation algorithm.

*2) Case 2:* In this case we will test the performance of the proposed technique in reaction to a change in DG output power. For the sake of simulation, assume that DG1 injects 200 kW and DG2 injects 300 kW. Based on the new power injections and after running the proposed algorithms, the capacitor RTU will get the following data for each possible reactive power injection:

| | $\mathbf{Q} = 0$ | $\mathbf{Q} = 20$ | $\mathbf{Q} = 40$ | $\mathbf{Q} = 65$ |
|---|---|---|---|---|
| **Feeder Max Voltage (p.u.)** | 1.05 | 1.0523 | 1.0559 | 1.0603 |
| **Feeder Min Voltage (p.u.)** | 1.0413 | 1.0417 | 1.0452 | 1.0425 |
| **Losses index** | 0.370 | 0.356 | 0.0353 | 0.0350 |

Although $Q = 65$ causes less losses, the corresponding voltage profile will not be acceptable, as it violate the 1.06 p.u. voltage rise limit. It is apparent that the optimal setting is $Q = 40$ kVAR. To validate this results a power flow algorithm was used to calculate the losses corresponding to each reactive power injection, the results are tabulated below:

| | $\mathbf{Q} = 0$ | $\mathbf{Q} = 20$ | $\mathbf{Q} = 40$ | $\mathbf{Q} = 65$ |
|---|---|---|---|---|
| Losses (kW) | 14.3 | 10.9 | 11.7 | 10.4 |

Fig. 11 shows the voltage profile obtained from the power flow algorithm and from the proposed voltage estimation algorithm.

*3) Case 3:* Fig. 12 shows the system under study. Loads and generation values are given in Table II. For all of the following cases we assume the following data:

- The station bus voltage $= 1.055$ pu.
- The maximum allowable voltage $= 1.06$ pu.
- The minimum allowable voltage $= 0.94$ pu.

After running the algorithm described in Section VII, regulator's RTU will get the data (shown at the bottom of the page) corresponding to each possible reactive power injection. Based on these data, the optimal reactive power is $Q1 = 0$ and $Q2 = 40$. The estimated and actual voltage profiles corresponding to this case are shown in Fig. 13. It should be noted that, based on the actual losses obtained from a standard power flow program, the losses corresponding to the case of $Q1 = 35$ kVar and $Q2 = 40$ kVar is the global minimum case. The algorithm could not get this point as it had to estimate the minimum voltage points of the voltage profile, thus, the calculation of the losses index is approximate. Even though the error is not significant, it is possible by efficient incorporation of network specific data

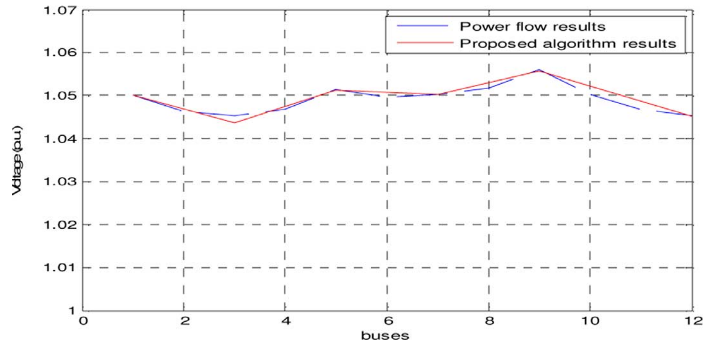


Fig. 11. Voltage profile of the test system: Capacitor reactive power $= 40$.

