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A Zonal Approach for Wide Area Temporary Voltage Quality Assessment in Smart Grid

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Abstract: Wide area voltage quality assessment represents one of the mandatory objectives for distribution system operators in development of advanced distribution management systems supporting smart grid requirements. This paper introduces a zonal approach for wide area temporary voltage quality evaluation in distribution network. The concept of temporary voltage quality evaluation and assessment is recommended to incentivize active/online management of voltage quality issues. Decision support system based on the simple deterministic rules is proposed for rating the voltage quality zones in distribution network and making recommendations to distribution system operator. Voltage RMS level, unbalance, and total harmonic distortion are considered as voltage quality indices representing the inputs in decision support system. Residential, commercial, and industrial load types are considered in setting the thresholds for voltage quality indices. The proposed zonal approach for division of distribution network in voltage quality zones is applied to the example of a typical European-type distribution network. The operation of decision support system is tested using the developed distribution smart grid model. The following simulation case studies are conducted: loads with low power factors, manual voltage regulation at MV/LV transformers, unbalanced loads, integration of solar power plant, and nonlinear loads. The obtained simulation results reveal the benefits of the proposed voltage quality assessment approach.

Keywords: *power quality; smart grid; distribution system operator, wide area monitoring; decision support system*

1. Introduction

The power quality (PQ) has recently become the important concept in all areas of energy management system (EMS). Distribution network (DN) is in the main focus of PQ analysis due to the constantly increasing number of nonlinear loads and integrated distributed energy resources (DERs). Smart grid (SG) concept is envisioned to be supported by advanced distribution management system (ADMS) enabling the high level of automatic monitoring, control, and recovery [1]. PQ online monitoring and decision support system (DSS) is expected to be an integral part of ADMS.

PQ can be defined as the combination of voltage quality (VQ) and current quality (CQ). VQ is concerned with deviations of the voltage from the ideal [2]. The majority of distribution network operators (DSO) in most countries have already established VQ monitoring systems [3]. The primary objective of VQ monitoring is to verify compliance with standards EN 50160 [4] and IEC 61000-3-6 [5] dealing with voltage disturbances. PQ monitoring devices, application techniques, and the interpretation of monitoring results are discussed in IEEE Std 1159-2019 [6].

1.1. Motivation and incitement

Active PQ management function is envisioned to be the part of ADMS supporting SG concept. Online VQ monitoring is a precondition for the development of active PQ management in DN. There are no many publications dealing with spatiotemporal assessment of VQ in DNs. Spatial or wide area analysis is important since voltage disturbances could be widespread in DNs. Temporal analysis is important since voltage disturbances could be of different duration. Advanced metering infrastructure (AMI) is expected to

enable both, special and temporal information on VQ, to ADMS. There is a clear need for research on how to assess spatiotemporal VQ data to provide decision support for DSO in performing active VQ management functions. The main motivation for research in this paper is to define a suitable framework for wide area VQ assessment in DN and to propose a corresponding DSS for more timely active VQ management (10-minute-based VQ ratings). The assumption is that suitable and enabling information and communication technologies (ICT) are available to DSO.

1.2. Literature review

A systematic literature review of more than 150 articles on PQ analysis in photovoltaic (PV) systems is presented in [7]. Detection of certain events and seeing the state of DN are identified as a two main objectives of the PQ analysis. PQ evaluation of PV grid interfaced inverter systems is analyzed in [8]. A novel method for assessing PQ associated with wind energy integration is recently proposed in [9]. The proposal of integrated PQ monitoring mechanism for microgrid is elaborated in [10]. The previous papers deal with PQ issues of specific systems (wind, PV, and microgrid) and not with VQ assessment of DN in general.

An overview of international industry practice on PQ monitoring is presented in [11]. The useful guidelines on PQ monitoring, considering measurement locations, processing, and presentation of data, are given in [12]. A number of relations between the transition to SG concept and PQ is summarized in [13]. The paper [14] provides an overview of PQ analysis, compensators, and control technologies under the new situation of SG. The importance of AMI in SG architecture for online management and assessment of PQ

issues is recently elaborated in [15]. The findings of the large scale and long lasting PQ monitoring project in Australia are reported in [16]. A proposal of an automatic system for the management of PQ monitoring data from Brazilian utilities is described in [17]. Voltage Quality Index (VQI) is suggested in [18] to integrally reflect frequency, total harmonic distortion, and dissymmetry. PQ evaluation in distributed generation systems based on the unified index combining six PQ metrics is presented in [19]. According to our best knowledge, there are no research papers published analyzing wide area assessment of VQ in DN and introducing the corresponding DSS as a part of ADMS. This paper represents an attempt to fulfill the previous research gap.

1.3. Contribution and paper organization

The main contributions of this research paper are as follows: introduction of a zonal approach for wide area VQ assessment in DN, proposition of temporary VQ concept, and recommendation of DSS for VQ active management based on a simple deterministic rules. The introduced zonal approach extends the idea of PQ gray zones (DN areas with violated PQ compliance) proposed in standard EN 50160 [4]. Temporary VQ concept is defined as an idea to actively assess wide area VQ state in regular 10-minute time intervals, thus enabling more timely VQ management response actions by DSO. Deterministic rules of DSS for active VQ management are defined separately for the selected VQ metrics: RMS level, unbalance, and total harmonic distortion (THD).

This paper is organized as follows. Section 2 describes wide area VQ in DN, including VQ metrics and AMI considerations, and introduces a temporary VQ concept. A zonal approach for wide area VQ assessment in DN is introduced in Section 3, elaborating on DN division in VQ zones and DSS for rating of VQ zones according to different VQ criteria (metrics). The distribution SG model used in numerical analysis is presented in Section 4. Division of distribution SG model in VQ zones according to the proposed zonal approach is also explained in Section 4. Section 5 presents the main simulation case studies and the corresponding results. The relevant discussions and future research ideas are given in Section 6. And finally, the paper is concluded in Section 7.

2. Wide area voltage quality in distribution network

In this paper, a wide-area VQ refers to the analysis of selected VQ metrics over a large area of the distribution network (DN). First, VQ metrics are analysed at low voltage loading points (LP), and then at medium voltage substation busbars across DN. In this way, a VQ is assessed using a bottom-up approach related to the voltage levels.

2.1. Voltage quality metrics suitable for wide-area monitoring

Most of the voltage-related electromagnetic phenomena tend to propagate through the DN. Maintaining the nominal voltage RMS levels across the DN's nodes is a crucial precondition for a normal operation of DN. Wide-area monitoring of voltage RMS levels is identified as an indispensable function of distribution system operators (DSO). The mean voltage RMS levels are affected by supply interruptions, voltage sags, and swells. Periodic data on

voltage RMS levels provide a time-regular snapshot of the wide-area voltage RMS state in DN.

In addition to voltage RMS levels, voltage unbalance (U_{unB}) and total harmonic distortion (THD_u) are identified as very suitable VQ metrics for wide-area monitoring. Wide-area monitoring of V_{unB} and THD_u could unveil their propagation functions and sources in DN. Previous functionality clearly advances DSO's assessment of wide-area VQ which is compliant with envisioned SG paradigm. According to [4], U_{unB} and THD_u are defined as:

$$U_{unB} [\%] = \frac{U_{1-ns}}{U_{1-ps}} \cdot 100, \quad (1)$$

$$THD_u [\%] = \frac{\sqrt{\sum_{n=2}^{\infty} U_n^2}}{U_1} \cdot 100, \quad (2)$$

where U_{1-ns} and U_{1-ps} are the RMS levels of negative and positive sequence symmetrical components of the 1st (fundamental) voltage harmonic, and U_n is the RMS level of nth voltage harmonic.

2.2. Advanced metering infrastructure enabling wide-area power quality measurements

AMI designed for SG is expected to support PQ online monitoring function. Online monitoring of PQ indicators is assessed in the same way as online monitoring of electricity consumption from Smart Meters (SMs). The conceptualized DSO PQ online monitoring center is presented in Fig. 1.

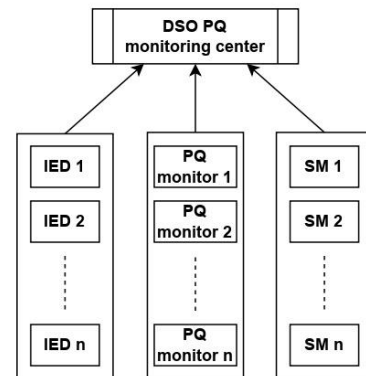


Fig. 1. Conceptualized DSO PQ online monitoring center collecting and analyzing data from IEDs, PQ monitors, and SMs

DSO PQ online monitoring center has the role to collect and analyze data from different devices capable of measuring PQ indicators. Intelligent electronic devices (IEDs) are typically located in HV/MV and MV1/MV2 substations across DN. IEDs are mainly used for power consumption measurements, relay protection, and switching device control. Some of the basic PQ monitoring functions could be embedded into existing IEDs. However, more advanced PQ monitoring functions, such as harmonic measurements, counters of voltage sags and swells, etc., are typically available in electronic devices specifically designed for PQ applications (PQ monitors). IEDs and PQ monitors are typically not available in MV/LV substations, however, the smart meters (SMs) with PQ measurement capabilities are being increasingly deployed at the LV network side.

In this analysis, it is assumed that IEDs or PQ monitors are available in all HV/MV and MV1/MV2 substations and that SMs are available at the LV sides of all MV/LV distribution transformers. Limited or partial measurement observability analysis is out of the scope of this paper. It is also assumed that AMI can provide PQ data to the DSO PQ monitoring center in regular 10-minute time intervals, as the minimum requirement for the SG paradigm. The analysis of ICT supporting AMI is out of the scope of this paper.

2.3. Temporary voltage quality concept

Assuming the availability of a previously conceptualized PQ online monitoring center, it would be possible to analyze VQ metrics in regular 10-minute time-intervals over wide-area of DN. Unlike in conventional VQ measuring systems, where 10-minute mean VQ indicators' values are used on a weekly basis to check compliance with relevant standards, this paper proposes a short-term or temporary VQ evaluation.

Temporary VQ ratings are estimated by the PQ monitoring center immediately after receiving 10-minute mean VQ indicators' values. The illustration of the proposed temporary VQ 10-minute time snapshots and ratings is presented in Fig.2.

