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Selecting and Redesigning Distribution Feeders for CVR Benefits

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SELECTINGAND REDESIGNINGDISTRIBUTIONFEEDERSFORCVRBENEFITS

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Selecting and Redesigning Distribution Feeders for CVR Benefits

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I. INTRODUCTION

Conservation Voltage Reduction (CVR) has been used as a cost-effective method for obtaining energy savings, peak demand reduction, and feeder loss reduction [1]-[3]. The main objective of CVR is to reduce the real power consumed by loads. If loads are voltage dependent, this goal is achieved by lowering customer utilization voltage. However, the voltage needs to remain within allowed ranges established by regulatory agencies and standards [4], [5].

One of the first CVR tests was reported by American Electric Power System (AEP) in 1973 [6]. Since then many electric utilities have tested CVR and reported peak reduction and energy savings, including the Bonneville Power Administration (BPA) [7], Northeast Utilities (NU) [8], BC Hydro [9], Hydro Quebec (HQ) [10], and Dominion Virginia Power [11]. These investigations report savings ranging from 0.3% to 1% reduction in energy per 1% voltage reduction [12]. Considering CVR implementation nationwide, significant economic and environmental benefits may be obtained.

Peak demand and energy consumption reduction plus a decrease in feeder losses are benefits of CVR. However, investments in CVR result in reduced revenue for utilities. Incentives from regulatory agencies are required that can compensate for the lost revenue and utility investments in CVR implementation.

For open-loop loads CVR can be effective for reduction in energy consumption. Examples of open-loop loads include lighting loads and unregulated motors [3], [13], [14]. However, it has been shown that CVR may not be effective for closed loop loads such as motor drives, loads with thermal cycles and regulated constant power loads [3], [12], [14]. A closed-loop load is a load that has feedback control that compensates for the reduction in voltage. The voltage dependency of loads is very important when considering CVR.

The effect of voltage reduction on energy consumption is quantified using the Conservation Voltage Regulation Factor (CVRF) metric which is defined as:

$$CVRF = \frac{Percentage\ change\ in\ energy}{Percentage\ change\ in\ voltage} \qquad (1)$$

The larger the CVRF, the more the energy savings per percent reduction in voltage. Therefore, CVRF provides a metric for choosing loads or feeders that are good CVR performers. For feeders CVRF is time-dependent and is generally not easy to measure.

There are two major methods used for measuring CVRF on feeders. The first method is the comparison method. It has been implemented with two approaches. In the first approach two feeders with similar loading are selected. CVR is applied to one of the feeders while normal voltage operations is used for the other feeder. The resulting energy consumptions of the two feeders are then compared. In the second approach for determining feeder CVRF, CVR and normal operation voltages are applied to the same feeder during two different time periods, where the two different time periods have similar weather and loading conditions. The difference in feeder energy consumption between the two time periods can then be used to estimate the CVRF [15], [16]. However, since CVR is time and season dependent, the comparison measurements need to be performed a number of times.

When results from a number of field measurements are available, regression can be used in CVRF modeling. Using regression, the energy

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dependency can be modeled as a function of voltage, temperature, and other variables [9], [17]-[21] as indicated in (2).

$$E = f\ (T, V, \ldots) \qquad (2)$$

Then CVRF can be computed as (1).

Previous CVR studies have mainly focused on the evaluation of energy savings [6]-[12], CVRF computation [15][21], or considering CVR as one of the objectives in an optimization problem [22]-[23]. However, few studies have assessed the characteristics of efficient distribution feeders for CVR Implementation.

When looking where to begin a CVR pilot or program, selection of distribution feeders with efficient CVR performance is of interest. Feeders with the best CVR performance would provide more return on investment. In the work reported here the CVR performance of approximately 1100 distribution feeders was compared. The comparison used measured winter and summer CVRF factors for two categories of feeders, urban and urban-rural. From the comparison 11 feeders with the best performance were selected. Characteristics of these 11 feeders that lead to the good CVR performance were evaluated. Also in the work reported here a feeder with poor CVR performance was chosen and its VVC scheme was redesigned.

