VOLT-VAR CONTROL AND POWER QUALITY (CIGRE/CIRED C4.24)

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ABSTRACT

This paper summarizes the state of discussions in CIGRE/CIRED joined working group C4.24, concerning expected impacts on the power quality of future methods for volt-var-control in the distribution grid. The positive impacts include the reduction of the number of overvoltage and undervoltages and also a reduction of voltage unbalance, when some control schemes are applied. Potential negative impacts include an increased number of short-duration undervoltages, rapid voltage changes, flicker, and voltage transients; a higher risk of harmonic resonances; and increased emission of supraharmonics. All these potential impacts are discussed in the paper.

INTRODUCTION

Joint working group C4.24, "*Power Quality and EMC Issues associated with future electricity networks*", is a joined working group of CIGRE and CIRED [1]. The mandate of the working group, as defined in its scope, contains, among other objectives, the evaluation of "*The positive and negative impact of* (..) *Volt and VAR control* (..) *on power quality* (..) *in the distribution system*". Therefore, one of the subjects currently discussed within the working group is the relation between volt-var control and power quality. In this paper, the general term "voltage and var control" ("volt-var control, VVC) is used to include advanced distribution applications like "conservation voltage reduction" CVR) and "volt-var optimization" (VVO).

This paper will give a brief description of VVC as it is expected to develop in the future and evaluates the different impacts of future VVC on power quality. The paper will close with a summary of preliminary findings, recommendations and ongoing discussions on this subject.

FUTURE VOLT-VAR CONTROL

Voltage control

The conventional voltage control in distribution grids is based on:

- Automatic on-load tap-changers (OLTC) of HV/MV transformers;
- Off-load or on-load tap-changers on MV/MV voltage regulators;
- Of-load tap-changers of MV/LV transformers
- Capacitor banks and voltage boosters along some MV and LV feeders.

This is expected to change in the future grid in a number of ways, partly due to new challenges, partly due to the availability of new technologies, in most cases due to a combination of the two.

Distribution networks

At this stage it might be important to emphasize the difference between two types of distribution networks, which will be referred to here for simplicity as "European networks" and "North-American networks". The difference is in the role of the low-voltage networks (referred to as "secondary distribution" in North America). Those ones are small in North America, supplying just a few customers and the voltage drop is limited. All voltage control takes place in the medium-voltage (MV) network ("primary distribution"). In European networks, the low-voltage (LV) networks are substantial, with 800-kVA distribution transformers being no exception. Voltage control therefore takes place at LV as well as at MV.

Solar power

The addition of solar power in some European countries is causing large supply voltage variations in LV distribution systems, which require the building of additional cables and transformers or improved voltage control. Future shifts from direct use of fossil fuel to energy-efficient use of electricity (electric cars, heat pumps) will further increase the demand for improved voltage control.

New technology

The availability of new technology enables a holistic view of the system to address supply voltage variations together with minimizing losses, reducing losses on consumption side and avoiding component overload. This is achieved by employing state-of-the-art monitoring, communication and control technologies, which assist the feeder reconfiguration application over a wide area, while focusing on global optimization rather than individual feeders used for traditional VVC. Such control systems are referred to as "volt-var optimization".

Depending on network topology the hosting capacity of LV networks for PV installations can also be increased by introducing voltage regulated MV/LV distribution transformers [3][4]. The voltage control can be realized by on-load tap changers or electronic switches.

Ancillary services

Future distribution systems will have a growing number of production units connected to the ac grid through power electronic interfaces. Some of these units will be able to provide network and system ancillary services, including contribution to voltage control and reactive power. Even if such ancillary services may be more efficient with tools like SVCs or STATCOMS, production units equipped with inverters are already present in the system, making the marginal costs small or even zero. The effectiveness of reactive power injection for voltage control is influenced by both location of the unit and properties of the network. It is therefore likely that coordinated control of inverters and the existing utility equipment is required [9].
Some European countries (i.e. Italy) are studying the necessary to define a multi-level process involving TSOs and DSOs, in which small production units actively participate in energy markets and provide ancillary services such as frequency regulation, voltage control, spinning reserves, standby reserve, backup reserve, load following, real-time balancing, reactive power service, etc. [10].

Transmission-system support

The shift from large conventional power stations to renewable energy and smaller non-conventional production units will result in operational states with a shortage of reactive power at the transmission level. The reactive power will instead have to be supplied by customers or production units connected to the distribution grid.