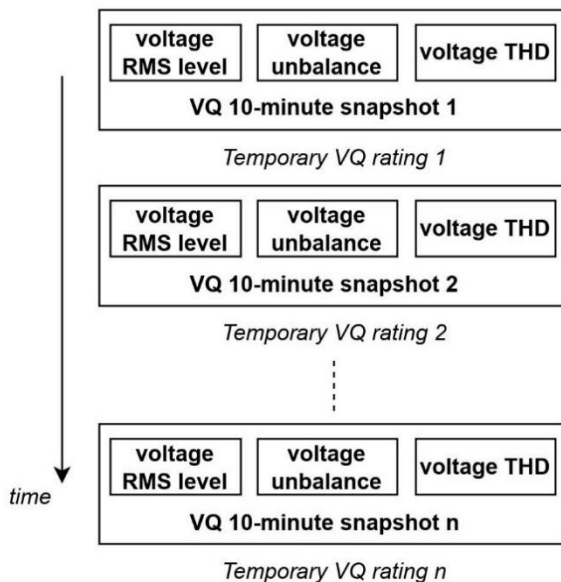


Fig. 2. Temporary VQ 10-minute time snapshots and ratings

The proposed temporary VQ ratings are intended to complement the standard-based weekly evaluation of VQ indicators (RMS level, unbalance, and THD). According to relevant standards, VQ indicators are evaluated once a week, using 1008 collected 10-minute mean measurements. Temporary VQ ratings are recommended to assist DSO in detecting and improving VQ issues in a timelier matter. Using the temporary VQ ratings DSO will be able to make temporary decisions leading to an overall improvement of the VQ state before checking the compliance with standards by the end of the measuring week. In the previous sense, wide-area temporary VQ ratings could significantly contribute to the SG paradigm.

3. A zonal approach for wide-area temporary voltage quality assessment

To properly assess temporary VQ for a wide area of DN it is necessary to identify meaningful areas/zones for the analysis of VQ indicators. The zonal approach proposed in this paper is based on considerations of DN topology and rated voltage levels.

3.1. Distribution network division into voltage quality zones

DN is topologically divided into substations, feeders, and loads. Typical European-type DN includes one or two medium-rated voltage levels (MV1, MV2). In this paper, HV/MV substations are conceptualized as topological boundaries of DN, as shown in Fig.3.

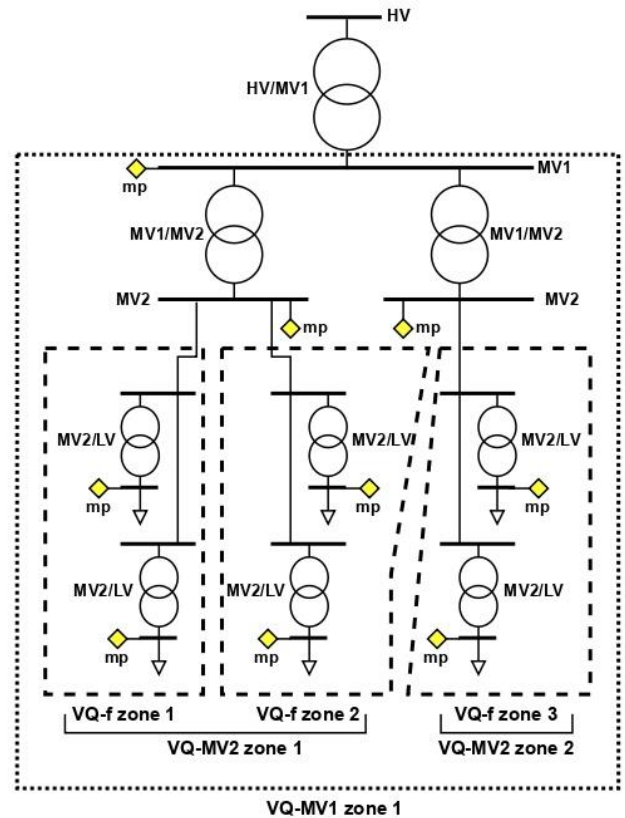


Fig. 3. DN division into VQ zones according to the proposed zonal approach

The primary and simultaneously the largest VQ zone (VQ-MV1 zone 1) is determined by the highest medium voltage level MV1. It starts from the MV1 busbars in HV/MV1 substation and includes all MV1 feeders and MV1 busbars in MV1/MV2 substations. The VQ indicators are analyzed at the MV1 level. It is possible to have multiple primary VQ zones in radial DNs. The number of primary VQ zones in radial DNs is determined by the number of HV/MV1 power transformers. In special cases, the single primary VQ zone could be determined by two HV/MV1 power transformers, as in the case of closed-ring configuration. Secondary VQ zones are determined by the first lower medium voltage level MV2 (VQ-MV2 zones). The number of secondary VQ zones in radial DNs is determined by the number of MV1/MV2 power transformers. Every secondary VQ zone is divided into feeder VQ zones (VQ-f zones). The number of VQ-f zones for a single zone VQ-MV2 is determined by the number of feeders starting from the corresponding MV2 busbars. VQ-f zones

represent the smallest wide-area VQ zone units according to the proposed zonal approach. The VQ indicators for VQ-f zones are analyzed based on the VQ measurements in MV1/MV2 substations and the measurements of SMs at the LV level. The VQ assessment begins with the analysis of VQ indicators at loading or measurement points (mp), as shown in Fig. 3. The VQ indicators for VQ-MV2 zones are determined by the VQ indicators for VQ-f zones. The VQ-f zones are encapsulated by VQ-MV2 zones, while VQ-MV2 zones are encapsulated by VQ-MV1 zones.

3.2. A decision support system for rating of temporary voltage quality zones

The rating system for temporary VQ zones is designed according to VQ indicators' value ranges complaint with EN 50160-2010 standard [4] and zonal/areal DN considerations. The recommended VQ indicators' value ranges are modified and expanded to enable a greater selection of recommendations available to the proposed decision support system. VQ zone ratings and recommendations are defined separately for selected VQ indicators: RMS level, unbalance, and THD, as shown in Tables 1, 2, and 3, respectively.

Table 1. The ratings of VQ zones - voltage RMS level criteria

VQ-loading points - LP (low voltage (400 V))		
<i>Voltage RMS range</i>	<i>Zone rating</i>	<i>Recommendation</i>
$0.95U_n < U < 1.05U_n$	VQ-RMS LP excellent	no control action required
$0.9U_n < U < 0.95U_n$	VQ-RMS LP good	non-urgent control action considered
$1.05U_n < U < 1.1U_n$	VQ-RMS LP good	non-urgent control action considered
$0.85U_n < U < 0.9U_n$	VQ-RMS LP moderate	non-urgent control action required
$U_{\text{undervoltage-prot}} < U < 0.85U_n$	VQ-RMS LP bad	urgent control action required
$1.1U_n < U < U_{\text{overvoltage-prot}}$	VQ-RMS LP bad	urgent control action required
$U < U_{\text{undervoltage-prot}}$	VQ-RMS LP critical	protection action required
$U > U_{\text{overvoltage-prot}}$	VQ-RMS LP critical	protection action required
VQ-feeder zones - F (medium voltage (11 kV))		
<i>Voltage RMS range and VQ loading points (LP) zone ratings</i>	<i>Zone rating</i>	<i>Recommendation</i>
$0.95U_n < U_{\text{busbar}} < 1.05U_n$ 80% of LP – VQ-RMS LP excellent 100% of LP – VQ-RMS LP good	VQ-RMS F excellent	no control action required
$0.95U_n < U_{\text{busbar}} < 1.05U_n$ 60% of LP – VQ-RMS LP good 100% of LP – VQ-RMS LP moderate	VQ-RMS F good	non-urgent control action considered
$0.9U_n < U_{\text{busbar}} < 1.1U_n$ 100% of LP – VQ-RMS LP moderate	VQ-RMS F moderate	non-urgent control action required
$U_{\text{bus-under-prot}} < U_{\text{busbar}} < U_{\text{bus-over-prot}}$ 100% of LP – VQ-RMS LP bad	VQ-RMS F bad	urgent control action required
all remaining cases	VQ-RMS F critical	urgent control/protection action required
VQ-MV2 zones – MV2 (medium voltage (11 kV))		
<i>VQ-feeder (F) zone ratings</i>	<i>Zone rating</i>	<i>Recommendation</i>
80% of F - VQ-RMS F excellent 100% of F - VQ-RMS F good	VQ-RMS MV2 excellent	no control action required
100% of F - VQ-RMS F good	VQ-RMS MV2 good	non-urgent control action considered
100% of F - VQ-RMS F moderate	VQ-RMS MV2 moderate	non-urgent control action required
100% of F - VQ-RMS F bad	VQ-RMS MV2 bad	urgent control action required
all remaining cases	VQ-RMS MV2 critical	urgent control/protection action required
VQ-MV1 zones – MV1 (medium voltage (33 kV))		
<i>VQ-MV2 (MV2) zone ratings</i>	<i>Zone rating</i>	<i>Recommendation</i>
80% of MV2 - VQ-RMS MV2 excellent 100% of MV2 - VQ-RMS MV2 good	VQ-RMS MV1 excellent	no control action required
100% of MV2 - VQ-RMS MV2 good	VQ-RMS MV1 good	non-urgent control action considered
100% of MV2 - VQ-RMS MV2 moderate	VQ-RMS MV1 moderate	non-urgent control action required
100% of MV2 - VQ-RMS MV2 bad	VQ-RMS MV1 bad	urgent control action required
all remaining cases	VQ-RMS MV1 critical	urgent control/protection action required

Table 2. Ratings of VQ zones - voltage unbalance criteria

VQ-loading points - LP (low voltage (400 V))		
<i>Voltage unbalance range</i>	<i>Zone rating</i>	<i>Recommendation</i>
$0\% < U_{\text{unbalance}} < U_{\text{unB-limit-1}}$	VQ-unB LP excellent	no control action required
$U_{\text{unB-limit-1}} < U_{\text{unbalance}} < U_{\text{unB-limit-2}}$	VQ-unB LP good	non-urgent control action required
$U_{\text{unB-limit-2}} < U_{\text{unbalance}} < U_{\text{unbalance-prot}}$	VQ-unB LP bad	urgent control action required
$U_{\text{unbalance}} > U_{\text{unbalance-prot}}$	VQ-unB LP critical	protection action required
VQ-feeder zones - F (medium voltage (11 kV))		
<i>Voltage unbalance range and VQ loading points (LP) zone ratings</i>	<i>Zone rating</i>	<i>Recommendation</i>
$0\% < U_{\text{bus-unbalance}} < U_{\text{unB-limit-2}}$ 80% of LP – VQ-unB LP excellent 100% of LP – VQ-unB LP good	VQ-unB F excellent	no control action required
$0\% < U_{\text{bus-unbalance}} < U_{\text{unB-limit-2}}$ 100% of LP – VQ-unB LP good	VQ-unB F good	non-urgent control action required
$0\% < U_{\text{bus-unbalance}} < U_{\text{unbalance-prot}}$ 100% of LP – VQ-unB LP bad	VQ-unB F bad	urgent control action required
all remaining cases	VQ-unB F critical	urgent control/protection action required
VQ-MV2 zones – MV2 (medium voltage (11 kV))		
<i>VQ-feeder (F) zone ratings</i>	<i>Zone rating</i>	<i>Recommendation</i>
80% of F - VQ-unB F excellent 100% of F - VQ-unB F good	VQ-unB MV2 excellent	no control action required
100% of F - VQ-unB F good	VQ-unB MV2 good	non-urgent control action required
100% of F - VQ-unB F bad	VQ-unB MV2 bad	urgent control action required
all remaining cases	VQ-unB MV2 critical	urgent control/protection action required
VQ-MV1 zones – MV1 (medium voltage (33 kV))		
<i>VQ-MV2 (MV2) zone ratings</i>	<i>Zone rating</i>	<i>Recommendation</i>
60% of MV2 - VQ-unB MV2 excellent 100% of MV2 - VQ-unB MV2 good	VQ-unB MV1 excellent	no control action required
100% of MV2 - VQ-unB MV2 good	VQ-unB MV1 good	non-urgent control action required
100% of MV2 - VQ-unB MV2 bad	VQ-unB MV1 bad	urgent control action required
all remaining cases	VQ-unB MV1 critical	urgent control/protection action required

Five different rating categories are defined for VQ zones based on voltage RMS levels: excellent, good, moderate, bad, and critical. First, the ratings are assigned to loading points (LP), and then to the feeder, MV2, and MV1 zones. The ratings of higher-level VQ zones are dependent on ratings of lower-level VQ zones. Every VQ LP zone is rated excellent or good if the voltage RMS level is compliant with a standard-defined acceptable range of $\pm 0.1U_n$. A moderate rating is assigned to the VQ LP zone if the voltage RMS level is in the range $0.85-0.9U_n$, which is still compliant with the standard. When the voltage RMS level is out of the standard-defined range $0.85-1.1U_n$, and the undervoltage and overvoltage protection thresholds are not exceeded, the VQ LP zone is rated as bad. In the case when undervoltage or overvoltage protection thresholds are exceeded, the VQ LP zone is rated critical.