Studying the characteristics of feeders with efficient CVR performance and investigating controls that can change a feeder with poor CVR performance into a good CVR performer are the main objectives of this work. The paper is organized as follows. Section II briefly discusses the major VVC methods. In section III the results of comparing the CVR performance of approximately 1100 feeders are presented and the characteristics of top CVR performers are discussed. In Section IV the control for a poor CVR performing feeder is redesigned, and the improvement obtained in the CVR performance is evaluated. Conclusions are presented in section V.

II. VOLT/VAR CONTROL

Maintaining acceptable utilization voltage levels and close to unity power factor are major objectives of VVC [24]. VVC has been used to reduce losses, energy consumption, power demand, and tear and wear on control devices. Typically, switched capacitor banks, substation load tap changing transformers (LTCs) and voltage regulators are the devices employed to perform VVC. However, smart grid initiatives have increased interest in more advanced VVC schemes. An efficient VVC system needs to meet the following criteria [14].

- Provides optimal coordinated control
- Provides user selectable operating objectives
- Performs self-monitoring
- Allows operator override during emergencies
- Adapts to feeder reconfiguration correctly.

Major VVC approaches that may be used by electric utilities are standalone VVC (traditional), SCADA driven Volt/VAR control, and Integrated Volt/VAR control (IVVC). The advantages and disadvantages of each of these approaches are discussed next.

Standalone VVC

In the standalone or traditional VVC, voltage regulation and reactive power control are performed by capacitors banks, LTCs or voltage regulators. Local voltage or current measurements determine the control actions. Low cost, scalability, and no need for field communications are advantages of the traditional VVC. On the other hand, standalone VVC cannot provide self-monitoring, coordination between control devices, optimal operation, and effective control with a high penetration of distributed generation [2].

SCADA Controlled Volt/VAR

With SCADA controlled Volt/VAR, control devices are equipped with communication capabilities through Supervisory Control and Data Acquisition (SCADA) systems. SCADA controlled Volt/VAR has been the most common VVC approach in the last 15 years [24]. Communication and coordination between controlling devices are the key points in SCADA controlled Volt/VAR. However, the control strategies are based on pre-defined rules which are determined by distribution system design engineers. SCADA controlled Volt/VAR usually consists of two separate subsystems which are VAR dispatch and voltage control. The VAR dispatch subsystem controls the capacitor banks to minimize feeder losses. The voltage control subsystem manages the LTCs and voltage regulators for minimizing the demand and energy consumption.

Higher efficiency, self-monitoring capability, and the ability to override operation during system emergencies are the advantages of the SCADA controlled Volt/VAR approach. However, it is less scalable and more complicated in comparison to traditional VVC. It does not adapt to feeder configuration changes and high distributed generation penetration. Furthermore, the VAR dispatch and voltage control subsystems are not usually coordinated and the system does not generally perform optimally [2].

Integrated Volt/VAR Control

The objective of IVVC is to determine the best (optimal) set of control actions. It determines the operation of LTCs, voltage regulators, capacitor banks and other control devices to achieve objectives in an optimal fashion while not violating operating constraints [25]-[27]. Optimal objectives may involve some combination of the following

- Minimizing losses
- Minimizing energy consumption
- Minimizing demand
- Minimizing voltage unbalance

- Minimizing control device actions

In IVVC an optimization problem is solved for control actions that provide optimal operating conditions. The computed set of control actions is sent to field control devices through the SCADA system. Voltage control and VAR dispatch are both coordinated in IVVC. IVVC can deal with complex feeder arrangements and reconfigurations. Finally, IVVC can handle high penetrations of distributed generation. On other hand, IVVC implementations may not be scalable, and the implementation can be costly [14].

