Abstract—In this paper, a new and completely distributed algorithm for integrated volt/var control is presented. The algorithm is based on a multiagent system, which provides distributed intelligence to smart grid. The voltage regulator and shunt capacitor controlled by intelligent agents collaborate to determine the optimal setting for the entire system. The optimization objectives include maintaining the system voltage profile within a specified range, minimizing system loss, and reducing the switching of shunt capacitors. To achieve these objectives, an updated agent-based distributed power flow solver is used. The proposed algorithm is validated through the modified IEEE 34 node test feeder.

Index Terms—Distribution automation (DA), multiagent system (MAS), shunt capacitor, smart grid, volt/var control (VVC), voltage regulator.

I. INTRODUCTION

VOLT/VAR control (VVC), which deals with voltage and reactive power control in distribution systems plays an important role in distribution automation (DA) systems. Mathematically, the VVC problem is an optimization problem with a specific objective, e.g., minimize system loss, while maintaining the system voltage profile within a specified range. The decision variables to be optimally determined are voltage regulator tap settings and shunt capacitor on/off status. Various schemes have been proposed to solve this problem and these may be categorized into centralized and decentralized (distributed) schemes.

For centralized schemes, the approaches are mixed integer linear programming [2], mixed integer nonlinear programming [10], neural network [27], gradient descent method [13], [14], [28], dynamic programming [7], [21], [26], fuzzy logic [8], [16], particle swarm optimization [11], [24], evolutionary algorithms [1], [23], and others. The optimization problem is solved by the control center with the information collected from the remote terminal units (RTUs) and the control action is sent back to the RTUs. This has good performance on small-scale systems. However, there are drawbacks of a centralized approach, especially for large or complicated systems. First, a large amount of data needs to be transferred between the control center and RTUs, which requires a costly communication system, since failure in communication may cause systemic breakdown. Second, the control center must be capable of handling a heavy computational load, which requires large capital costs. Due to the above reasons, a distributed scheme is an attractive way to augment a centralized scheme.

For distributed schemes, most of the existing work for VVC is related to distributed generation control without consideration of the cooperation from voltage regulators and shunt capacitors [17]–[19]. Even though controlling the output of distributed generation could improve the voltage profile, voltage regulators and shunt capacitors are the fundamental devices for a utility to realize voltage regulation. In [22], the distributed control is achieved by using a neural network, but the performance of voltage control is dependent on the training data, which will not work when there is sudden change in the system. In [12], a multiagent system (MAS) is implemented for all the voltage control devices and VVC is realized through two-way communication between all intelligent agents. However, the two-way communication network would not be scalable as new agents are added.

In summary, the main contributions of this paper are as follows.

1) VVC is achieved through a new and completely distributed algorithm.

2) The algorithm is easily customizable to fit in various distribution systems.

3) The algorithm provides a platform for other optimization applications in VVC.

The rest of this paper is organized as follows. Section II presents the previous work [simulation platform and distributed power flow solver (DPFS)]. Sections III and IV propose agent models for a voltage regulator and a shunt capacitor. Section V proposes a volt/var control strategy with coordinated voltage regulator agents and shunt capacitor agents. To validate the proposed control scheme, a case study on the modified IEEE 34 node test feeder is presented in Section VI. Section VII concludes this paper.

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II. Previous Work

A. Simulation Platform

The MAS is developed on Java agent development framework [9] and the intelligent agents fall into two classes: 1) switching agents (circuit breaker agent, switch agent, and sectionalizer agent); and 2) VVC agents (voltage regulator agent and shunt capacitor agent). Switching agents are responsible for fault detection, location, isolation, and even system restoration [5] while VVC agents are responsible for VVC. Each intelligent agent receives data from measurement devices, communicates with other intelligent agents in its team [3] and makes decisions to improve the system.

B. Distributed Power Flow Solver

Power flow solvers for distribution systems can be classified into two categories: 1) Newton–Raphson and Gauss–Seidel methods; and 2) forward/backward sweep methods [20]. The DPFS in this paper is developed based on the second approach.

