The Measures of Power Quality in Energy Access and Cost-Effective Monitoring Tools as an Enabler

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***Abstract*—Monitoring power quality (PQ) in microgrids is essential for preventing connected appliances from malfunctioning, yet existing standards are often impractical in the context of energy access. Alternatively, pragmatic approaches such as the Multi-Tier Framework (MTF) and the Quality Assurance Framework for Mini-Grids (QAF) offer viable measures. Despite their practicality, both MTF and QAF necessitate at least voltage measurements for proper implementation, which can be challenging due to resource constraints in remote areas. Therefore, this study proposes the addition of cost-effective remote monitoring tools as a mandatory requirement of microgrid design. This is essential for PQ assessments that are suggested by MTF and QAF, while also enabling the additional assessments for transients and harmonics. Furthermore, proper PQ monitoring also facilitates timely interventions, thereby minimizing the possibility of system failure.**

Keywords—energy access, monitoring, MTF, power quality, QAF, remote areas

I. INTRODUCTION

The Sustainable Development Goal 7 aims to ensure universal access to affordable, reliable, and modern energy services by 2030. This goal includes providing electricity to the most rural and isolated communities around the world. To assess the quality of electricity connection, one commonly used method is the Multi-Tier Framework (MTF), which was introduced by the Energy Sector Management Assistance Program (ESMAP). Unlike the binary measure of 'connected' or 'not connected,' the MTF evaluates electricity access through seven attributes: capacity, availability, reliability, quality, affordability, legality, and health and safety. Each attribute is classified into six tiers, ranging from 0 to 5, indicating the level of energy access [1]. In most cases, the primary focus on assessing electricity access tends to be only on measuring the capacity and availability attributes. This is because assessing capacity and availability is relatively straightforward and can be accomplished through reviewing design documents, operation and maintenance plans, or site observations. In contrast, the remaining attributes often receive less attention, which is partly because they are more challenging to assess and require specific equipment or data that may not be readily available. This paper discusses one of those overlooked attributes, specifically the quality attribute.

Power quality (PQ) is an important aspect of an electrical system because it helps to determine the system's condition. Good PQ in an electrical system ensures a stable and efficient operation of electrical components connected to it, minimizing the possibility of damage or failure. Standards such as IEC 61000 and IEEE 519 provide comprehensive guidelines for defining PQ phenomena, their characteristics, and methods for measurement and evaluation. However, standards may not always be practical in the context of energy access due to the required measurement and processing needed to acquire and evaluate the data. On the other hand, to provide a more practical measure of PQ, the MTF defines the quality attribute as "… voltage problems do not prevent the use of desired appliances (voltage is within the parameters specified by the prevalent grid code)" [1]. Although the definition of the quality attribute in MTF is limited—since steady-state voltage value is only one aspect of power quality—its practical approach is essential for ease of implementation in the energy access context. Alternatively, a Quality Assurance Framework for Mini-Grids (QAF) was introduced a year after the MTF. The QAF, which was introduced by the National Renewable Energy Laboratory (NREL), expands on the MTF's quality attribute by adding measures such as the occurrence of voltage events and the availability of transient protection [2].

Building upon the MTF and QAF, this paper aims to identify practical measures that can adequately define the PQ of an electrical system and are feasible to implement in the energy access context. The work compares MTF and QAF and investigates the gaps between them. Furthermore, a reflection on the established standards is performed as the reference of an extensive PQ assessment. Through this analysis, this paper aims to bridge the simplified measures introduced in MTF and QAF, the comprehensive guidelines provided by the standards, and the practical needs of assessing the level of energy access, with a specific focus on the quality attribute.

II. POWER QUALITY ISSUES IN ENERGY ACCESS CONTEXT

Off-grid microgrids with renewable energy sources have emerged as one of the promising solutions to electrify the most isolated and remote areas. However, keeping them up and running poses significant challenges due to the characteristics of remote areas such as geographically challenging access, limited infrastructure and resources, and distance from economic activities [3]. In some instances, a minor failure can trigger a cascade of failures, leading to the entire system being down and abandoned. Some of those initial failures were caused by PQ issues such as in-rush current and voltage surge, which show the significance of electromagnetic compatibility (EMC) in the context [4]–[6]. Poor EMC leads to PQ issues, thus, it is essential to understand the conditions that could aggravate the EMC problems in remote microgrids. This includes observing the environmental challenges, constraints in building power infrastructure, demand characteristics, and availability of resources.