Table 1 : Characteristics and Saving of the Selected Feeders for CVR Implementation

Feeder Name	Type	Annual MWh (Base Case)	Annual MWh with CVR (Coordinated Control)	Percentage Improvement	Saving (MWh)	Feeder Length (Mile)	Control Category
1	Urban-Rural	23728	22609	4.72%	1119	18.4	VVC Devices
2	Urban-Rural	23885	22794	4.57%	1091	22.9	VVC Devices
3	Urban	20567	19493	5.22%	1074	13.5	Flat VP
4	Urban	18336	17350	5.38%	986	9.4	Flat VP
5	Urban	18668	17690	5.24%	977	9.4	Flat VP
6	Urban-Rural	20245	19291	4.71%	954	11.1	VVC Devices
7	Urban	17931	16979	5.31%	953	14.5	Flat VP
8	Urban-Rural	20365	19433	4.58%	932	18.7	VVC Devices
9	Urban-Rural	17402	16614	4.53%	788	15.6	Flat VP
10	Urban-Rural	14279	13615	4.65%	664	13.0	Flat VP
11	Urban-Rural	13498	12840	4.87%	658	4.1	Flat VP

III. CHARACTERISTICS OF THE BEST CVR PERFORMERS

Using experimentally determined summer and winter CVRFs, the CVR performance of approximately 1100 urban and urban-rural distribution feeders under a VVC scheme was evaluated. The energy savings for each feeder were computed, and the eleven feeders that had the best CVR performance were selected. Power flow calculations based on SCADA measurements were used in the evaluations of the eleven feeders, where the power flow calculations were run for each hour of a year, 8760 times, for each feeder to calculate energy supplied and feeder losses. Table I shows the best CVR performers' estimated annual energy savings, energy consumption reduction, length and category.

Studying the topology and voltage profiles of the best performers, it is observed that a good performer has a flat voltage profile due to either the topology/loading conditions or sufficient Volt/VAR control devices to create a flat voltage profile. Fig. 1 shows a relatively flat voltage profile, in terms of customer level voltage, for a top CVR performing feeder at peak load (Feeder 9 in Table 1 - a short feeder without VVC). The percentage voltage deviation versus distance from the substation is also illustrated for Feeder 9. The voltage drop for Feeder 9 is approximately 1.7V from an initial 125V at the substation.

Fig. 2 presents the voltage drop for an efficient CVR performer with VVC devices, Feeder 2. It can be seen that the voltage level is boosted 4 times by regulators. Fig. 2 also shows the percent voltage deviation versus distance for Feeder 2. As shown in Table I, Feeder 2 was the second top CVR performer in terms of energy savings. Fig. 3 shows results for Feeder 8, a relatively short feeder with VVC. The effect of the capacitor banks on Feeder 8 can be seen around 1.9 miles from the substation. It should be noted that Figs 1-3 are plotted for the phase which has the least voltage at the end of the feeder.

A scatter plot of feeder annual MWh consumption versus annual MWh savings is plotted in Fig. 4 for the eleven top CVR

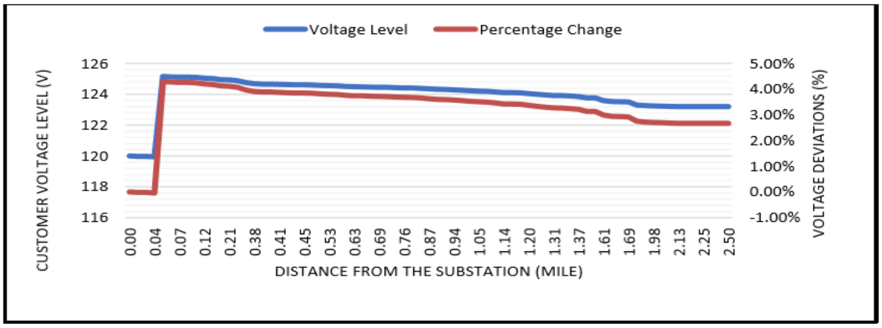

Figure 1 : Voltage Drop Versus Distance for Feeder 9, A Short Feeder Without VVC Devices