VQ LP zone ratings are used to give the corresponding recommendations to DSO to make actions for VQ improvement. There are two types of actions considered: control and protection actions. Control actions are assumed to be performed by PQ control/improvement equipment available in DN. Protection actions are assumed to be performed by relay protection equipment in DN. Control actions are divided into urgent and non-urgent. Urgent control actions are the ones expected to be executed before the next

VQ 10-minute snapshot becomes available. Non-urgent control actions are not required to be executed fast by DSO. Their time of execution is up to the specific DSO and DN operation rules.

The rating excellent gives the recommendation to DSO that no control action is required (temporary voltage RMS level is excellent at considered LP location). The rating good gives the recommendation to DSO that non-urgent control action should be considered. In the case of a moderate rating, DSO is recommended to execute a non-urgent control action. Since the rating bad indicates a violation of standard-allowed voltage RMS levels, DSO is recommended to execute urgent control action. If the corresponding VQ issue is treatable, DSO will be able to improve the rating before the next VQ 10-minute snapshot consideration. Finally, protection actions are recommended in the case of critical rating. Protection actions are expected to be executed automatically by protection equipment, and DSO is expected to be notified shortly after.

The zone ratings and recommendations are similar in the case of VQ-f zones. Zone ratings depend on the RMS level of voltage at the corresponding busbars connecting the feeders (U_{busbar}) and the zone ratings of LPs along the feeder. For example, the moderate rating is assigned to the VQ-f zone if the U_{busbar} level is in the standard-allowed range of $\pm 0.1U_n$

and if the minimum 100% of the corresponding VQ LP zones have a rating of moderate or better (good or excellent). The multiple conditions for the same rating are linked by a logical operator AND. If there is only one VQ LP zone with a rating bad along the feeder or if U_{busbar} level is out of the range of $\pm 0.1U_n$, the VQ-f zone is rated bad or critical.

VQ MV2 zones are rated based on the number of associated VQ-f zones with particular ratings. Similarly, VQ MV1 zones are rated based on the number of associated VQ MV2 zones with particular ratings. U_{busbar} level condition is indirectly included in ratings since VQ-f zones are encapsulated by VQ MV2 zones, and VQ MV2 zones are encapsulated by VQ MV1 zones.

Ratings of VQ zones according to voltage unbalance criteria are shown in Table 2. Four different zone ratings are defined: excellent, good, bad, and critical. The moderate rating is omitted in this case since there is no expanded

voltage unbalance range allowed by the standard [4] for LP (low voltage level). In the case of voltage RMS level criteria, the expanded range $0.85-0.9U_n$ is used for the definition of moderate rating. The VQ unbalanced zone ratings are correlated with the corresponding recommendations for DSO.

In the case of VQ LP zones two voltage unbalance thresholds are defined: $U_{unB-limit-1}$ and $U_{unB-limit-2}$. $U_{unB-limit-1}$ threshold should be set below the standard-defined threshold of 1.3% to indicate an excellent zone rating. $U_{unB-limit-2}$ should be set as a boundary between good and bad zone ratings. VQ LP zone should be rated as bad when the standard-defined threshold becomes exceeded. However, in the case of voltage unbalance criteria, $U_{unB-limit-1}$ and $U_{unB-limit-2}$ are set to different values for different load types. As will be discussed later, some load types are more sensitive to voltage unbalance than others. Similar conclusions hold for the protection settings.

Table 3. Ratings of VQ zones - voltage THD criteria

VQ-loading points - LP (low voltage (400 V))		
<i>Voltage THD range</i>	<i>Zone rating</i>	<i>Recommendation</i>
$0\% < THD_v < THD_{v-limit-1}$	VQ-THD LP excellent	no control action required
$THD_{v-limit-1} < THD_v < THD_{v-limit-2}$	VQ-THD LP good	non-urgent control action required
$THD_{v-limit-2} < THD_v < THD_{v-prot}$	VQ-THD LP bad	urgent control action required
$THD_v > THD_{v-prot}$	VQ-THD LP critical	protection action required
VQ-feeder zones - F (medium voltage (11 kV))		
<i>Voltage THD range and VQ loading points (LP) zone ratings</i>	<i>Zone rating</i>	<i>Recommendation</i>
$0\% < THD_{v-bus-1} < THD_{v-bus-1-limit}$ 80% of LP – VQ-THD LP excellent 100% of LP – VQ-THD LP good	VQ-THD F excellent	no control action required
$0\% < THD_{v-bus-1} < THD_{v-bus-1-limit}$ 100% of LP – VQ-THD LP good	VQ-THD F good	non-urgent control action required
$0\% < THD_{v-bus-1} < THD_{v-bus-1-prot}$ 100% of LP – VQ-THD LP bad	VQ-THD F bad	urgent control action required
all remaining cases	VQ-THD F critical	urgent control/protection action required
VQ-MV2 zones – MV2 (medium voltage (11 kV))		
<i>Voltage THD range and VQ-feeder (F) zone ratings</i>	<i>Zone rating</i>	<i>Recommendation</i>
80% of F – VQ-THD F excellent 100% of F – VQ-THD F good	VQ-THD MV2 excellent	no control action required
100% of F – VQ-THD F good	VQ-THD MV2 good	non-urgent control action required
100% of F – VQ-THD F bad	VQ-THD MV2 bad	urgent control action required
all remaining cases	VQ-THD MV2 critical	urgent control/protection action required
VQ-MV1 zones – MV1 (medium voltage (33 kV))		
<i>Voltage THD range and VQ-MV2 (MV2) zone ratings</i>	<i>Zone rating</i>	<i>Recommendation</i>
$0\% < THD_{v-bus-2} < THD_{v-bus-2-limit}$ 60% of MV2 – VQ-THD MV2 excellent 100% of MV2 – VQ-THD MV2 good	VQ-THD MV1 excellent	no control action required
$0\% < THD_{v-bus-2} < THD_{v-bus-2-limit}$ 100% of MV2 – VQ-THD MV2 good	VQ-THD MV1 good	non-urgent control action required
$0\% < THD_{v-bus-2} < THD_{v-bus-2-prot}$ 100% of MV2 – VQ-THD MV2 bad	VQ-THD MV1 bad	urgent control action required
all remaining cases	VQ-THD MV1 critical	urgent control/protection action required

In the case of VQ-f zones, only the $U_{\text{unB-limit-2}}$ threshold is used. There is a single threshold for voltage unbalance recommended by the standard [4] regardless of DN nominal voltage level. VQ-f zone ratings depend on voltage unbalance at the corresponding busbars connecting the feeders ($U_{\text{bus-unbalance}}$) and the zone ratings of LPs along the feeder. Similar to voltage RMS criteria, VQ MV2 zones are rated based on the number of associated VQ-f zones with particular ratings. While VQ MV1 zones are rated based on the number of associated VQ MV2 zones with particular ratings.

Ratings of VQ zones according to voltage THD criteria are shown in Table 3. Standard [4] recommends the following voltage THD thresholds: 2.5%, 2%, and 1.5% for rated voltage levels 400 V, 11 kV, and 33 kV, respectively. The same zone ratings are defined as in the case of voltage unbalance criteria: excellent, good, bad, and critical. The VQ THD zone ratings are correlated with the corresponding recommendations for DSO.

In the case of VQ LP zones two voltage THD thresholds are defined: $THD_{v\text{-limit-1}}$ and $THD_{v\text{-limit-2}}$. $THD_{v\text{-limit-1}}$ threshold should be set below the standard-defined threshold of 2.5% to indicate an excellent zone rating. $THD_{v\text{-limit-2}}$ should be set as a boundary between good and bad zone ratings. $THD_{v\text{-limit-1}}$ and $THD_{v\text{-limit-2}}$ are set to different values for different load types. Different load types have different sensitivities to different values of voltage THD. Similar conclusions hold for the protection settings.

When considering VQ-f zones, the threshold related to voltage THD is stricter than in the case of VQ LP zones. $THD_{v\text{-bus-1-limit}}$ threshold should be set to 2% to differentiate between good and bad zone ratings. However, it is meaningful to account for load type sensitivity in settings of $THD_{v\text{-bus-1-limit}}$. The feeders are commonly dominantly loaded by particular load types. Additionally, VQ-f zone ratings also depend on VQ LP zone ratings associated with the considered feeder.

VQ MV2 zones are rated based on the number of associated VQ-f zones with ratings and threshold $THD_{v\text{-bus-1-limit}}$ which is equal to the corresponding one for VQ-f zones (feeders are connected to MV2 busbars). VQ MV1 zones are rated based on the number of associated VQ MV2 zones with ratings and threshold $THD_{v\text{-bus-2-limit}}$. $THD_{v\text{-bus-2-limit}}$ threshold should be set to 1.5% to differentiate between good and bad zone ratings (MV1 busbars). The $THD_{v\text{-bus-2-limit}}$ threshold is also dependent on the dominant load type in the VQ MV1 zone. Similar conclusions hold for the protection settings.

3.3. VQ zone rating conditions and different load types

LPs in DN can be divided into different categories according to dominant load types. The most common load type categories in DN are industrial, commercial, and residential. The sensitivities of different load types to VQ issues are different. The standard [4] does not recommend different allowed ranges of VQ indicators for different load types. A decision support system proposed in this paper includes recommendations for modifications of ranges of VQ indicators for different load types. Detailed analysis of VQ related to specific loads is out of the scope of this paper. However, VQ zone rating conditions could be easily modified to better describe the VQ issues for specific loads, such as induction motors, home electronic devices, etc.