The algorithm consists of two basic steps: 1) forward sweep; and 2) backward sweep, which are repeated until convergence is achieved. The forward sweep step calculates the voltage drop with possible current or power flow updates. The backward sweep step sums current or power flows with possible voltage updates [20]. The original distribution subsystem is partitioned into subsystems according to the MAS structure. An agent only needs to know the local subsystem information to which its device is connected. Multiagent communication is utilized during the solution process to transfer boundary information between subsystems. The comparison between the power flow solution of DPFS and the centralized power flow solution (Newton–Raphson method based) on IEEE 13 node test feeder shows that the maximum difference of voltages is 0.0011%. The details of the algorithm are introduced in [6].

III. Voltage Regulator Agent

The voltage regulator agent works under two modes.

1) Line Drop Compensator Control (LDCC) Mode: The traditional voltage regulator maintains voltage within a specified range at a remote load center by changing its taps. The position of the tap is determined by a line drop compensator (LDC) [25].

2) VVC Mode: Under VVC mode, instead of setting voltage regulator tap with LDC, the voltage regulator agent will coordinate with other agents to find the optimal setting for the entire system.

Fig. 1 shows the finite state machine diagram of the voltage regulator agent with five states. The figure also describes the conditions for a voltage regulator agent to move from one state to another. Below is the detailed description of each state.

1) NORMAL state.
   a) Tap == Tap_cal \Rightarrow \text{Calculated tap setting based on LDC matches original tap setting.}
   b) Mode = 1 \Rightarrow \text{LDCC mode.}

2) TRANSIENT state.
   a) Tap \neq Tap_cal \Rightarrow \text{Calculated tap setting based on LDC does not match original tap setting.}
   b) Mode = 2 \Rightarrow \text{VVC mode.}

3) LAUNCHDPFS_LDCC state.
   a) Mode = 1 \Rightarrow \text{Set working mode to LDCC.}
   In this state, the agent selects Tap_cal to be the candidate tap setting, then launches the distributed power flow by sending a REQUEST:LAUNCHDPFS_LDCC message and setting TLaunchDPFS_LDCC = -1 (DPFS is requested to make sure no voltage violation occurs for the entire system with Tap_cal, since Tap_cal is calculated by LDC and may cause a voltage violation at a location other than the load center). Depending on the success (TLaunchDPFS_LDCC = 1, IsVHiOk—high-voltage limit satisfied, and IsVLoOk—low-voltage limit satisfied) or failure (TLaunchDPFS_LDCC = 0) of the DPFS, the agent will move on.

4) LAUNCHDPFS_VVC state.
   a) Mode = 2 \Rightarrow \text{Set working mode to VVC.}
   In this state, the agent selects VVC as its working mode, then launches the distributed power flow by sending a REQUEST:LAUNCHDPFS_VVC message and setting TLaunchDPFS_VVC = -1. The DPFS is run with a series of tap settings based on the VVC scheme. Depending on the success (TLaunchDPFS_VVC = 1) or failure (TLaunchDPFS_VVC = 0) of the DPFS, the agent will move on.

5) CHANGE_TAP state.
   a) Change tap setting with Tap_cal (Mode = 1) or request tap setting (Mode = 2).
IV. SHUNT CAPACITOR AGENT

Fig. 2 shows an updated finite state machine diagram of the shunt capacitor agent with nine states. The original work is introduced in [3]. Below is the detailed description of each state.

1) NORMAL state.
   a) Vm2ss ⇒ the measured voltage is good.

2) TRANSIENT state.
   a) !Vm1ss ⇒ the measured voltage is not low.
   b) !Vm2ss ⇒ the measured voltage is not good.
   c) !Vm3ss ⇒ the measured voltage is not high.
   d) !TIsOutage ⇒ the team line segment is not out-aged.

3) EMERGENCY_LO state.
   a) Vm1ss ⇒ the measured voltage is low.

4) EMERGENCY_HI state.
   a) Vm3ss ⇒ the measured voltage is high.

5) OPENING state (switch off one cap bank).

6) CLOSING state (switch on cap bank in state 8).

7) SHUTDOWN state (switch off all cap banks).

8) LAUNCHDPFS_VVC state.
   a) Vm1ss ⇒ the measured voltage is low.
   b) Vm2ss ⇒ the measured voltage is good.

In this state, the agent selects an available capacitor bank as the candidate to switch on, then launches the distributed power flow by sending REQUEST:LAUNCHDPFS_VVC message and setting TLaunchDPFS_VVC = −1. The DPFS is run with new candidate capacitor status based on the VVC scheme. Depending on the success (TLaunchDPFS_VVC == 1 and Request_Close—request close check flag) or failure (TLaunchDPFS_VVC == 0) of the DPFS, the agent will move on.