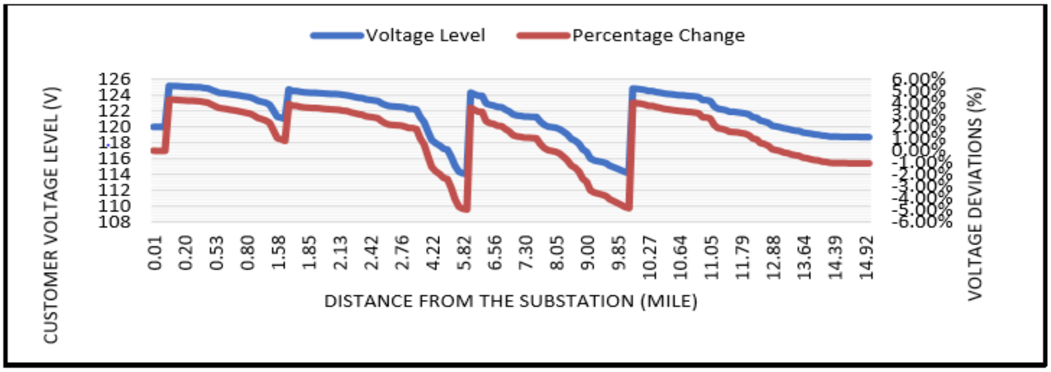

Figure 2 : Voltage drop versus distance for Feeder 2 with VVC devices

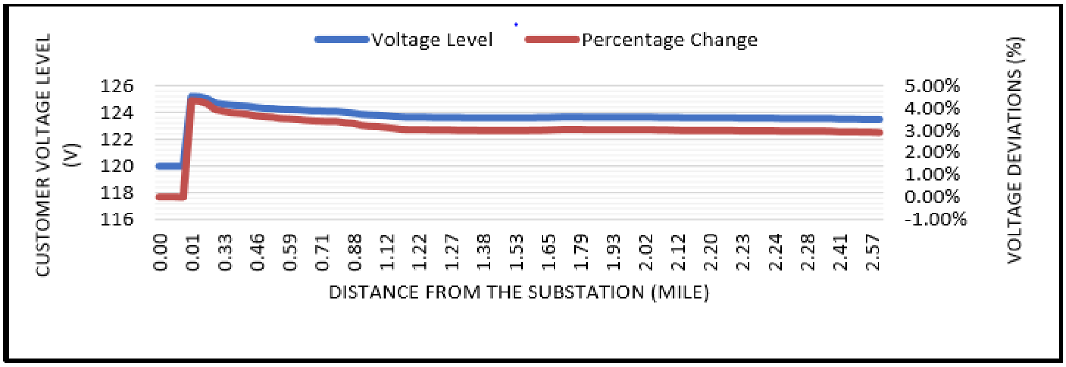

Figure 3 : Voltage drop versus distance for Feeder 8, a feeder with VVC devices and a relatively flat voltage profile

performing feeders. When the top CVR performing feeders are categorized according to their characteristics, a natural flat voltage profile or VVC devices, a more precise correlation is found among the feeders. This is illustrated in figs 5 and 6, where the R2 correlation criterion increases from 0.848 in Fig. 4 to 0.919 and 0.898 for figs 5 and 6, respectively. In addition, figs 5 and 6 illustrate that when a selection is to be made as to whether CVR should be implemented on one feeder or another, where both feeders have a flat voltage profile, the feeder with the higher energy consumption can provide more energy and thus dollar savings.