The ratings of VQ zones according to voltage RMS level criteria accounted for different load types by recommending different undervoltage and overvoltage settings. In the case of residential and commercial loads, the following protection thresholds are recommended: $U_{\text{undervoltage-prot}} = 0.8U_n$; $U_{\text{overvoltage-prot}} = 1.15U_n$; $U_{\text{bus-under-prot}} = 0.85U_{n\text{-busbar}}$; $U_{\text{bus-over-prot}} = 1.15U_{n\text{-busbar}}$. And in the case of industrial loads the following protection thresholds are recommended: $U_{\text{undervoltage-prot}} = 0.75U_n$; $U_{\text{overvoltage-prot}} = 1.15U_n$; $U_{\text{bus-under-prot}} = 0.8U_{n\text{-busbar}}$; $U_{\text{bus-over-prot}} = 1.15U_{n\text{-busbar}}$. Industrial loads are generally more robust to undervoltage issues than residential and commercial loads. Undervoltage protection threshold affects the bad and critical ratings of VQ zones (voltage RMS level criteria).

The ratings of VQ zones according to voltage unbalance criteria accounted for different load types by recommending different thresholds. The following voltage unbalance thresholds are recommended: $U_{\text{unB-limit-1}} = 0.6\%$, $U_{\text{unB-limit-2}} = 1.3\%$ (industrial load type); $U_{\text{unB-limit-1}} = 1\%$, $U_{\text{unB-limit-2}} = 2\%$ (commercial load type); $U_{\text{unB-limit-1}} = 1.5\%$, $U_{\text{unB-limit-2}} = 3\%$ (residential load type). The strictest thresholds are set for industrial load type since the high voltage unbalances commonly cause very high current unbalances. The protection threshold is set using the sensitivity factor $k = 1.5$: $U_{\text{unbalance-prot}} = k \cdot U_{\text{unB-limit-2}}$.

Different load type categories are considered also in the case of voltage THD criteria. Different thresholds are recommended for residential, commercial, and industrial load types. Residential loads are typically more sensitive to voltage THD than commercial and industrial loads. Many types of residential loads, such as appliances and electronics, are more susceptible to problems caused by harmonics, such as less efficient operation, interference with electronic devices, etc. It could be argued that commercial loads are typically more sensitive to voltage THD than industrial loads. Many types of commercial loads, such as office equipment and lighting systems, are more susceptible to problems caused by voltage THD. Generally, industrial loads are considered to be more robust and able to tolerate higher levels of voltage THD. Considering the previous analysis, voltage THD thresholds are set to be the lowest for residential loads and the highest for industrial loads. The recommended values for voltage THD thresholds are given in Table 4. Since voltage THD criteria are unconventionally used in relay protection, only indicative uniform values of all sensitivity factors are recommended: $k_{r1} = k_{c1} = k_{i1} = 3$; $k_{r2} = k_{c2} = k_{i2} = 2.5$; $k_{r3} = k_{c3} = k_{i3} = 2$.

Table 4. Voltage THD thresholds for zone ratings

Voltage THD thresholds	Load types		
	residential	commercial	industrial
$THD_{v\text{-limit-1}}$	1.5%	2%	3%
$THD_{v\text{-limit-2}}$	2.5%	4%	5%
$THD_{v\text{-prot}}$	$k_{r1} \cdot 2.5\%$	$k_{c1} \cdot 4\%$	$k_{i1} \cdot 5\%$
$THD_{v\text{-bus-1-limit}}$	2%	3%	4%
$THD_{v\text{-bus-1-prot}}$	$k_{r2} \cdot 2\%$	$k_{c2} \cdot 3\%$	$k_{i2} \cdot 4\%$
$THD_{v\text{-bus-2-limit}}$	1.5%	2%	3%
$THD_{v\text{-bus-2-prot}}$	$k_{r3} \cdot 1.5\%$	$k_{c3} \cdot 2\%$	$k_{i3} \cdot 3\%$

4. Distribution Smart Grid model

Modeling of DNs for performing PQ-related studies is not an easy task. Usually, harmonic power flow calculations are recommended in the case of wide-area steady-state analyses. If studying a specific element of DN or its small part, time domain studies could be used. Wide-area steady-state DN analysis has been performed in this paper. Unconventionally, time domain calculations have been used due to the available computing resources and designed DN model capabilities. Common modeling approximations related to harmonic power flow calculations have been avoided in this way. Modeling of SGs often includes joint DN and ICT system modeling. The idealized models of measurement and ICT devices have been used in this paper for simplification purposes. Previous models have been mandatory for modeling the proposed temporary VQ monitoring system. Detailed modeling of the ICT system is out of the scope of this paper.

Designed distribution SG (dSG) model unifies the models of basic power system elements (transformers, overhead and cable lines, loads, DERs, etc.), substation switching and measurement devices (circuit breakers, voltage, and current transformers, sectionalizing switches (SSs), etc.), and idealized ICT devices (IEDs, SMs, PQ monitors, DSO monitoring and control center, etc.). The capabilities of the dSG model include transient and steady-state power system studies, balanced, and unbalanced three-phase power system operation analysis, power system harmonic analysis, power system short-circuits analysis, automatic voltage regulation (AVR) studies, power system protection studies, advanced metering infrastructure (AMI) studies, energy management system (EMS) studies, etc. The model is numerically implemented using the simulation platform Simulink available as a part of the software package MATLAB 2020b [20].

4.1. Distribution network elements, topology, and configuration

A typical European-style DN with three MV1/MV2 (33/11 kV/kV) substations in an open-ring configuration has been chosen for analysis. The base (default) configuration of the dSG model is shown in Fig.4. The model of AVR has been activated for HV/MV1 and MV1/MV2 transformers as a part of the base dSG model configuration. The solar power plant (SPP) model is disconnected, and SSs are normally open in the base configuration. The MV1/MV2 substations Sub1 and Sub2 are supplied from the HV/MV1 (132/33 kV/kV) substation mSub1 by the overhead lines OHL11 (12 km), OHL12 (12 km), and OHL2 (8 km), while the MV1/MV2 substation Sub3 is supplied from the same HV/MV substation mSub1 by the overhead line OHL4 (10 km). DN configuration could be switched to a closed ring by energizing the overhead line OHL3 (15 km), thus connecting the substations Sub2 and Sub3. Alternatively, the substation Sub3 could be supplied from another HV/MV substation mSub2 by energizing the overhead line OHL5 (10 km). The rated voltage levels and powers of the models of power system elements are also shown in Fig.4.

Substation Sub1 supplies the suburban residential load area (R-suburban zone Sub11 – feeder 1) and two industrial

load areas (I zone Sub12 – feeder 3 and I zone Sub12 – feeder 4). Substation Sub2 supplies the four suburban residential load areas (R-suburban zone Sub21 – feeders 5, 6, 7, and R-suburban zone Sub22 – feeder 9). SPP with a rated power of 2 MW could be connected to feeder 9. Substation Sub3 supplies the three urban residential load areas (R-urban zone Sub31 – cable feeders 1, 2, and 3) and commercial load areas (C zone Sub32 – cable feeder 4). The industrial load areas could be alternatively supplied from the substation Sub3 by feeder 8 (4 km). The urban residential load areas could be alternatively supplied from the substation Sub2 by section 4 of feeder 9 (4 km).

4.2. Determination of VQ zones

According to the proposed zonal approach, VQ zones have been determined for the case of the proposed DN topology. LPs are automatically determined by the adoption of certain DN topology. All LPs are enumerated using the form $Xn1n2$. X represents the load type. n1 and n2 represent the ID number of the substation and load. For example, R12 LP represents residential load with ID number 1, supplied from substation 1 (Sub1).

As can be seen in Fig.4, the three VQ-MV1 zones could be determined: Sub1, Sub2, and Sub3. Previous substations determine VQ-MV1 zones since the corresponding 33 kV busbars exist. Main supplying substations mSub1 and mSub2 are not considered VQ-MV1 zones since there are no feeders supplying the loads from them directly.

VQ-MV1 zone Sub1 encapsulates the two VQ-MV2 zones: Sub11 and Sub12 since there exist two MV1/MV2 transformers in Sub1. VQ-MV2 zone Sub11 encapsulates only one residential VQ-feeder zone Sub11-feeder 1. Only feeders supplying loading areas are considered VQ-feeder zones. VQ-feeder zone Sub11-feeder 1 encapsulates 6 VQ LP zones. VQ-MV2 zone Sub12 encapsulates the following two industrial VQ-feeder zones: Sub12-feeder 3 and Sub12-feeder 4.

VQ-MV1 zone Sub2 encapsulates the following two VQ-MV2 zones: Sub21 and Sub22. VQ-MV2 zone Sub21 encapsulates the following residential VQ-feeder zones: Sub21-feeder 5, Sub21-feeder 6, and Sub21-feeder 7. Previous VQ-feeder zones encapsulate 2, 3, and 5 VQ LP zones, respectively. VQ-MV2 zone Sub22 encapsulates only one residential VQ-feeder zone Sub22-feeder 9. The previous VQ-feeder zone encapsulates 5 VQ LP zones.

Finally, VQ-MV1 zone Sub3 encapsulates the following two VQ-MV2 zones: Sub31 and Sub32. VQ-MV2 zone Sub31 encapsulates the following urban residential VQ-feeder zones (cable feeders): Sub31-c-feeder 1, Sub31-c-feeder 2, and Sub31-c-feeder 3. Previous VQ-feeder zones encapsulate 3, 2, and 2 VQ LP zones, respectively. VQ-MV2 zone Sub32 encapsulates the one commercial VQ-feeder zone (cable feeder): Sub32-c-feeder 4. The previous VQ-feeder zone encapsulates 4 VQ LP zones.

The determined VQ-feeder zones in the DN base configuration are marked with different colors to highlight the different load types (Fig.4). Different reconfiguration actions in DN could lead to different VQ zone encapsulations.