Several solutions are under discussion, with either compulsory requirements or some market-based solution. In either case, situation may occur with a large flow of reactive power from the distribution to the transmission grid. This could interfere with the voltage control in the distribution system and a coordinated approach is needed. The other way around, a situation may occur where the voltage limits in the distribution grid may limit the ability of the distribution grid to fulfil the reactive power demand at transmission level.

Conservation Voltage Reduction

The Conservation Voltage Reduction (CVR) approach has been used by US electric utilities for many years to decrease demand by reducing the voltage delivered to the load, especially during the peak load periods [2]. The allowable voltage range of 114-126 Volts (±5% of 120V) must be maintained during normal system operation. CVR was implemented initially by reducing voltage at the substation using on-load tap changers. The technique was subsequently complemented using switchable capacitor banks along the feeders in addition to voltage regulators, which also allows for minimized losses.

Discrete versus continuous control

A distinction is made here between “discrete VVC” (based on switching, like transformer tap-changers or capacitor banks) and “continuous VVC” (based on a controllable source of reactive power like the voltage-source converter in a solar panel). Although both methods will maintain the voltage within the regulatory limits, their additional impact on PQ is rather different.

IMPACT ON POWER QUALITY

The introduction of new methods for VVC will have a positive impact on the supply voltage variations; both undervoltages and overvoltages will diminish. Very fast methods for voltage control may even improve voltage flicker and reduce the number of severe voltage dips and swells.

Next to this, some other types of disturbances may be adversely impacted by VVC. The latter is the main point of discussion within the working group and some of the early results, including several points or on-going discussions, are summarized in the forthcoming sub-sections.

Short-duration undervoltages

When CVR is used, the voltage level will be more often close to the minimum-acceptable value. A voltage reduction of just a few percent will more often result in the undervoltage limit being exceeded. From the viewpoint of the customer, more short-duration undervoltages including voltage dips are expected. This could result in end-user equipment tripping more often.

Here it is also important to consider both the criterion used when controlling the voltage magnitude and the speed with which the control system reacts to changes in voltage magnitude. When, for example, a 10-minute average is used (as the voltage quality requirements are based on 10-minute values) and this value is kept close to the undervoltage limit, the number of short-duration events dropping below this limit may increase a lot. When instead a 1-second average would be used to control the voltage, the number of such events would be much lower. The latter will however be unlikely to be achieved by discrete VVC, as the number of rapid voltage changes (see next subchapter) would become unacceptable. Very short averaging times will also require fast control algorithms and with multiple controllers acting closely together, such fast control may result in control instabilities. Finally, it is worthwhile noting that new voltage "medium speed" variations (i.e. variations related to the clouds movement for small LV PV systems) with dynamics lower than 10 minutes but higher than some seconds are expected to appear in distribution systems.

Sudden events like voltage dips due to faults or equipment starting cannot be predicted by most control systems and will still result in about the same drop in voltage as with conventional voltage control. As the voltage will be close to the undervoltage limit more often, the number of events dropping below a certain threshold (like 80 or 90% of nominal voltage) is likely to increase.

However, very limited actual data on this is available and a study done by Hydro Quebec in 2010 [5] showed that the risk of undervoltage is very low when using CVR. It also showed that there would be at most a small increase in number of equipment trips related to voltage dips.

Very fast controllers, reacting within some tens of milliseconds, will be able to limit duration of voltage dips, but the above-mentioned stability issues with multiple controllers will be even bigger.

Rapid voltage changes

When using discrete VVC, step changes in voltage magnitude will occur every time the controller takes an action. Such step changes are referred to as “individual rapid voltage changes”, typically abbreviated as “rapid voltage changes” (RVC). The more strict the voltage band, e.g. for conservation voltage reduction, the higher the number of rapid voltage changes that are expected. This is only a concern for discrete VVC, not for continuous VVC.

In Germany an increased use of voltage regulated distribution transformers is expected and therefore respective limits are recommended for planning purposes. In case the transformer switches only a few times a day (less than one switching per 100 minutes) flicker is no issue, but the maximum voltage change must not exceed 6 %. In case of more frequent switching operations, the resulting flicker severity must satisfy $P_{st} \leq 0{,}35$; $P_{lt} \leq 0{,}25$. Moreover the maximum voltage change should be less than 3%. These values are likely to be taken over by the branch organisation of network operators in Germany, Austria, Switzerland and Czech Republic for the next revision of the “Technical Rules for Assessment of Network Disturbances”.