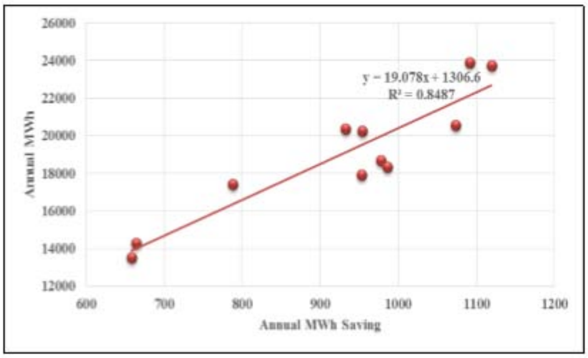

Figure 4 : Correlation between annual saving and feeder annual consumption for the eleven top CVR performing feeders

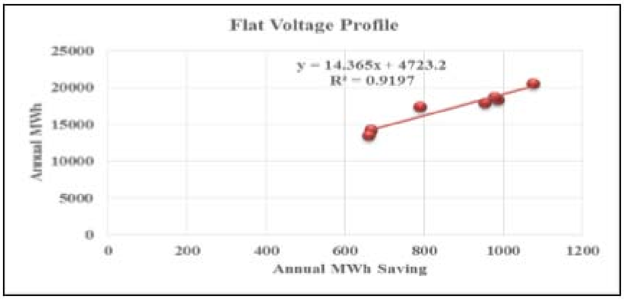

Figure 5 : Correlation between annual MWh savings and MWh consumption for top CVR performing feeders with relatively flat voltage profiles

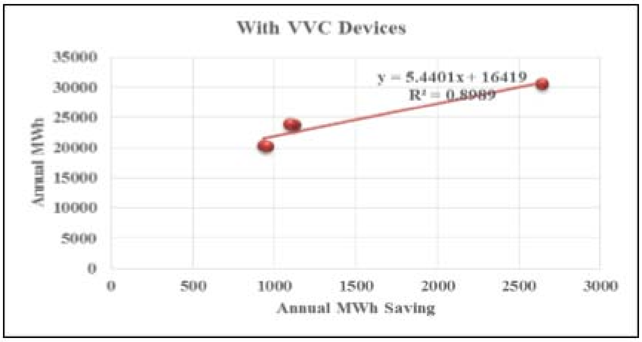

Figure 6 : Correlation between annual MWh savings and annual MWh consumption for top CVR performing

IV. MODIFYING A POOR CVR PERFORMER INTO A TOP PERFOMER

In this section, a poor CVR performing feeder is chosen and its VVC scheme is redesigned. The goal is to create a flatter voltage profile to achieve better CVR performance. Voltage dependency factors of -0.1 and -0.6, as defined by equation 1, were employed for summer and winter, respectively.

The selected feeder originally had two voltage regulators (one at the substation), four 3-phase fixed capacitors, and one 3-phase switched capacitor, where the capacitors all together represented 3450 kVAR. The existing standards require the utilization voltage to be between 114 and 126 V. The goal for the redesigned VVC is to maintain the primary system voltage, in terms of customer level voltage, to be greater than 116 V. This would allow for a 2 volt drop in the secondary. Figs 7 and 8 show the percent voltage drop before and after redesigning the VVC system and applying the CVR control for summer and winter conditions, respectively.

Nine single-phase, small switched capacitors were employed in the new VVC scheme, representing a total of 1500 kVAR, which is less than half of the original VAR support. Discrete Ascent Optimal Programming (DAOP) was employed to place the switched capacitors [28]. Table II presents the capacitor types and kVARs employed in the feeder before and after redesigning the VCC scheme. The new VVC system improved the voltage profile such that CVR can be implemented with 120V at the substation and 118 V at the second regulator. In summer, the maximum voltage drop before the redesign was approximately 2.5%. The maximum voltage drop after the VVC redesign was 1.5% and after CVR implementation was about 3.5%. In winter, before redesigning the VVC system, the maximum percent voltage drop was about 2%. However, after redesigning the VVC scheme, the maximum percent voltage drop was approximately 1% and after CVR implementation was about 3%. Since the percent voltage drop requirement was 5% or less, additional CVR savings could be obtained by reducing the regulator set-points even further. The configuration of the feeder's VVC devices before and after the VVC scheme redesign is shown in figs 9a and 9b, respectively.