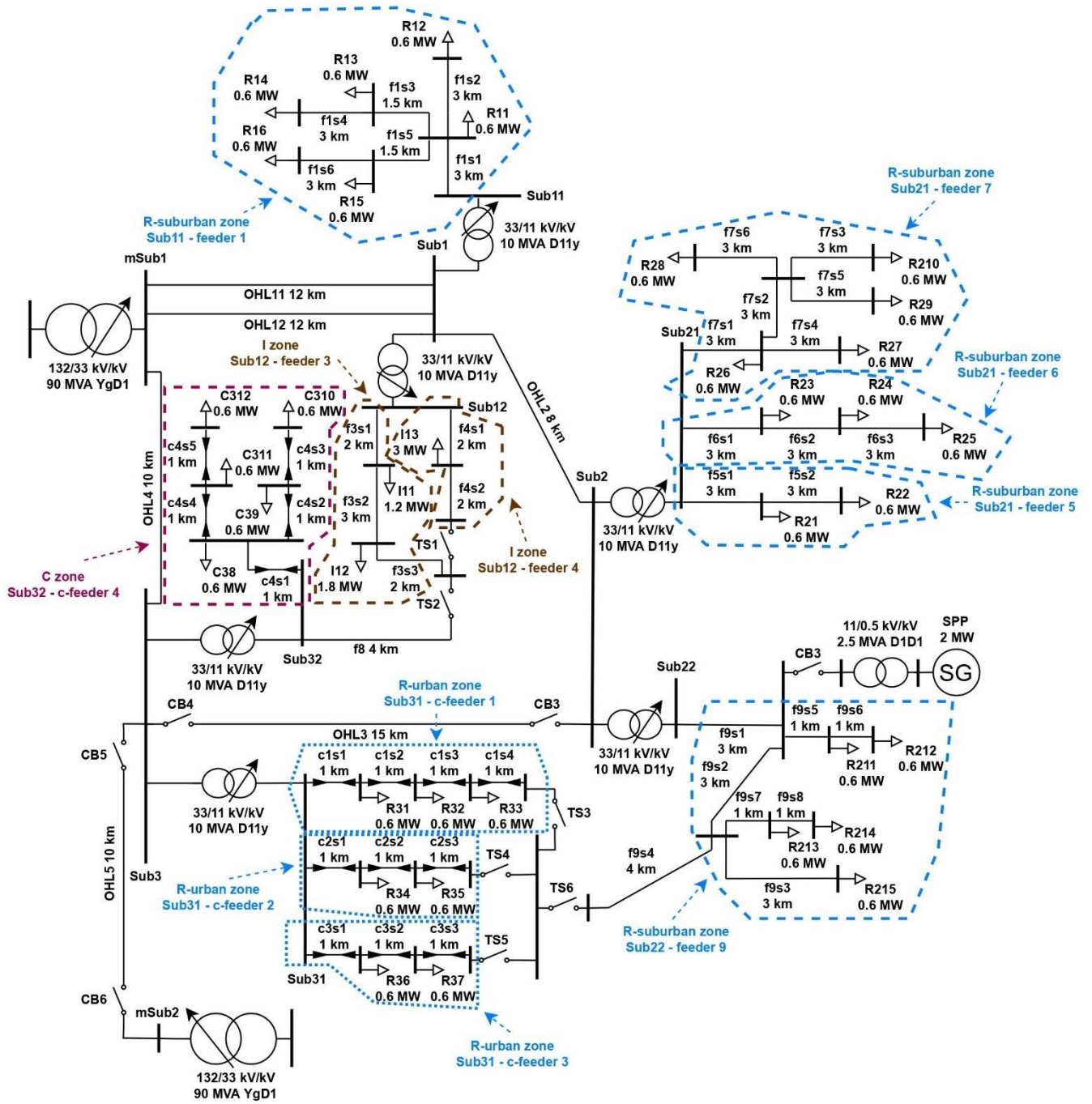


Fig. 4. DN model - base configuration with marked VQ-feeder zones

5. Simulation case studies and results

The time domain power system analysis has been performed to estimate the values of VQ indicators simulating 10-minute average values of PQ indicators expected to be collected by the DSO PQ monitoring center, as conceptualized in Fig.1. Measuring sources (IEDs, PQ monitors, SMs) are indicated as measuring points in Fig.2. VQ indicators compliance with standard defined constraints has been analysed based on the results of the simulation case studies. The classification and rating of determined VQ zones have been performed according to the rules of the proposed temporary VQ decision support system. The following simulation case studies have been analyzed: DN operation – a base case, the impact of loads with low power factors, the impact of manual voltage regulation at MV/LV transformers,

the impact of unbalanced loads, the impact of the integration of SPP, and impact of nonlinear loads.

5.1. Distribution network operation – a base case

A base case of DN operation is determined by the base configuration of the DN model (Fig.4), nominal loading, and activated AVR at HV/MV1 and MV1/MV2 transformers. On-load tap-changer (OLTC) parameters are set as follows: voltage step = 1.25%, number of steps = ± 16 , deadband/2 = 0.75 x voltage step and reference voltage = 1 pu.

The simulation stops when all OLTCs converge to final step positions. The final positions of OLTCs' steps determine the analyzed steady states of DN. The previous steady states of DN are used to represent temporary VQ states (simulated 10-minute average values).

Voltage RMS level profiles of feeders: Sub11 – feeder 1, Sub21 – feeder 7, and Sub32 – c-feeder 4, are shown in Fig. 5. The ratings of VQ-MV1 and VQ-MV2 zones are shown in Table 5, while the ratings of VQ LP and VQ-f zones are shown in Table 6.

Sub11 – feeder 1 voltage RMS profile curve is in proximity to the $0.9U_n$ limit under nominal loading conditions. The same conclusion holds for Sub21 – feeder 7 voltage RMS profile curve for remote loads R28, R29, and R210. Sub32 – c-feeder 4 voltage RMS profile curve is in proximity to the U_n under nominal loading conditions. Cable feeders are of short lengths, consequently leading to lower voltage drops.

According to the results in Tables 5 and 6, the overall rating of temporary VQ based on voltage RMS level criteria is between good and excellent. VQ-f zones: Sub11-feeder 1, Sub21-feeder 7, and Sub22-feeder 9, are rated with good with all corresponding VQ LP zones rated with good. DSO is recommended to consider non-urgent control actions to additionally improve VQ (Table 1). All VQ-f zones of VQ-MV1 zone Sub3 are rated with excellent, and no control actions are required. AVR is able to achieve a good VQ quality.

Table 5. The ratings of VQ-MV1 and VQ-MV2 zones based on the voltage RMS level criteria – DN base case

VQ-MV1 zones	VQ-MV2 zones	zone rating
Sub1	Sub11	good
good	Sub12	good
Sub2	Sub21	good
good	Sub22	good
Sub3	Sub31	excellent
excellent	Sub32	excellent

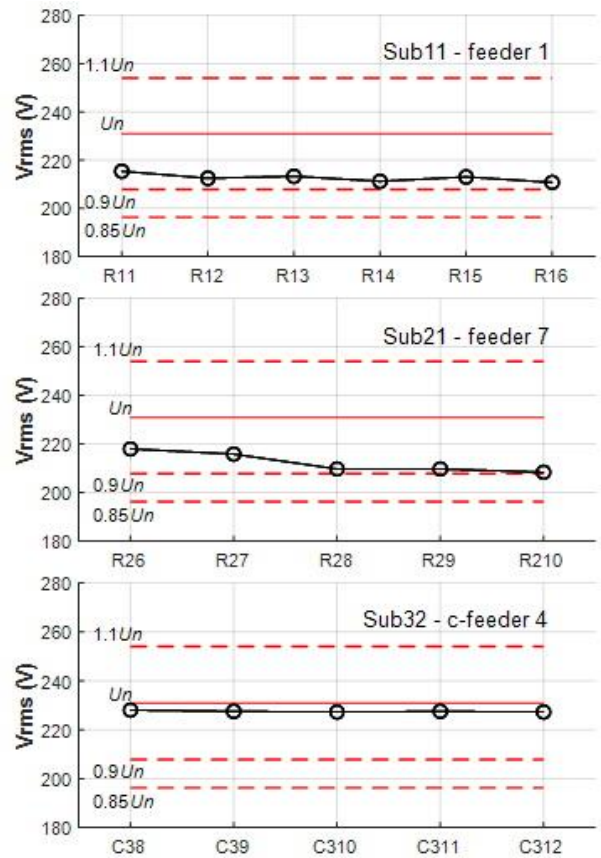


Fig. 5. Voltage RMS level profiles of different feeders – DN base case

Table 6. The ratings of VQ LP and VQ-f zones based on the voltage RMS level criteria – DN base case

VQ-f zones	VQ LP zones					
Sub11-feeder 1	R11	R12	R13	R14	R15	R16
good	good	good	good	good	good	good
Sub12-feeder 3	I11	I12	/	/	/	/
good	excellent	good	/	/	/	/
Sub12-feeder 4	I13	/	/	/	/	/
good	good	/	/	/	/	/
Sub21-feeder 5	R21	R22	/	/	/	/
excellent	excellent	excellent	/	/	/	/
Sub21-feeder 6	R23	R24	R25	/	/	/
good	excellent	good	good	/	/	/
Sub21-feeder 7	R26	R27	R28	R29	R210	/
good	good	good	good	good	good	/
Sub22-feeder 9	R211	R212	R213	R214	R215	/
good	good	good	good	good	good	/
Sub31-c-feeder 1	R31	R32	R33	/	/	/
excellent	excellent	excellent	excellent	/	/	/
Sub31-c-feeder 2	R34	R35	/	/	/	/
excellent	excellent	excellent	/	/	/	/
Sub31-c-feeder 3	R36	R37	/	/	/	/
excellent	excellent	excellent	/	/	/	/
Sub32-c-feeder 4	C38	C39	C310	C311	C312	/
excellent	excellent	excellent	excellent	excellent	excellent	/

5.2. Loads with low power factors

In the previous base case of DN operation, all loads were assumed to be with power factors of 0.95. The following power factors are assumed for different loads in this case study: 0.85 – residential suburban, 0.9 – residential urban, 0.85 – commercial, 0.7 – industrial I11, and 0.8 – industrial I12 and I13. The nominal active power loading has been also assumed.

Voltage RMS level profiles of feeders: Sub11 – feeder 1, Sub21 – feeder 7, and Sub12 – feeder 3 and 4, are shown in Fig. 6. The ratings of VQ-MV1 and VQ-MV2 zones are shown in Table 7, while the ratings of VQ LP and VQ-f zones are shown in Table 8. The ratings of VQ-f and VQ LP zones encapsulated by VQ-MV1 zone Sub3 are equal as in the DN base case (excellent). VQ rating in Sub3 has not been changed when compared to the DN base case.

According to the results from Fig.6, voltage RMS profile curves have been reduced in the case of loads with low power factors (blue lines). Since more reactive power was demanded by loads, the voltage drops increased when compared with the DN base case (black lines). The worst-case voltage reduction occurred on industrial feeders: Sub12-feeder 3 and Sub12-feeder 4.

The results related to the decision support system, shown in Tables 7 and 8, clearly indicate the deterioration of VQ based on the voltage RMS level criteria. Sub1 and Sub2 VQ-MV1 zones' ratings declined from good to moderate status. VQ ratings have declined in 3 VQ-MV2 zones and 5 VQ-f zones. Remote suburban residential loads and industrial loads have been affected the most by lower VQ ratings. DSO is alerted to perform a non-urgent control action by the decision support system. Since standard-defined voltage RMS thresholds have not been violated, required urgent control actions are not mandatory. Power factor correction procedures could be initiated to improve voltage RMS levels if available to DSO direct control. Manual voltage regulation at MV2/LV transformers could be considered to support AVR, especially if VQ ratings remain at the corresponding values for a longer period. VQ-MV1 zone Sub3 (urban area) has not been affected by lower VQ ratings.