Here it should be strongly emphasized that these limits for maximum voltage change apply for distribution transformers with automatic tap changers. When capacitors are used for voltage control, voltage steps of 3% or higher should be avoided, as will be discussed in the next section.

With the expected increase in number of (individual) RVC it is important to have a generally accepted standardized method for measuring them. Such a method is part of the recently approved IEC/TR 62759 and also part of the latest draft of IEC 61000-4-30 [6]. More experience with the use of these measurement methods is needed.

Resonances

The presence of a capacitor bank as part of VVC schemes will introduce new resonances to the system. In most of the advanced schemes, regular switching of the capacitor bank is necessary, which will result in regular changes in resonance conditions, with large variations and less predictability in harmonic levels as a result. Changing resonance frequencies is only a concern for discrete VVC not for continuous VVC.

The presence of resonances is not a concern by itself. Only when those resonances are excited by harmonic emission and when the damping is low, with high harmonic distortion result. Damping is typically lower at medium voltage than at low voltage, so that the first concern would be for capacitor banks connected to medium voltage. Voltage control schemes at low voltage are not expected to appear in North America, but they may occur in rural grids in Europe. The main emission reaching the medium voltage network is at harmonic orders 5, 7, 11 and 13. For single-phase feeders also harmonic orders 3 and 9 will be present. Resonance frequencies around these harmonic orders should be avoided as much as possible. Resonance frequencies around the second harmonic could result in instabilities with power-electronic converters.

There is a strong relation between the resonance frequency f_{res} and the voltage step ΔV due to switching the capacitor [8]:

$$f_{res} = \frac{f_0}{\sqrt{\Delta V}}$$

Where f_0 is the power-system frequency (50 or 60 Hz). A resonance frequency at harmonic 7 corresponds to a voltage step of about 2%, harmonic 5 to 4%; and a step of 6% corresponds to a resonance frequency around harmonic 4. As harmonics 5 and 7 are the dominating ones at distribution level, any voltage step of 2% or higher due to capacitor bank switching has a high probability of high distortion due to resonance.

Conventionally, when harmonic resonances were a concern, the capacitor banks would be combined with a reactance either by tuning the resonance frequency to short-circuit the harmonic currents or by detuning the resonance frequency so that it would always stay away from the harmonics being emitted. Neither of this appears practical in case of multiple resonance frequencies that change regularly. Adding damping either in the form of resistances part of passive filters or by means of active filters is a possible solution that should be further investigated [11].

When using harmonic filters to mitigate or avoid resonances it should be considered that including passive harmonic filters will introduce new resonance frequencies that in turn change with every change in the grid. In some countries, the use of harmonic filters is prohibited as they may interact with other equipment in the system.

Harmonic distortion

Continuous VVC could use existing devices or additional devices. In the latter case, this new device is continuously being connected to the distribution grid. Next to reactive power at fundamental frequency there will also be exchange at higher frequencies (so-called “harmonic distortion”). The amount and frequency of the distortion will depend on the kind of technology used for the control of reactive power. Most of the modern applications are based on voltage-source converters using active control. The result is a rather low distortion for lower-order harmonics but higher distortion than normal at higher frequencies, so-called “supraharmonics”. The origin, spread and properties of supraharmonics will be discussed in other chapters of the working group; see [7] for the status of that part of the work. There are also indications, but no confirmed cases, that certain switching and control schemes will result in higher levels of interharmonics and even harmonics.

When already existing converters like those in PV installations will be used to control voltage or reactive power, the impact on harmonic levels depends on the implemented control algorithms. While some inverters result in no change of harmonic levels, others can show differences in the harmonic currents up to 30% for selected harmonic orders [12].

Switching transients

Switching of capacitor banks will result in switching transients, which can have detrimental effect on the operation of end-user equipment. This is only a concern for discrete VVC, not for continuous VVC.

The magnitude of the capacitor energizing transient depends strongly on the amount of damping present in the network. Earlier measurements have shown overvoltages up to 1.5 to 1.8 times the pre-event voltage magnitude. However, recent measurements by Hydro Quebec, specifically related to energizing of capacitors part of a VVC scheme, showed overvoltage up to only 1.2 times the pre-event voltage magnitude. Further studies are needed here to decide to which extend capacitor energizing transients could be a concern. More information on damping of switching transients in distribution networks is needed.