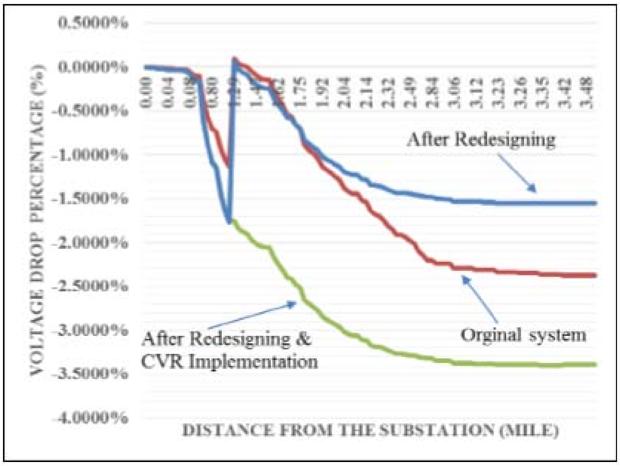

Figure 7 : Percent voltage drop before and after redesigning the VVC system for the selected poor performing feeder during summer

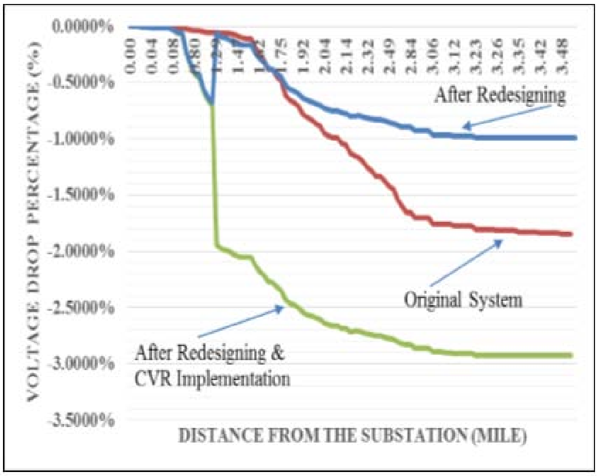

Figure 8 : Percent voltage drop before and after redesigning the VVC system for the selected poor performing feeder during winter

Table III presents the characteristics of the selected poor CVR performing feeder before and after the VVC redesign. Annual consumption before redesigning the VVC system was 27130 MWh. After the VVC redesign the annual consumption decreased to 26148 MWh, which provided a savings of 983 MWh per year. This corresponds to a 3.63% increase in energy savings. Note that the modified poor performing feeder now ranks in the top five performing feeders shown in Table I.

This VVC redesign case study shows that employing many VVC devices is not a necessary condition for reasonable CVR performance of a feeder. While VVC devices can help in improving the voltage profile, efficient design of the VVC scheme and consideration of CVR implementation in its design can significantly improve the CVR performance of a feeder. Moreover, the significant decrease in VAR support (more than 50% decrease) showed the effect of distributing VVC devices in improving the CVR performance.

Table 2 : VVC Devices Before and After Redesign

Before		
Phase	**Capacitor Type**	**Capacity (kVAR)**
3 (ABC)	Fixed	1200
3 (ABC)	Fixed	900
3 (ABC)	Fixed	600
3 (ABC)	Fixed	450
3 (ABC)	Switched	300
	Total	3450
After		
Phase	**Capacitor Type**	**Capacity (kVAR)**
1 (A)	Switched	200
1 (A)	Switched	200
1 (A)	Switched	100
1 (A)	Switched	150
1 (B)	Switched	200
1 (B)	Switched	200
1 (B)	Switched	200
1 (C)	Switched	150
1 (C)	Switched	100
	Total	1500