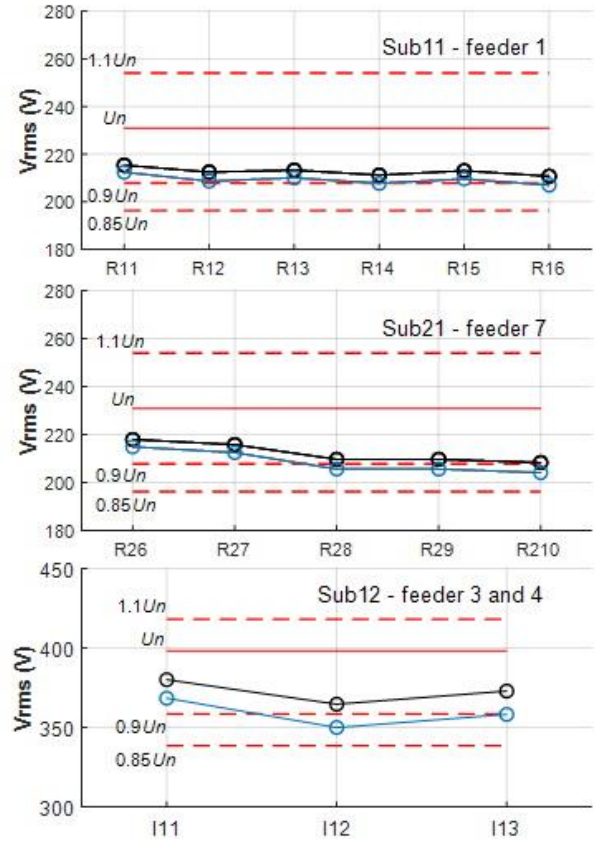


Fig. 6. Voltage RMS level profiles of different feeders – loads with low power factor case

Table 7. The ratings of VQ-MV1 and VQ-MV2 zones based on the voltage RMS level criteria – loads with low power factors case

VQ-MV1 zones	VQ-MV2 zones	zone rating
Sub1	Sub11	good
↓ moderate	Sub12	↓ moderate
Sub2	Sub21	↓ moderate
↓ moderate	Sub22	↓ moderate
Sub3	Sub31	excellent
excellent	Sub32	excellent

Table 8. The ratings of VQ LP and VQ-f zones based on the voltage RMS level criteria – loads with low power factors case

VQ-f zones	VQ LP zones					
Sub11-feeder 1	R11	R12	R13	R14	R15	R16
good	good	good	good	↓ moderate	good	↓ moderate
Sub12-feeder 3	I11	I12	/	/	/	/
↓ moderate	↓ good	↓ moderate	/	/	/	/
Sub12-feeder 4	I13	/	/	/	/	/
↓ moderate	↓ moderate	/	/	/	/	/
Sub21-feeder 5	R21	R22	/	/	/	/
↓ good	excellent	↓ good	/	/	/	/
Sub21-feeder 6	R23	R24	R25	/	/	/
good	excellent	good	good	/	/	/
Sub21-feeder 7	R26	R27	R28	R29	R210	/
↓ moderate	good	good	↓ moderate	↓ moderate	↓ moderate	/
Sub22-feeder 9	R211	R212	R213	R214	R215	/
↓ moderate	good	good	↓ moderate	↓ moderate	↓ moderate	/

5.3. Manual voltage regulation at MV2/LV transformers

In this simulation case study, the same power factors have been assumed for loads as in the previous case (loads with low power factors). Manual voltage regulation at MV2/LV transformers has been simulated in addition to existing AVR at HV/MV1 and MV1/MV2 transformers. The parameters of the manual tap changer are voltage step = 2.5% and the number of steps = ± 2 . Manual tap changers at all MV2/LV transformers belonging to Sub1 and Sub2 have been set to increase the secondary voltage by 2.5% and 5%, respectively. Manual voltage regulation has not been applied to MV2/LV transformers belonging to Sub3 since VQ ratings were already excellent in the previous case.

Voltage RMS level profiles of feeders: Sub11 – feeder 1, Sub21 – feeder 7, and Sub12 – feeder 3 and 4, are shown in Fig. 7. The ratings of VQ-MV1 and VQ-MV2 zones are shown in Table 9, while the ratings of VQ LP and VQ-f zones are shown in Table 10.

According to the results from Fig.8 the voltage RMS level profiles of all considered feeders improved after applying manual voltage regulation (green curves). Even the voltage RMS level of industrial load I12 is higher than the $0.9U_n$ threshold. VQ-MV1 zones Sub1 and Sub2 are rated with a good grade because of new improved rating of VQ-MV2 zones Sub12, Sub21, and Sub22 (Table 9). The ratings of VQ-f zones are back to the levels from the DN base operation case. According to the results in Table 10, there are no moderate ratings in the case of any VQ LP zone. The 4 VQ LP zones: R24, R26, R211, and R212 improved ratings to better levels than in the DN base operation case. The value of manual voltage regulation in terms of improving voltage RMS levels is clearly demonstrated. The decision support system rated overall wide area VQ in DN as good or excellent in the considered case. DSO is advised to only consider additional non-urgent control actions to further improve voltage RMS levels. DSO could initiate power factor correction procedures (if available) instead of manual voltage regulation to lower the voltage drop burden at MV2/LV transformers and save the tap changers' operations.

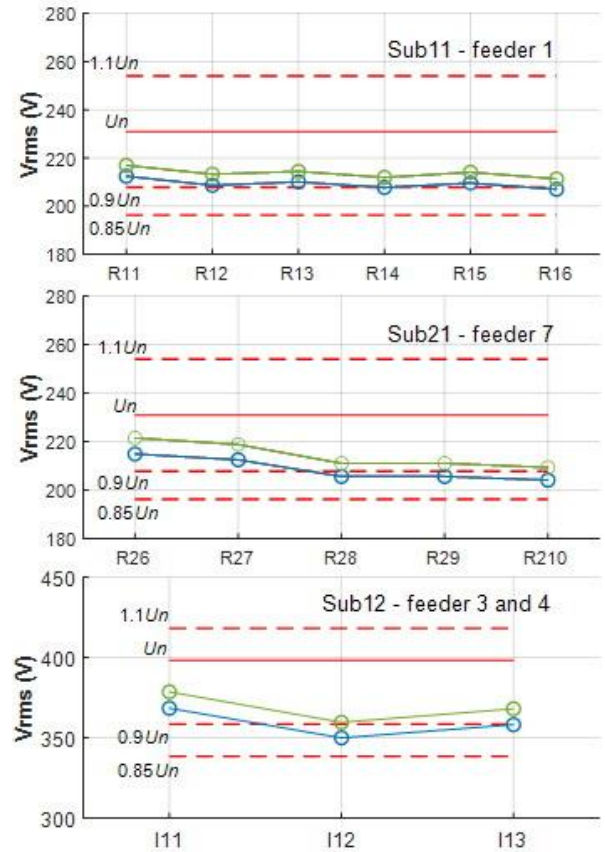


Fig. 7. Voltage RMS level profiles of different feeders – manual voltage regulation case

Table 9. The ratings of VQ-MV1 and VQ-MV2 zones based on the voltage RMS level criteria – manual voltage regulation case

VQ-MV1 zones	VQ-MV2 zones	zone rating
Sub1	Sub11	good
↑ good	Sub12	↑ good
Sub2	Sub21	↑ good
↑ good	Sub22	↑ good
Sub3	Sub31	excellent
excellent	Sub32	excellent

Table 10. The ratings of VQ LP and VQ-f zones based on the voltage RMS level criteria – manual voltage regulation case

VQ-f zones	VQ LP zones					
Sub11-feeder 1	R11	R12	R13	R14	R15	R16
good	good	good	good	↑ good	good	↑ good
Sub12-feeder 3	I11	I12	/	/	/	/
↑ good	↑ excellent	↑ good	/	/	/	/
Sub12-feeder 4	I13	/	/	/	/	/
↑ good	↑ good	/	/	/	/	/
Sub21-feeder 5	R21	R22	/	/	/	/
↑ excellent	excellent	↑ excellent	/	/	/	/
Sub21-feeder 6	R23	R24	R25	/	/	/
good	excellent	↑ excellent	good	/	/	/
Sub21-feeder 7	R26	R27	R28	R29	R210	/
↑ good	↑ excellent	good	↑ good	↑ good	↑ good	/
Sub22-feeder 9	R211	R212	R213	R214	R215	/
↑ good	↑ excellent	↑ excellent	↑ good	↑ good	↑ good	/

5.4. Unbalanced loads

Besides the voltage RMS level, the voltage unbalance represents an important VQ issue to deal with in DNs. The ratings of VQ zones based on voltage unbalance criteria are shown in Table 2 as a part of the proposed VQ decision support system.

In this simulation case study, unbalance loading has been assumed at the following suburban feeders: Sub11 – feeder 1, Sub21 – feeder 7, and Sub22 – feeder 9. All loads connected to Sub11 – feeder 1 have been assumed to be equally unbalanced. The following load active powers have been set per different phases: $P_A = P_n$, $P_B = 0.9P_n$, and $P_C = 0.8P_n$. The underloading has been set in phases B and C. Uniform unbalance conditions have been assumed for all loads connected to Sub21 – feeder 7. The following load active powers have been set per different phases: $P_A = P_n$, $P_B = P_n$, and $P_C = 0.6P_n$. The previous is the case of the significant underloading (40 %) in phase C. Finally, all loads connected to Sub22 – feeder 9 are assumed to be equally unbalanced with the following active powers set per different phases: $P_A = P_n$, $P_B = 0.2P_n$, and $P_C = 0.5P_n$. The previous is the case of the critical unbalance loading. All remaining loads in DN have been assumed to be balanced.

Voltage unbalance profiles of feeders: Sub11 – feeder 1, Sub21 – feeder 7, and Sub22 – feeder 9, are shown in Fig. 9. The ratings of VQ-MV1 and VQ-MV2 zones are shown in Table 11, while the ratings of VQ LP and VQ-f zones are shown in Table 12.

According to the results from Fig.8, the highest voltage unbalance is present at Sub22 – feeder 9. Even the adopted unbalance protection threshold is reached. In the case of Sub21 – feeder 7, the first unbalance threshold is reached for three remote loads. And finally, the voltage unbalance measured at all loading points is lower than the first unbalance threshold in the case of Sub11 – feeder 1.

VQ-MV1 zone Sub1 is rated with a good because VQ-MV2 zone Sub12 (industrial area) is rated with good (Table 11). VQ-f zone Sub11 – feeder 1 is rated with excellent as shown in Table 12 which is anticipated since the corresponding voltage unbalance feeder profile curve is below the first unbalance threshold (Fig. 8).

