Voltage Reduction Field Test on a Distribution Substation

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Abstract—This paper highlights the relationship between power demand and voltage level on the distribution network. It shows how a small change in voltage with existing assets delivers a very meaningful response in power demand and in energy consumption. A 24 hour field trial at a utility without any experience with Conservation Voltage Reduction (CVR) is described. CVR effects are assessed by a combined comparison-regression method resulting in at least 9.42MWh energy saved during the test, equivalent to the consumption of 848 households in the region. The energy savings achievable within the network under this study have been characterized and the attainable yearly energy savings on the Canary Islands distribution networks, are on the whole estimated.

Index Terms—conservation voltage reduction (CVR), demand reduction, distribution efficiency, energy saving, field trial

I. INTRODUCTION

The power demand of certain loads changes with voltage [1]. This is the working principle of Conservation Voltage Reduction (CVR) a mode of operation to reduce energy consumption and peak demand. The voltage is lowered on the distribution system in a controlled manner so that service voltage at customer terminals is set within the lower half of its statutory limits, causing no damage to consumer appliances. CVR effects are evaluated by the conservation voltage reduction factor (CVR). It is calculated from the percent energy savings divided by the percent voltage reduction. The CVR obtained in different published assessments vary between 0.40 and 1.00 [2] and the maximum achievable has been estimated in 2.00 [3].

Although this is a cost-effective way to save energy, it is not adopted as widely as it could be. There are three main arguments to justify why:

- There is a lack of incentives to reduce load consumption, specially since costs are born by distribution networks operators and benefits accrue mainly for end users.
- Scepticism exists on CVR performance and its potential negative effects on power quality and system reliability [4]. CVR effects are heavily dependent on network characteristics, mostly on the nature of the loads (type and mix) and the topology of the network. It is hard to predict the precise response of the network, summarized in its CVR factor. For this issue, distribution loads modeling [5] and estimation of its response to voltage changes [6] are emerging research topics.
- The practice extent of voltage reduction is quite limited to avoid exceeding statutory limits. The advent of smart grids and the advanced metering infrastructure generalization will enable increasing this voltage reduction to allow bigger energy savings [7]. Smart meters will provide real-time voltage readings to guide voltage trimmings. The consumer terminals with greater voltage drops and the lowests service voltages in the network will be monitored ensuring that limits are not exceeded. Closed-loop control algorithms will adjust the voltage according to remote metering.

This paper presents a voltage reduction field test on a distribution substation. The experience pretends to highlight the relationship between power demand and voltage encouraged by results obtained in other networks [8], [9] and aspires to answer how much energy saving is achievable on the Canary Islands (Spain) distribution networks with a voltage optimization strategy. It is in the scope of the research of integrated Volt/VAr control in isolated power systems [10]. The rest of this paper is structured as follows. Firstly it is described the experiment design, including substation selection process, network features, voltage reduction extent determination and savings expected. Then the results obtained are presented and the CVR performance is evaluated. Next section exploits the results of the analysis and estimates the savings achievable by extrapolation of these results to other feasible networks in the region. Finally, the results are summarized and subjects for further research are suggested.

II. TEST DESIGN DESCRIPTION INTRODUCTION

As this was the first CVR field test carried out by the utility, the approach was conservative. The main premise was to avoid any claim from consumers and guarantee power quality. The criteria to select the target for the trial were: limited phase imbalance, good power factor, with not very long feeders, high load density and low distributed generation penetration. These characteristics
are fuzzy but with the assistance of an experimented operator at control centre the selection of a proper substation was possible.

The studied distribution network starts with a (66kV/22kV) power transformer equipped with on-load tap changer (OLTC) to regulate the secondary bus voltage. The reactive power compensation is accomplished with 4.2MVAr non-stepped shunt capacitor banks. There are 5 feeders connected to the busbar which supply 104 transformer stations and through them 20,112 customers. The operator is unable to regulate each feeder with different voltages. Voltage line drop is compensated by off-load tap changer at transformer stations. The voltage control devices in the network are solely OLTC and the capacitor switch. There are neither regulating transformers nor capacitor along the feeders.

There is no information about load composition though a customer class breakdown may be derived from supply contracts. Table I shows this breakdown detailed for feeder and totalized to network level.