9) VVC_SUPPORT state.
   a) Vm1ss ⇒ the measured voltage is low.

In this state, the agent sends REQUEST:VVC message to seek support from other shunt capacitor agents or voltage regulator agents in the system for volt/var control.

V. VOLT/VAR CONTROL SCHEME

Based on the agent model proposed above, VVC is initiated by either voltage regulator agent or shunt capacitor agent. The VVC scheme is carried out by the intelligent agent next to the substation (LAUNCHDPFS_AGENT).

The voltage regulator agents and shunt capacitor agents involved in the scheme should be ranked separately.

1) The voltage regulator agents are ranked according to the distance between their locations and substation (the first one has the shortest distance to the substation). The voltage regulator close to the substation has a bigger impact on the voltage profile than the voltage regulator far from the substation. The distance is estimated through the list of voltage regulator agent IDs saved in the REQUEST:LAUNCHDPFS_VVC message. When the REQUEST:LAUNCHDPFS_VVC message passes through the voltage regulator agent, the message will add the voltage regulator agent ID into its content and list in order. Finally, the message that is delivered to the LAUNCHDPFS_AGENT will include the IDs of all the voltage regulators located between the substation and the message initiator. The last agent ID put into the list is the voltage regulator agent with the shortest distance to the substation.

2) The shunt capacitor agents are ranked by the operation times during a day (the one with least usage will be ranked first) to avoid overusing the shunt capacitor. Due to the desire to limit usage of shunt capacitors, the VVC scheme will only be started with voltage regulators. The shunt capacitors will be added according to their ranking list only if the voltage regulators could not eliminate all violations. No matter the combination of the candidate equipment, the scheme will always focus on voltage regulators first, since each voltage regulator has 32 768 (32×32×32) different tap settings and shunt capacitor only have ON or OFF status.

The VVC scheme includes three stages (shown in Figs. 3–5, assume voltage regulators in the system has ranking number 1 to N).

1) Stage 1 ⇒ Test the lowest tap position of each regulator at each phase to check for low-voltage violations. If low-voltage violation occurs then add next shunt capacitor according to its ranking list or terminate the program if all capacitors are added and no solution exists.

2) Stage 2 ⇒ For the regulators 1 to N−1, fix the tap at the lowest position that has no voltage violation.

3) Stage 3 ⇒ Find the lowest tap position of the regulator N that has no voltage violation.

Take VVC of two regulators for example:

H1A highest tap position of REG1 (voltage regulator 1) phase A. (H1A, H1B, H1C, H2A, H2B and H2C are all set to position 16);

L1A lowest tap position of REG1 phase A with no low-voltage violation;

HV flag for high-voltage violation;
LVV flag for low-voltage violation; NVV flag for no voltage violation. The same strategy is applied to other phases and regulators. The scheme presented above will maintain the voltage of the entire system right above the lower limit. This is suitable for system loss reduction of the distribution system when majority of the loads are either constant impedance load or constant current load. However, the scheme could also be modified to maintain the voltage right below the high limit for the distribution system when most of the loads are constant power load. Moreover, the scheme could be applied to the distribution system with more than two voltage regulators and multiple shunt capacitors. Power factor control at the substation could also be achieved through DPFS.

The final solution of the proposed algorithm may not lead to the optimal result of the entire system. The exact solution could be achieved by running a exhaustive search in the feasible solution space. However, this is not efficient and requires expensive computation, so it is only done for comparison of solution quality. The main goal of the proposed strategy is to provide the new distributed volt/var control platform with a simple method to approach the optimal solution. Various optimization methods could be applied based on this platform.

VI. CASE STUDY

A. Modified IEEE 34 Node Test Feeder (Shown in Fig. 6)

The simulation in this section is based on the IEEE 34 node distribution system available online [15]. The voltage profile of the original IEEE 34 node test feeder is shown in Fig. 7. According to the American National Standards Institute Standard C.84.1, the customer voltage is required to be within ±5% range (114–126 V for 120 base). In Fig. 7, there are two low-voltage violations: 1) node 816 phase A and 2) node 890 phase ABC. In order to fix the violation, two shunt capacitors have been implemented: 1) single phase shunt capacitor with capacity of 60 kvar installed on node 816 (SHC_16) at phase A and 2) parallel three phase shunt capacitors with capacity 70 kvar (SHC_90_1) and 50 kvar (SHC_90_2) installed on node 890 at phase ABC (SHC_90_1 is on and SHC_90_2 is off). The voltage profile of the modified case is shown in Fig. 8.