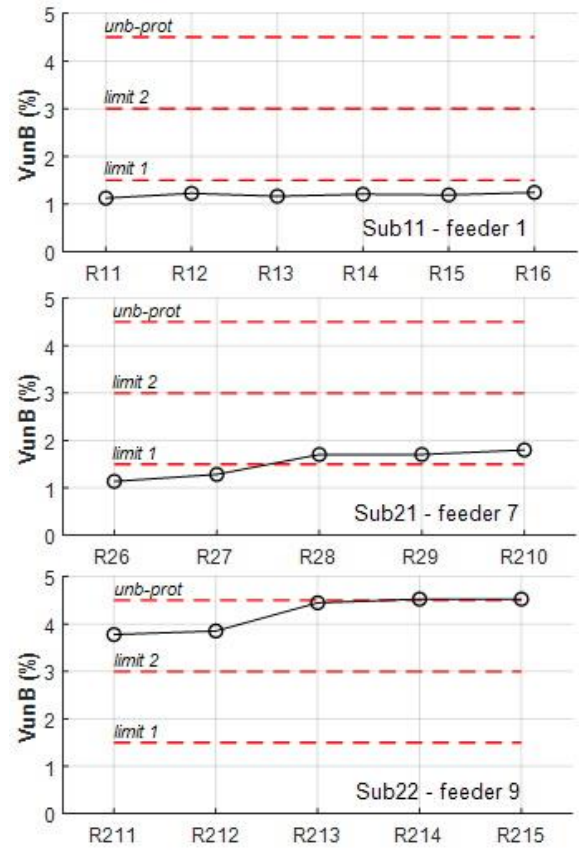


Fig. 8. Voltage unbalance profiles of different feeders – unbalanced loads case

Table 11. The ratings of VQ-MV1 and VQ-MV2 zones based on the voltage unbalance criteria – unbalanced loads case

VQ-MV1 zones	VQ-MV2 zones	zone rating
Sub1 good	Sub11	excellent
	Sub12	good
Sub2 ! critical	Sub21	good
	Sub22	! critical
Sub3 excellent	Sub31	excellent
	Sub32	excellent

Table 12. The ratings of VQ LP and VQ-f zones based on the voltage unbalance criteria – unbalanced loads case

VQ-f zones	VQ LP zones					
Sub11-feeder 1 excellent	R11 excellent	R12 excellent	R13 excellent	R14 excellent	R15 excellent	R16 excellent
Sub12-feeder 3 good	I11 good	I12 good	/	/	/	/
Sub12-feeder 4 good	I13 good	/	/	/	/	/
Sub21-feeder 5 excellent	R21 excellent	R22 excellent	/	/	/	/
Sub21-feeder 6 excellent	R23 excellent	R24 excellent	R25 excellent	/	/	/
Sub21-feeder 7 good	R26 excellent	R27 excellent	R28 good	R29 good	R210 good	/
Sub22-feeder 9 ! critical	R211 bad	R212 bad	R213 bad	R214 ! critical	R215 ! critical	/

VQ-f zones Sub12 – feeder 3 and 4 (industrial loads) are assigned with a good rating because of unbalance loading of Sub11 – feeder 1 (suburban residential loads). Voltage unbalance thresholds are set lower in the case of industrial loads by the decision support system. DSO is recommended to initialize a non-urgent control action to mitigate voltage unbalance in the considered area.

VQ-f zones Sub21 – feeder 5 and 6 (suburban residential loads) are rated with excellent, besides the rating of VQ-MV1 zone Sub2 which is critical as shown in Table 11. The rating critical of VQ-MV1 zone Sub2 is a consequence of the rating critical of VQ-MV2 zone Sub22. The worst rating of critical is assigned to VQ-f zone Sub22 – feeder 9 which is expected if observing the voltage unbalance profile of the corresponding feeder (Fig. 8). VQ LP zones R214 and R215 are rated critical. DSO is alerted to initiate an urgent control/protection action to mitigate the voltage unbalance. VQ-f zone Sub22 – feeder 7 is rated with good, but not significantly affecting the adjacent VQ-f zones Sub21 – feeder 5 and 6 (Table 12). VQ-MV1 zone Sub3 is not significantly affected by voltage unbalance, and it is rated as excellent (Table 11).

The considered simulation case study reveals the benefits of wide-area voltage unbalance assessment for DSO. Using the proposed decision support system DSO can detect critical VQ zones and simultaneously analyze the effects on other VQ zones in DN (wide-area propagation of high voltage unbalance).

5.5. Integration of solar power plant

This simulation case study analyzes the impact of 2 MW SPP integration at Sub22 – feeder 9, 3 km from Sub2 (Fig. 4), on voltage RMS levels and voltage THDs. The cases of nominal and low feeder loading have been considered. The low feeder loading has been assumed to be 10% of the nominal feeder loading.

2 MW SPP model embedded in Simulink platform [20] has been used in this analysis. The embedded model has been developed according to recommendations available in papers [21], [22]. The previous model has been slightly modified to support the analysis in this paper. The nominal frequency of 50 Hz has been set instead of the default frequency of 60 Hz. A reactive power regulator has been modified to enable SPP operation with an approximate unity power factor (> 0.99). The discrete simulation step has been set to 0.05 ms to exactly match the discrete simulation step used for the dSG model. SPP model is connected to Sub22 – feeder 9 through a 0.5/11 kV/kV substation transformer with a rated power of 2.25 MVA, as shown in Fig.4.

SPP consists of two PV arrays with rated powers equal to 1.5 MW and 0.5 MW at standard conditions (1000 W/m² irradiance and 25°C cell temperature). Boost converters are individually controlled by the maximum power point tracking (MPPT) perturb and observe techniques. A three-level neutral point clamped (NPC) inverter has been used to convert the 1000 V DC voltage to 500 V AC voltage. DC voltage regulation has been applied to maintain the DC voltage to a constant value of 1000 V.

Voltage RMS level and THD profile of Sub22 – feeder 9 are shown in Fig.9 and Fig.10, respectively, for the case studies: DN base case, integration of SPP with nominal feeder loading, and integration of SPP with low feeder loading.

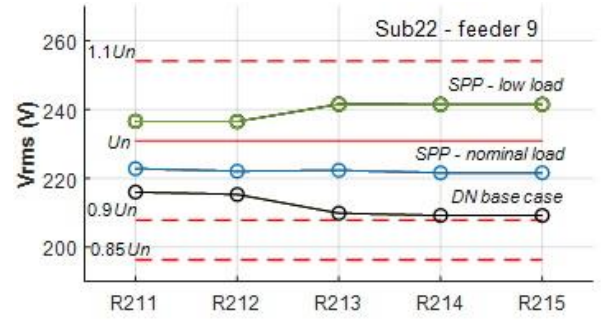


Fig. 9. Voltage RMS level profile of Sub22 – feeder 9 – DN base case and SPP integration cases

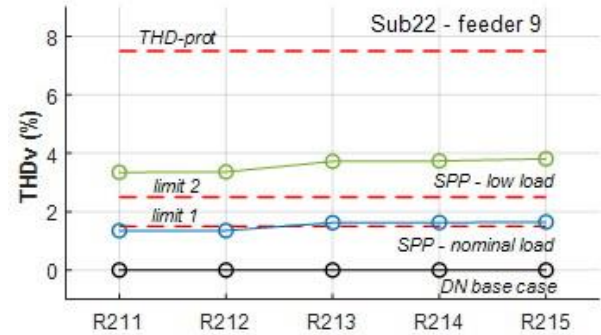


Fig. 10. Voltage THD profile of Sub22 – feeder 9 – DN base case and SPP integration cases

According to the results shown in Fig.9, the integration of SPP improves the voltage RMS profile of the nominally loaded feeder when compared to the DN base case. In the case of low feeder loading overvoltages occur after the integration of SPP. However, voltage RMS levels remain lower than the $1.1U_n$ threshold.

Since there are no nonlinear loads and power electronic converters, voltage THD values are negligible in the DN base case, as shown in Fig.10. The operation of power electronic converters causes an increase of voltage THD values after the integration of SPP. The first adopted THD limit is overreached for loads R213, R214, and R215 in the case of nominal feeder loading. The second adopted THD limit is overreached for every load in the case of low feeder loading.

The ratings of VQ LP zones encapsulated by VQ-f zone Sub22-feeder 9 based on the voltage RMS level for the cases of DN base operation and SPP integration with nominal and low feeder loading are shown in Table 13. The corresponding ratings based on voltage THD criteria are shown in Table 14. The results from Table 13 indicate the improvement of the VQ-f zone Sub22-feeder 9 rating based on the voltage RMS level criteria after the integration of SPP. VQ-f zone is rated excellent in both cases, nominal, and low feeder loading. Additionally, all VQ LP zones are rated as excellent in both previous cases. VQ-MV2 zone Sub22 is rated as excellent, and VQ-MV1 zone Sub2 is rated as good as in the DN base case. All remaining VQ zones in DN are rated the same as in the DN base case. No control actions are recommended to DSO; however, the overvoltage case should be monitored regularly. The significant effects of SPP integration are constrained only to VQ-f zone Sub22-feeder 9 (the ratings of other VQ zones are unchanged).

Table 13. The ratings of VQ LP zones encapsulated by VQ-f zone Sub22-feeder 9 based on the voltage RMS level criteria for the cases of DN base operation and SPP integration with nominal and low feeder loading

Simulation case study	VQ-f zone	VQ LP zones				
		R211	R212	R213	R214	R215
DN base operation case	good	good	good	good	good	good
SPP integration nominal feeder loading	excellent	excellent	excellent	excellent	excellent	excellent
SPP integration low feeder loading	excellent	excellent	excellent	excellent	excellent	excellent

Table 14. The ratings of VQ LP zones encapsulated by VQ-f zone Sub22-feeder 9 based on the voltage THD criteria for the cases of DN base operation and SPP integration with nominal and low feeder loading

Simulation case study	VQ-f zone	VQ LP zones				
		R211	R212	R213	R214	R215
DN base operation case	excellent	excellent	excellent	excellent	excellent	excellent
SPP integration nominal feeder loading	good	excellent	excellent	good	good	good
SPP integration low feeder loading	bad	bad	bad	bad	bad	bad

According to the results shown in Table. 14, SPP integration caused a decrease in VQ-f zone Sub22-feeder 9 rating based on voltage THD criteria. In the case of nominal feeder loading, VQ-f zone Sub22-feeder 9 is rated as good. VQ LP zones: R213, R214, and R215 are rated as good. VQ-MV2 zone Sub22 is rated as good, and consequently, VQ-MV1 zone Sub2 is also rated as good. Feeder's loads are only partially supplied by SPP power in the case of nominal loading. The remaining power is supplied from DN (Sub2). DSO is recommended to initiate a non-urgent control action to mitigate voltage harmonics.