<table>
<thead>
<tr>
<th>CUSTOMER CLASS BREAKDOWN</th>
<th>Residential</th>
<th>Commercial</th>
<th>Industrial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[kW] [%]</td>
<td>[kW] [%]</td>
<td>[kW] [%]</td>
</tr>
<tr>
<td>Feeder 1</td>
<td>6,749.9</td>
<td>90.1</td>
<td>692.3</td>
</tr>
<tr>
<td>Feeder 2</td>
<td>14,869.5</td>
<td>79.2</td>
<td>2,340.30</td>
</tr>
<tr>
<td>Feeder 3</td>
<td>13,797.9</td>
<td>82.6</td>
<td>3,037.0</td>
</tr>
<tr>
<td>Feeder 4</td>
<td>16,163.8</td>
<td>59.1</td>
<td>9,635.8</td>
</tr>
<tr>
<td>Feeder 5</td>
<td>14,166.0</td>
<td>51.5</td>
<td>12,940.8</td>
</tr>
<tr>
<td>Total</td>
<td>72,747.1</td>
<td>68.3</td>
<td>29,555.1</td>
</tr>
</tbody>
</table>

The reference voltage for the secondary busbar voltage during regular operation is 21.0kV and the threshold values are defined at 20.3kV (-3.33%) and 21.6kV (+2.86%), in Spain statutory limits for service voltage values are defined at 20.3kV (-3.33%) and 21.6kV (+1.30%).

With voltage percent reduction (ΔU%) and CVR, known, the mean power demand percent reduction is calculated by (2) resulting in 2.7819%.

\[
\Delta P_m(\%) = CVR \cdot \Delta U(\%) = 2.7819\% \quad (2)
\]

Power demand mean values on yearly, ongoing month and the same day of the week before the test basis were 13.32MW, 12.56MW and 14.44MW respectively. The estimation of mean power demand reduction achievable by this network is presented in the right section of Table II on the three bases, using minimum, average and maximum CVR and the proposed percent voltage reduction. The calculation for average CVR, and mean daily power demand is shown in (3). As the most likely behaviour of the network corresponds with that shown the same day of the week before the test, the estimated mean power demand reduction is in the range [59.95 ~ 642.02 kW] with an expected value of 401.71 kW. Finally, the expected energy saving (ΔEm) during one day operating with voltage reduction strategy is obtained by (4).

\[
\Delta P_m (\%) \cdot \Delta P_m (\%) = 0.4017MW \quad (3)
\]

\[
\Delta E_m = \Delta P_m \cdot t = 9,640.95 \text{ kWh} \quad (4)
\]

According to the customer service protection policy, the incidence management software will be monitored during the test and any complaint or event in circuits affected by the trial will be studied. Additionally, personnel at the zone and maintenance crews will be aware of the voltage reduction test to detect and alert early about any matter related.

### III. TEST RESULTS

The voltage reduction field test started on Thursday January 30th at 10:00 am, and it lasted 24 hours. It was scheduled at that time to suit the personnel timetable and allow the maximum attention during the first hours of the trial. The selection of the day was random, it was not a holiday and there were no special conditions that could affect the normal service of the network such as weather alerts or any work programmed along the feeders.

Fig. 1 shows the voltage profile during the test. The red line is the reference value. There was absolutely no incidence in any circuit dependent on the network. Over voltage is appreciable from 22:41:36h till 06:57:56h. At that time it was tap position 1, there were no more taps to reduce voltage, and the capacitor shunt was already

\[
CVR_f = R \cdot CVR_R + C \cdot CVR_C + I \cdot CVR_I \quad (1)
\]

where \( R \), \( C \) and \( I \) represent the load share and CVR_R, CVR_C and CVR_I represent the CVR factor for residential, commercial and industrial customers respectively. Left section of Table II summarizes published CVR values of different customer classes [2] and the resulting CVR by application of (1) with the load share of the network under study. It is obtained a range [0.1171~1.2538] with an average value of 0.7845, which will be the CVR_ for energy savings estimation.

### TABLE II. CVR FACTOR BY SYNTHESIS FROM CUSTOMER CLASSES AND MEAN POWER DEMAND REDUCTION ESTIMATIONS

<table>
<thead>
<tr>
<th>Customer Class</th>
<th>CVR_R</th>
<th>CVR_C</th>
<th>CVR_I</th>
<th>ΔP_m (YEAR)</th>
<th>ΔP_m (MONT)</th>
<th>ΔP_m (DAY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td></td>
<td></td>
<td></td>
<td>[kW]</td>
<td>[kW]</td>
<td>[kW]</td>
</tr>
<tr>
<td>Commercial</td>
<td></td>
<td></td>
<td></td>
<td>[kW]</td>
<td>[kW]</td>
<td>[kW]</td>
</tr>
<tr>
<td>Industrial</td>
<td></td>
<td></td>
<td></td>
<td>[kW]</td>
<td>[kW]</td>
<td>[kW]</td>
</tr>
</tbody>
</table>