B. Simulation Result

For the simulation, eight switching agents (circuit breaker agent: AGT_BRK_02; switch agent: AGT_SWI_18, AGT_SWI_42, AGT_SWI_32, and AGT_SWI_62; and sectionalizer agent: AGT_SCT_28, AGT_SCT_52, and AGT_SCT_46) and six VVC agents (voltage regulator agent: AGT_REG_14 and AGT_REG_52 and shunt capacitor agent: AGT_SHC_16, AGT_SHC_90, AGT_SHC_44, and AGT_SHC_48) have been implemented.

The VVC scheme implemented for this case is trying to maintain the voltage magnitude right above the lower limit since most of the loads in the case are constant impedance loads and constant current loads.
The communication latency is considered and configured according to the parameter listed in Table I.

The information for how to implement communication latency in the agent platform is introduced in [4].

The simulation starts at time 0.

1) At $t = 0.0000$ s, AGT_REG_52 moves from NORMAL state to TRANSIENT state since the calculated tap setting does not match current tap setting according to LDC (phase A voltage at load center is higher than the upper limit).

2) At $t = 20.0002$ s, AGT_REG_52 sends REQUEST message for LAUNCHDPFS_LDCC after waiting for a specified time (20 s) with calculated tap setting $(12, 11, 12)$ and AGT_BRK_02 receives the message at $t = 20.5005$ s.

3) At $t = 20.5006$ s, AGT_BRK_02 launches DPFS for LDCC.

4) At $t = 29.9415$ s, the DPFS is done with a confirmation message received by AGT_BRK_02, AGT_BRK_02 sends INFORM message to AGT_REG_52 at $t = 29.9416$ s.

5) At $t = 30.5056$ s, AGT_REG_52 receives INFORM message from AGT_BRK_02 and decides to change its tap setting since $T_{LaunchDPFS_LDCC}$ = 1, $IsVHiOk$ is true and $IsVLoOk$ is true.

6) At $t = 30.5056$ s, REG_52 changes tap position from $(13, 11, 12)$ to $(12, 11, 12)$.

7) At $t = 30.5057$ s, the entire system operates under normal state since all the switching equipment are closed and all the VVC equipments are in normal state.

8) At $t = 150.0000$ s, a three phase to ground fault occurs at node 848.
9) At \( t = 150.0001 \) s, AGT_REG_14 and AGT_REG_52 transit from NORMAL state to TRANSIENT state since the calculated tap setting does not match current tap setting.

10) At \( t = 150.0101 \) s, AGT_SCT_46 opens its sectionalizer to isolate the fault after counting a required number of fault current samples.

11) At \( t = 152.0000 \) s, AGT_SHC_48 shuts down its capacitor bank since TlsOutage is true after counting a required number of fault voltage samples.

12) At \( t = 152.3336 \) s, AGT_REG_52 receives REQUEST message for LAUNCHDPFS_VVC initiated by AGT_SHC_90. The message includes AGT_REG_52 in its content. At the same time, AGT_REG_52 sets Request_VVC to true and moves to LAUNCHDPFS_VVC.

13) At \( t = 152.6339 \) s, AGT_REG_14 receives REQUEST message for LAUNCHDPFS_VVC initiated by AGT_SHC_90. The message includes AGT_REG_14 in its content. At the same time, AGT_REG_14 sets Request_VVC to true and moves to LAUNCHDPFS_VVC.

14) At \( t = 152.6340 \) s, AGT_REG_14 sends REQUEST message for LAUNCHDPFS_VVC.

15) At \( t = 152.8007 \) s, AGT_BRK_02 receives REQUEST message for LAUNCHDPFS_VVC initiated by AGT_SHC_90.

16) At \( t = 152.8109 \) s, AGT_BRK_02 receives REQUEST message for LAUNCHDPFS_VVC initiated by AGT_REG_52.

17) At \( t = 152.8254 \) s, AGT_BRK_02 receives REQUEST message for LAUNCHDPFS_VVC initiated by AGT_REG_14.