A. Harsh Environment and Ad-hoc Modifications

A study on an off-grid microgrid in Indonesia showed that harsh environments can eventually lead to PQ problems [7]. The observed site, which is located close to the sea, showed a high level of corroded equipment. Corroded equipment could aggravate EMC problems by reducing the effectiveness of the grounding connection. In this specific study, it was reported that one of the PV inverters failed due to a lightning current that could not be safely directed to the earth, which was allegedly caused by corroded grounding. To address the issue, an ad-hoc modification of cable rerouting was implemented to ensure that the critical load could still be operated despite the failed equipment. While the ad-hoc modification may partly restore the system functionality, it also potentially worsens or introduces additional EMC problems. In this case, the ad-hoc modification of rerouting load connection introduced a risk of overloading the inverter [7]. Even though the inverter's capacity seems sufficient to handle the additional load, there remains a possibility of exceeding its operating limits, particularly during peak load periods and due to the high inrush current when the critical load starts up.

B. Necessities of Long Cables and Nonlinear Appliances

Compared to the main grid with big power plants, substations, high and medium voltage transmissions, and robust distribution networks, remote microgrids are typically powered by a small diesel generator and/or renewable sources and battery systems. In some cases where the generation and demand are located relatively far away from each other, resources are limited, and building power infrastructure is expensive, using long low-voltage cables (over 1 km in length) can become a necessity to provide electricity. From the load's perspective, a long cable means a higher supply impedance that will result in exacerbated EMC issues when combined with nonlinear appliances (e.g., chargers, TVs, LED lamps, inverter air conditioners) [8]. On the other hand, employing medium voltage power distribution is typically used to transfer power over a long distance if the geographical situation is suitable and the investment is economically justified (e.g., the demand is substantial enough to generate profit). While this approach can reduce voltage drop and transmission losses, the presence of a transformer becomes an additional point of EMC problems, particularly due to the ever-increasing use of power electronics in household appliances. The presence of appliances with power electronics, also known as nonlinear appliances, introduces non-sinusoidal current that can distort the voltage along the line and at the transformer, potentially leading to disruption in other households and overheating the transformer [9]. This is a plausible presumption since many household appliances are now nonlinear.

C. Less Robust Appliances

Remote areas are naturally located far away from the main economic activities. Consequently, the appliances that are available in that particular market are likely to be less robust than the ones that can be found in urban areas. This discrepancy is not only due to the limited resources and supply chain constraints but also due to the limited financial capability of the locals to buy robust appliances, which are typically more expensive. Less robust appliances often have compromised features, leading to issues such as introducing a relatively high electromagnetic interference (EMI). For example, a study on commercially available dc power sources showed over-voltages when tested with a pulsed current, indicating one of the causes of premature battery failure due to poor voltage regulation capability [10]. Reflecting on a larger scale, employing a less robust inverter in a remote microgrid potentially introduces poor PQ across the entire system, which can undermine system operations such as equipment overheating, increased losses, and nuisance tripping [11]. This shows the correlation between the use of less robust equipment, PQ issues, and compromised system performance.

III. MEASURES OF POWER QUALITY

Assessing the PQ of microgrids in remote areas necessitates the use of practical and easily understandable measures. The measure should be implementable with relatively simple and affordable tools to ensure its feasibility. To offer practicality in assessing PQ in remote areas, there are two frameworks that can be used: the MTF and the QAF. This section compares these measures, investigates the gaps between them, and reflects on the available standards. The goal is to identify the more effective approaches for monitoring and improving PQ in remote areas, thus providing a reliable electricity supply.

A. Muti-Tier Framework

In MTF, Tier 5 quality attribute indicates that the household voltage is stable and within parameters specified in the prevalent grid code, appliances can operate properly, little to moderate impact in terms of financial losses or productivity or service delivery reduction, and no brightness issues perceived by user [1]. These indicators are aimed to be practical, thus they should be easy to observe and evaluate. Despite the offered practicality, some aspects remain vague. The elaboration on stable voltage given in MTF only mentions 'minimum' and 'adequate', which insinuates the value of a steady-state voltage. However, other crucial voltage parameters, such as transient occurrences and harmonics, are not specified. These two parameters are particularly important because even if the steady-state voltage is within the acceptable range, indicating a Tier 5, the repercussion of transients or the presence of harmonics would eventually lower the tier. This is due to the accelerated degradation of appliances caused by transients and harmonics, potentially leading to early failure [11].