Min. 0.06 0.26 0.10 0.11 55.30 52.15 59.95
Avg. 0.79 0.82 0.40 0.78 370.55 349.41 401.71
Max. 1.30 1.20 0.83 1.25 592.22 558.43 642.02

\[
\Delta P_m(\%) = CVR \cdot \Delta U(\%) \quad \Delta E_m = \Delta P_m \cdot t \quad (2)
\]

\[
\Delta P_m (\%) \cdot \Delta P_m (\%) = 0.4017MW \quad (3)
\]

\[
\Delta E_m = \Delta P_m \cdot t = 9,640.95 \text{ kWh} \quad (4)
\]
switched off (capacitors were disconnected after first on-peak hour, at 13:54:35h when demand fell and voltage started rising up), therefore the controller had no way to regulate voltage so its profile reflects high voltage evolution. Fig. 2 displays the voltage progress at the transmission boundary. At that time the voltage was already 67kV and it still rose to 68.2kV during the night. These considerations regarding voltage optimization performance will be taken into account when assessing the CVR potential of the network.

The estimated demand during the day of the test without CVR in the pilot network is calculated applying (6) to every record in the time series where subindex (Est) refers to estimated values.

\[ P_{1}\text{Est} = \frac{(P_1 / P_2) / (U_1 / U_2)}{(P_2 / U_2) \cdot U_{1}\text{Est}} \]  

The resulting demand curve is shown in Fig. 5. It is compared with the power demand resulting with CVR. The estimation error for the inference method was quantified in ±0.86% [12]. The energy saved this day rose at least 9.42MWh.

To estimate the CVR factor of the network, the average percent voltage reduction is calculated. It is presented in Fig. 6. Table III summarizes the results from the comparison, these calculations are repeated discarding records between 22:41:36 h and 06:57:56h to find out the network CVR potential. The resulting CVR estimation for this network is 0.8211.
V. CVR ADVANTAGES

The daily average power demand reduction obtained was 392.57kW, -2.72% demand reduction. This may be a valuable strategy to defer network reinforcement investments and to reduce power demand at the time of system peaks. The daily energy savings are estimated at 9.42MWh. The average monthly household consumption in the Canary Islands is 333.08kWh [13], so the voltage reduction strategy equals the supply to 848 households.

These conclusions result from a conservative voltage reduction strategy in just half a substation whereas in the Canary Islands there are 54 substations. Assuming that at least in 10% of them (5.5 substations) the strategy is applicable (that means limited phase imbalance, good power factor, not very long feeders, high load density and low distributed generation penetration) the amount of energy that can be saved easily is huge. It is shown in Table IV in an annual basis.

With present OLTC performance, increasing voltage reduction extent is not possible. Most of time the tap was on its lower position. But with other taps distribution, such as (+14 and -7) instead of present (+6 and -15) over nominal 22/66kV ratio tap, or with a new agreement for voltage regulation at transmission boundaries, the amount of energy saved would only depend on the network’s CVR factor and on the voltage reduction extent. That would allow increasing the reduction extent, if not to 7% for caution, to 5%. Table IV presents the yearly savings achievable with this voltage reduction in the pilot network and in 10% regional distribution networks where (E) is the yearly energy saving. The calculations are on the basis of the average power demand in 2013, 13.32MW.

When the utility completes its ongoing conventional to smart meter changing process, customer terminals with greater voltage drops and the lowests service voltages in the network might be monitored and the voltage reduction might be extended to regulatory or technically achievable limits improving the energy efficiency of the network.

VI. CONCLUSIONS, DISCUSSION AND FURTHER RESEARCH

A 24 hour voltage reduction field trial has been performed in a distribution substation under real conditions. Customers within the test area did not notice any impact on their appliances. The pilot test shows that a small change in voltage can deliver a very meaningful response in power demand and in energy consumption. The energy saved during the test has been estimated in at least 9.42MWh, equivalent to the daily consumption of 848 households. This strategy may be implemented using existing assets and though benefits accrue mainly for end users, it may be used to defer network reinforcement investments and to reduce power demand at the time of system peaks. Anyway, to extend its deployment, authorities and regulators should promote conservation programs. A way could be rewarding utilities for the energy saved.

The energy savings achievable in the network under study have been characterized by a CVR factor of 0.8211. A value well into the range predicted by synthesis from customer classes, and only 4.66% above the average published results. Further research in the CVR field may include field validated load models for accurate calculation of the energy conservation gains and new voltage reduction field trials in other substations in order to assess networks suitability for the strategy.

REFERENCES

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