18) At \( t = 160.0000 \) s, after all the messages arrive, AGT_BRK_02 picks AGT_REG_14, AGT_REG_52 and AGT_SHC_90 as candidate equipment for VVC, ranks AGT_BRK_02 with REG1 and AGT_REG_52 with REG2, and starts VVC scheme (the details of the VVC actions are given in Appendix A).

a) Step 1: Two voltage regulators only.
   i) Stage 1: Low-voltage violation on phase A occurs when both voltage regulators have their taps at their highest tap position (no Solution, go to step 2).

b) Step 2: Two voltage regulators with one shunt capacitor.
   i) Stage 1: \( L1A = 10, L1B = 0, L1C = 3, L2A = 3, L2B = -9, \) and \( L2C = -5. \)

C. Result Analysis

With stage 4 (shown in Fig. 10) implemented, the solution is listed in Table III (the detailed simulation results are given in Appendix B).

Based on the results shown in Table II and Fig. 9, both solutions maintain the voltage right above the low limit for the...
Fig. 10. Stage 4.

Table III

<table>
<thead>
<tr>
<th></th>
<th>Distributed VVC</th>
<th>Exhaustive Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>REG_14 Tap Setting</td>
<td>15 / 9</td>
<td>15 / 10</td>
</tr>
<tr>
<td>REG_52 Tap Setting</td>
<td>5 / 4</td>
<td>4 / 4</td>
</tr>
<tr>
<td>SHC_50 / 02 Status</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>Reactive Power Loss</td>
<td>225.070kW</td>
<td>224.130kW</td>
</tr>
<tr>
<td>Reactive Power Loss</td>
<td>1.487kVAR</td>
<td>0.904kVAR</td>
</tr>
</tbody>
</table>

In order to achieve a better solution, the strategy could be customized by adding a fourth stage.

With the implementation of stage 4, the solution of the distributed VVC scheme is getting close to the solution of the exhaustive method. The difference is due to the mutual effect between phases. The simulation takes about 100 s to finish stage 4 (the power flow needs to be solved ten more times).

VII. CONCLUSION

A novel and completely distributed VVC scheme has been presented in this paper with a predictive capability based on a DPFS. The shunt capacitor agent and voltage regulator agent work collaboratively to achieve VVC based on the scheme. Moreover, simulation results were presented that confirm the efficiency of the new algorithm. The accuracy was further improved by customizing the scheme with the knowledge of the load dependence on voltage.

For future work, additional devices could be included, such as distributed generators, energy storage units and static var compensators to explore distributed VVC with this equipment involved.

APPENDIX A

Action Log of Stages 1–3

See Table IV, where T stands for “true” and F stands for “false.” A, B, and C are for the three phases.

APPENDIX B

Action Log of VVC (Stage 4)

See Table V.

Fig. 11. Voltage profile of phase B.
TABLE V
ACTION LOG OF STAGE 4

<table>
<thead>
<tr>
<th>REG.1</th>
<th>REG.3</th>
<th>REG.5</th>
<th>REG.9</th>
<th>REG.0</th>
<th>0.2</th>
<th>LV</th>
<th>HV</th>
<th>NVV</th>
<th>P Vin(kW)</th>
<th>Q(W) VAR</th>
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</thead>
<tbody>
<tr>
<td>10 0 4 10 8</td>
<td>ON</td>
<td>F</td>
<td>F</td>
<td>T</td>
<td>229.006</td>
<td>8.082</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 1 5 9 7 8</td>
<td>ON</td>
<td>F</td>
<td>F</td>
<td>T</td>
<td>228.417</td>
<td>7.009</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>15 5 9 5 3 4</td>
<td>ON</td>
<td>F</td>
<td>F</td>
<td>T</td>
<td>225.684</td>
<td>2.568</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>16 6 1 0 4 2 3</td>
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<td>F</td>
<td>T(AC)</td>
<td>F</td>
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<td>1.420</td>
<td></td>
<td></td>
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<td>16 6 9 5 2 4</td>
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<td>F</td>
<td>F</td>
<td>T</td>
<td>225.483</td>
<td>2.211</td>
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<tr>
<td>16 5 9 5 1 4</td>
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<td>T</td>
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<td></td>
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</tr>
<tr>
<td>15 8 5 0 6 4</td>
<td>ON</td>
<td>F</td>
<td>T(R)</td>
<td>F</td>
<td>225.070</td>
<td>1.487</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

REFERENCES


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