The presence of multiple capacitors introduces two additional potential problems:

- The occurrence of high-frequency transients with back-to-back capacitor switching. The impact of repeated occurrence of high-frequency transients on end-user equipment is not known and needs to be investigated.
- When energizing a capacitor in a system where already capacitors are present, multiple resonance frequencies occur. For certain combinations of frequencies, the magnitude of the energizing transient can be much higher than normal and values up 4 per unit have been measured. But those measurements did not concern VVC schemes, so it is not known if those high overvoltages can also occur there.

Doing measurements in advanced VVC schemes is certainly encouraged but as the number of schemes remains limited, and because very high overvoltage values may only occur in very specific situations, simulations studies should be done in parallel with those measurements.

Possible methods to avoid high energizing overvoltages are the use of synchronized switching and the use of a damping resistor.

Unbalance

Voltage unbalance will be reduced by some of the optimization schemes, mainly those were individual voltage control is used in the three phases. For three-phase control schemes, like three-phase capacitor banks of three-phase distribution transformers with automatic tap-changers, only the positive-sequence voltage can be controlled. Both zero-sequence and negative-sequence voltages will remain the same.

DISCUSSION AND CONCLUSIONS

Findings

Volt-var control will likely be different in the future from what it is today. This will be partly driven by necessity, partly by the availability of new technology. Whereas overall this will have a positive impact on the voltage variations in the distribution network, there are also a number of potential negative impacts.

Some of the potential negative impacts include:

- Increased number of short-duration undervoltages including shallow voltage dips.
- An increased number of (individual) rapid voltage changes and the associated increase in flicker severity.
- Additional resonances with the risk of high levels of harmonic distortion.
- The emission of harmonics and supraharmonics by some of the devices used for VVC.
- A higher number of switching transients, including higher frequencies due to back-to-back switching and higher overvoltages due to multiple resonance frequencies being excited.

The actual impact will depend strongly on the aim and implementation of the VVC.

Recommendations

Many of the potential impacts are ill-understood, in part because the details of the future control algorithms are often not known yet. Studies are needed towards quantifying the adverse impact on power quality of different control algorithms.

Guidelines are needed on what are acceptable sizes and numbers of voltage steps in distribution networks. Experience is needed on standardized methods to measure and analyse rapid voltage changes.

The use of power-electronic converters part of end-user equipment to introduce damping at harmonic frequencies should be seriously investigated.

Studies are needed, both simulations and measurements after damping provided by the low and medium-voltage networks and by equipment connected to it. Information on damping is needed for estimating the amplification of harmonic levels due to resonances and also to estimate the overvoltages due to capacitor energizing.

The impact of repeated switching transients on end-user equipment should be investigated.

On-going discussions

The main question that should be asked, and that is still waiting for an answer, is whether there are cases where the negative impacts of VVC are more than the positive impacts. It is important that these cases are identified and be the base for recommendations to network operators that want to introduce new ways of VVC.

New types of disturbances, or types of disturbances occurring more often than in the past, may require additional indices, to be properly tracked and studied. There is on the other hand a need for simplified reporting on power quality, where a small number of indices is the desired situation. A discussion is on-going within the group on this dilemma.

Using power-electronic controllers, like the ones present in more and more equipment that is anyway already connected to the distribution network, allows for very fast and accurate voltage control. The results would include a very smooth and constant voltage and an improvement of voltage quality over a range of phenomena and timescales. This will however require a complete overhaul of the existing VVC philosophies and will also require that the network operator relies on equipment beyond its control. The issue of adverse interactions between many fast controllers will also have to be solved.

A related point of discussion is if additional requirements should be placed on VVC to improve voltage quality. Here one may think of averaging times less than 10 minutes and even algorithms mitigating dips, swells and severe voltage flicker as part of the overall control system.

Limits on maximum size of rapid voltage changes do not consider the high risk of resonances when capacitor banks are used for voltage control. The higher the voltage step due to the switching a capacitor bank the lower the resonance frequency. Either separate recommendations are needed for voltage control using capacitor banks or alternatively, all voltage steps are to be limited such that no resonances will occur at low-order harmonics. There is no consensus within the group yet on which way to go.

Contributions

Like with all international working groups, contributions are very welcome. Readers having opinions and contributions that may be of interest to the working group are strongly encouraged to contact the authors of this paper.

ACKNOWLEDGEMENTS

Although the authors have tried to describe the state of the discussions within the working group as accurate as possible, this paper is not a working group paper. The opinions expressed in this paper may deviate from the ones of the working group, from CIGRE and from CIRED.

The contributions from other working group members to the discussions are gratefully acknowledged.

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