Table 3 : Characteristics and Saving of the Modified Feeder After Cvr Implementation

Feeder Name	Type	Annual MWh (Base Case)	Annual MWh with CVR (Coordinated Control)	Percentage Improvement	Saving (MWh)	Feeder Length (Mile)	Control Category
12	Urban-Rural	27130	26148	3.62%	983	25.2	VVC Devices

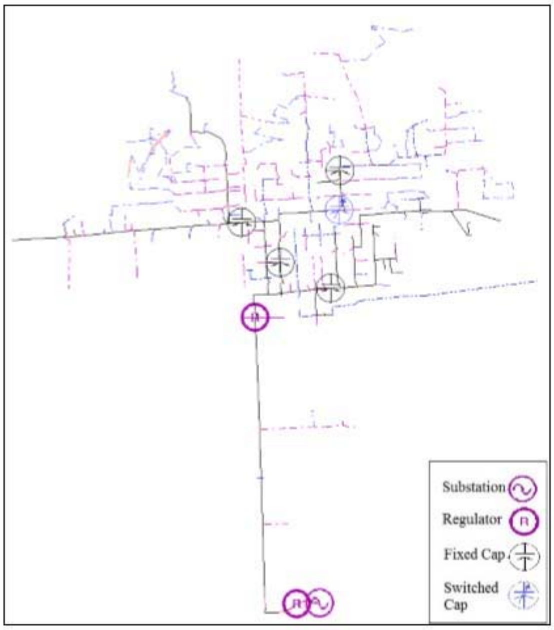

Figure 9 a. Placemen of control devices for selected poor CVR Performing feeder before redesigning the VVC scheme

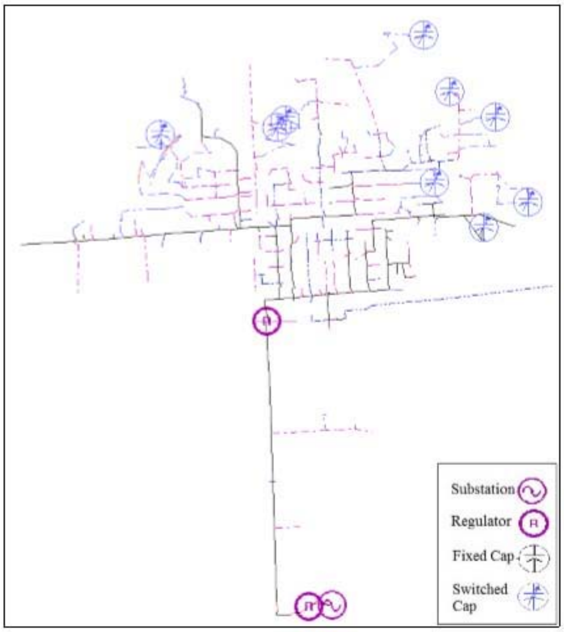

Figure 9 b. Placemen of control devices for selected poor CVR Performing feeder after redesigning the VVC scheme

V. CONCLUSION

When considering CVR implementation across a large number of feeders, selecting the best CVR performing feeders is of interest. Initially investing in the best CVR performers will provide the greatest benefits from the investment. This work evaluated over 1100 distribution feeders using their seasonal CVRFs and computed energy saving under a CVR scheme. After selecting the best CVR performers, their characteristics, as well as their energy savings, were identified. It was observed that efficient CVR performers had a relative flat voltage profile due to either topology/loading patterns or sufficient VVC devices.

A feeder with poor CVR performance was chosen and its VVC scheme redesigned. After redesigning the VVC scheme, the poor CVR performer changed into one of the top CVR performing feeders, providing a significant increase in CVR energy savings. This case study also illustrated that significant decrease in VAR support could be obtained when a distributed VVC scheme was utilized. Future work needs to address integration of intermittent renewable energy resources in a combined CVR and VVC scheme.

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