In the case of low feeder loading, VQ-f zone Sub22-feeder 9 is rated as bad. All VQ LP zones are rated as bad. VQ-MV2 zone Sub22 is rated bad, and consequently, VQ-MV1 zone Sub2 is also rated bad. Feeder's loads are completely supplied by SPP power in the case of low loading. The power flow on feeder section f9s1 connecting SPP and Sub2 (Fig.4) is reversed in this case. The previous conditions cause higher voltage THD values at loading points, as shown in Fig. 11. DSO is recommended to initiate an urgent control action to mitigate voltage harmonics. The harmonic filtering procedures could be initiated if available to DSO. In the case of a fast enough response (remote filtering control), the following VQ 10-minute time snapshot could be improved. Since there is no significant voltage THD increase in all

remaining VQ zones in DN (the ratings remain unchanged when compared to the DN base case), DSO is aware that the voltage THD issue is constrained only to VQ-f zone Sub22-feeder 9.

5.6. Nonlinear loads

Several types of nonlinear loads have been considered in this simulation case study:

- Six-pulse voltage-source adjustable speed drive (ASD)
- Data center-personal computer (PC)
- Residential air conditioner (RAC)
- Fluorescent lighting-magnetic ballast (FL-MB)
- Fluorescent lighting-electronic ballast (FL-EB)

A harmonic current injection method has been used to model the nonlinear loads at harmonic frequencies. The odd and even harmonic frequencies have been considered with the upper limit of 19 x base frequency (19 x 50 Hz). It has been assumed that all nonlinear loads are connected at low voltage level sides of distribution transformers (400 V and 690 V). Harmonic current spectrums corresponding to the considered nonlinear loads are obtained from the measurement data available in [23]. The characteristics and locations of nonlinear loads in DN (Fig.4) are given in Table 15.

Table 15. The characteristics and locations of nonlinear loads in DN

Nonlinear load	Nominal quantities	Location in DN
ASD1	$P_n = 200 \text{ kW}, V_{in} = 690 \text{ V}$	I11 (I zone – Sub12 – feeder 3)
ASD2	$P_n = 300 \text{ kW}, V_{in} = 690 \text{ V}$	I13 (I zone – Sub12 – feeder 4)
PC1	$P_n = 50 \text{ kW}, V_{in} = 400 \text{ V}$	C39 (C zone – Sub32 – c-feeder 4)
PC2	$P_n = 60 \text{ kW}, V_{in} = 400 \text{ V}$	C310 (C zone – Sub32 – c-feeder 4)
RAC1	$P_n = 100 \text{ kW}, V_{in} = 400 \text{ V}$	R31 (R-urban zone – Sub31 – c-feeder 1)
RAC2	$P_n = 100 \text{ kW}, V_{in} = 400 \text{ V}$	R35 (R-urban zone – Sub31 – c-feeder 2)
FL-MB1	$P_n = 100 \text{ kW}, V_{in} = 400 \text{ V}$	R37 (R-urban zone – Sub31 – c-feeder 3)
FL-EB1	$P_n = 100 \text{ kW}, V_{in} = 400 \text{ V}$	C311 (C zone – Sub32 – c-feeder 4)

The ratings of VQ zones based on voltage THD criteria are shown in Table 3 as a part of the proposed VQ decision support system. Voltage THD profiles of the following feeders: Sub12 – feeder 3 and 4, Sub31 – c-feeder 1, and Sub32 – c-feeder 4, are shown in Fig. 11. The ratings of VQ-MV1 and VQ-MV2 zones are shown in Table 16, while the ratings of VQ LP and VQ-f zones are shown in Table 17.

According to the results shown in Fig.11, the voltage THD profile curve of Sub12 – feeder 3 (industrial loads I11 and I12) is above the second adopted limit, while the voltage THD profile curve of Sub12 – feeder 4 (industrial load I13) is above the first adopted limit. The increase of voltage THD values is caused by nonlinear loads ASD1 and ASD2. The voltage THD profile curve of Sub31 – c-feeder 1 (R-urban zone) is above the first adopted limit, and below the second adopted limit for residential loads. And finally, the voltage THD profile curve of Sub32 – c-feeder 4 (C-zone) is above the second adopted limit for loads C39 and C310, and above the first adopted limit for loads C38, C311, and C312.

VQ-MV1 zones Sub1 and Sub3 are rated as bad, as shown in Table 16. The previous rating is a consequence of the bad rating of VQ-MV2 zones Sub12, Sub31, and Sub32. All nonlinear loads are located in previous VQ zones. VQ-MV1 zone Sub2 is rated excellent since there are no nonlinear loads connected in this part of DN. According to the results shown in Table 17, all VQ-f zones in Sub1 and Sub3 are rated bad, except the VQ-f zone Sub11 – feeder 1 (excellent rating). VQ-f zone Sub11 – feeder 1 is electrically decoupled from the industrial area through two 33/11 kV/kV transformers, and there are no nonlinear loads in this zone. DSO is alerted to initiate urgent control actions in industrial VQ-f zones.

All VQ-f zones encapsulated by VQ-MV1 zone Sub3 are rated with bad, although the majority of the corresponding VQ LP zones are rated with good. The reason for the previous case is the violation of *THDv-bus-1-limit* at 11 kV busbars in Sub3 (2% for residential feeder loading and 3% for commercial feeder loading). The six remaining nonlinear loads are located in VQ-MV1 zone Sub3 (Table 15). DSO is alerted to initiate urgent control actions to mitigate voltage THD values. Remote filtering control could be initiated if available.

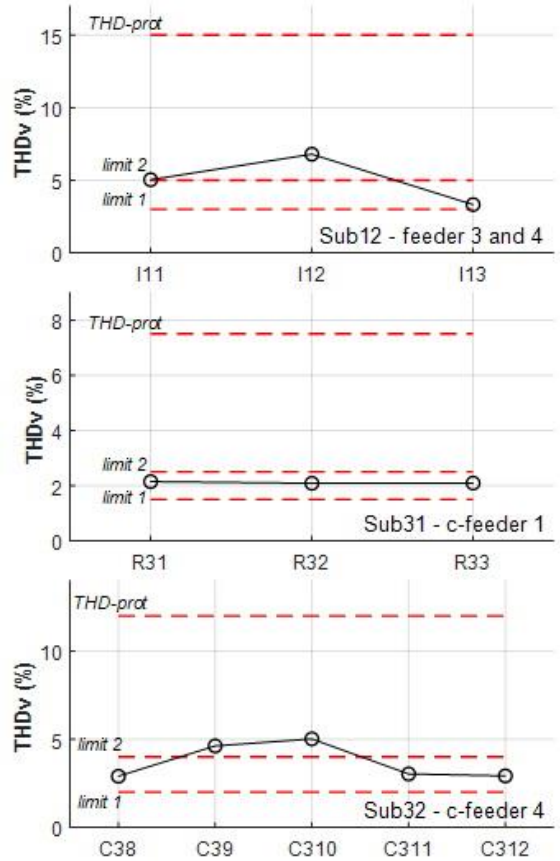


Fig. 11. Voltage THD profiles of different feeders – nonlinear loads case

Table 16. The ratings of VQ-MV1 and VQ-MV2 zones based on the voltage THD criteria – nonlinear loads case

VQ-MV1 zones	VQ-MV2 zones	zone rating
Sub1 bad	Sub11	excellent
	Sub12	bad
Sub2 excellent	Sub21	excellent
	Sub22	excellent
Sub3 bad	Sub31	bad
	Sub32	bad

Table 17. The ratings of VQ LP and VQ-f zones based on the voltage THD criteria – nonlinear loads case

VQ-f zones	VQ LP zones					
Sub11-feeder 1	R11	R12	R13	R14	R15	R16
excellent	excellent	excellent	excellent	excellent	excellent	excellent
Sub12-feeder 3	I11	I12	/	/	/	/
bad	bad	bad	/	/	/	/
Sub12-feeder 4	I13	/	/	/	/	/
bad	good	/	/	/	/	/
Sub31-c-feeder 1	R31	R32	R33	/	/	/
bad	good	good	good	/	/	/
Sub31-c-feeder 2	R34	R35	/	/	/	/
bad	good	good	/	/	/	/
Sub31-c-feeder 3	R36	R37	/	/	/	/
bad	good	good	/	/	/	/
Sub32-c-feeder 4	C38	C39	C310	C311	C312	/
bad	good	bad	bad	good	good	/

6. Discussions and future research

Zonal VQ indices are very beneficial even if all LP VQ indices are available (fully observable DN). If observing PQ indices only at node level it is possible to identify critical nodes, but it could be very challenging to identify the propagations of VQ issues through DN. Zonal indices could reveal DN vulnerabilities related to VQ issues. For example, the same VQ issue in some critical nodes could have higher or lower impact on the VQ of remaining nodes depending on their location in DN. If DSO only has information on VQ at the node level it would be difficult to make correct and timely control or protection actions, even in the case of fully observable DN. Usually, it is the case that control, or protection actions are limited to substations supplying the large number of nodes.

Zonal indices should be defined in such a way to avoid masking, where a zone can be declared as satisfactory when one or more nodes have severe non-compliances. For example, VQ-feeder zones - F (medium voltage (11 kV)) are rated as moderate only in the case if all the corresponding VQ-loading points - LP (low voltage (400 V)) are rated as moderate (100 %). Severe non-compliances usually impact the whole zones, and their corresponding rating should be reflective of the severe non-compliance. LP (node) severe non-compliances are also visible to DSO in any case if DN is fully observable. Thresholds for the zone indices (60% or 80% of LP per zone) should be reconsidered and adapted depending on the specific real DN case studies.

More complicated VQ indices, such as VQ index (VQI), unifying frequency, THD, and dissymmetry variations are not considered in this paper since they are not officially included in the relevant PQ standards yet. Future research will be focused on expanding the presented VQ to PQ evaluation (including more indices).

7. Conclusion

Wide area assessment of VQ in DN is analyzed in this paper. The proposed zonal approach provides a suitable methodology for the inclusion of active VQ management function in ADMS. Temporary VQ concept recommends the evaluation of VQ metrics in regular 10-minute time intervals, thus assuming the existence of AMI and enabling ICT. Temporary VQ concept is suitable for SG objectives related to DN self-awareness supported by more timely response of DSO. The proposed zonal wide area temporary VQ approach could incentivize DSO to plan a suitable and faster control actions considering spatiotemporal VQ state in DN. DSS based on the simple deterministic rules for temporary VQ evaluation is designed to be a suitable addition to ADMS when dealing with PQ issues in DN. DSS is able to evaluate temporary VQ state in different zones according to three different VQ indices (metrics): RMS level, unbalance, and THD. DSS is designed to be adaptable in dealing with different load types (residential, commercial, and industrial). The effectiveness of the proposed zonal approach with DSS is evaluated on various examples of VQ issues using the developed dSG model. Temporary VQ state is determined for the following simulation case studies: loads with low power factors, manual voltage regulation at MV/LV transformers, unbalanced loads, integration of SPP, and nonlinear loads. A suitable recommendations for DSO are obtained in all

considered case studies. The research results presented in this paper could initiate the new research ideas dealing with wide area PQ assessment in SG. More advanced DSS could be developed to include feeders with mixed load types, CQ metrics, DER-specific rules, etc.

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