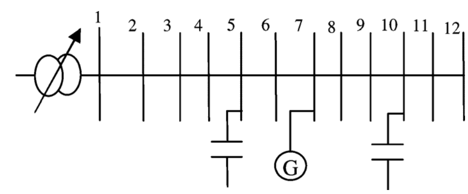


Fig. 12. System used for simulation study of case 3.

| **Possible reactive power injection** | **Maximum voltage of the feeder** | **Minimum voltage of the feeded** | **Estimated Losses index** | **Actual losses using a power flow program (kW)** |
|---|---|---|---|---|
| $\mathbf{Q}1 = 0, \mathbf{Q}2 = 0$ | 1.0550 | 1.0275 | 0.6823 | 11.6 |
| $\mathbf{Q}1 = 0, \mathbf{Q}2 = 40$ | 1.0592 | 1.0381 | 0.5843 | 9.1 |
| $\mathbf{Q}1 = 0, \mathbf{Q}2 = 30$ | 1.0574 | 1.0355 | 0.6030 | 9.7 |
| $\mathbf{Q}1 = 20, \mathbf{Q}2 = 0$ | 1.0550 | 1.0299 | 0.6764 | 10.7 |
| $\mathbf{Q}1 = 20, \mathbf{Q}2 = 40$ | 1.0616 | 1.0405 | 0.5916 | 8.5 |
| $\mathbf{Q}1 = 20, \mathbf{Q}2 = 30$ | 1.0598 | 1.0379 | 0.6068 | 8.9 |
| $\mathbf{Q}1 = 35, \mathbf{Q}2 = 0$ | 1.0562 | 1.0316 | 0.6760 | 10.1 |
| $\mathbf{Q}1 = 35, \mathbf{Q}2 = 40$ | 1.0633 | 1.0423 | 0.6017 | 8 |
| $\mathbf{Q}1 = 35, \mathbf{Q}2 = 30$ | 1.0592 | 1.0381 | 0.6142 | 8.4 |

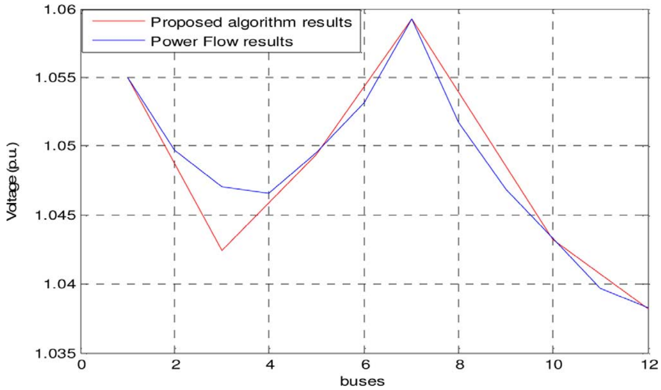


Fig. 13. Voltage profile of the system of Fig. 12 with $Q1 = 0, Q2 = 40\ \mathrm{kVar}$.

TABLE II
LOAD AND GENERATION VALUES OF THE SYSTEM OF FIG. 12

| Bus # | P(kW) | Q(kVar) |
|---|---|---|
| 2 | 26 | 60 |
| 3 | 40 | 30 |
| 4 | 55 | 55 |
| 5 | 20 | 0 |
| 6 | 60 | 15 |
| 7 | -400 | 0 |
| 8 | 45 | 45 |
| 9 | 35 | 0 |
| 10 | 35 | 0 |
| 11 | 40 | 30 |
| 12 | 30 | 15 |

to get a better estimation for the minimum point by assuming a more realistic load distribution between RTUs.

## IX. CONCLUSION

A decentralized reactive power control scheme was proposed in this paper to efficiently control the switched capacitors of the distribution feeder in order to minimize system losses while maintaining feeder's voltage profile. The proposed scheme is based on the coordination of several RTU located at DG buses and capacitor buses. These RTU form a multiagent system. Novel decentralized algorithm for the estimation of the change of the voltage profile due to the injection of reactive power at the capacitor bus was presented. Simulation results showed the effectiveness of the proposed technique in optimally managing the reactive power resources of the system. The proposed technique will help in the realization of advanced distribution automation by optimally control the switched capacitors of the system to maintain acceptable voltage profile, minimize the system losses and integrate more DGs in distribution systems by effective coordination between DGs and capacitors.

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