B. Quality Assurance Framework for Mini-Grids

Unlike the MTF, the QAF defines energy access attributes into two main categories: (1) the level of service framework and (2) the accountability framework [2]. Despite the QAF's extensive definition compared to the MTF, it is designed only as a general guidance to maintain its flexibility in implementation. There is an inherent trade-off between comprehensiveness and flexibility within both the MTF and QAF, which is investigated in this study, focusing specifically on the service level of PQ. In classifying the service levels of PQ, QAF divides them into three categories: base, standard, and high. The base level ensures a minimum limit of safety, while the high level is comparable to a big and stable main grid. In addition to the MTF, QAF includes critical parameters such as transients, voltage variations, and frequency variations, providing a more comprehensive assessment of PQ by considering the cause of accelerated appliance degradation. Additionally, QAF also addresses PQ phenomena in DC systems, which is highly relevant since households with low-tier supply often use small dc standalone systems like pico-solar lights or solar home systems to provide electricity [12], [13].

In terms of indicators used in QAF, some of the parameters used to determine service levels (e.g., voltage imbalance, voltage and frequency variations, voltage drop, and percent ripple) require specialized measurement tools and trained personnel, as well as necessitate periodic monitoring.

Therefore, despite QAF's comprehensive and clear measures of PQ, the need for specialized equipment and periodic monitoring can be a drawback.

C. Applicable Standards

Standards offer a significantly more comprehensive framework than MTF and QAF, which one of the primary purposes is to set recommended limits or benchmarks for measurement, ensuring the stable operation of systems. For example, the IEC 61000 series, particularly IEC 61000-3, on limits including harmonic current emissions, voltage changes, voltage fluctuations, low-frequency electromagnetic immunity, and emissions. Similarly, IEEE standards provide specific guidelines related to PQ such as IEEE 519 on harmonics, IEEE 1662 on power electronic practice, IEEE 1547 on interconnection of distributed energy resources, IEEE 1453 on voltage fluctuation limits associated with flicker, and IEEE 1159 on PQ in general. However, these existing standards may not be fully applicable in remote areas due to unique conditions that limit the ability to perform the necessary measurements and monitoring for proper implementation as well as situations that exacerbate the EMC issues as elaborated in Section II. In addition, many low-tier households rely on small dc standalone systems for electricity, but standards for PQ in dc systems are considered to be underdefined [10], [14]. Existing standards on dc systems, such as those for maritime dc microgrids (IEEE Std 1709 and IEC 60092-101) and USB standards, do not adequately address the specific context of energy access [10]. This lack of relevance results in standards that are often inapplicable and fail to provide clear benchmarks for stable operation, thereby increasing the possibility of early failure. Therefore, it is crucial to adjust the current PQ standards for ac systems to incorporate the conditions of remote systems and to develop robust PQ standards for dc systems making them more relevant and applicable in the energy access context.

IV. DISCUSSION

Ensuring EMC is crucial for the reliable operation of a microgrid throughout its designed lifespan. While assessing the PQ of the microgrids is not the only approach, it plays a significant role in ensuring EMC by verifying that the evaluated parameters comply with relevant standards. Standards recommend an extensive assessment, which yields comprehensive information that helps better identify and address EMC issues. However, conducting such extensive assessments is often not applicable in remote areas, one of the reasons is that the results will not be repeatable due to the environment that cannot be controlled and unpredictable.

In contrast, frameworks such as the MTF and QAF offer a more pragmatic approach on PQ assessment. These frameworks provide less exhaustive evaluations compared to the existing standards. A comparative overview of MTF and QAF, focusing on their quality attributes, is summarized in Table I. An example of implementing the MTF to measure energy access was conducted in Maluku and North Maluku, Indonesia [4], with the results shown in Fig. 1. Specifically, in terms of the quality attribute, 98% of the assessed population have voltage fluctuations of less than 10%, meeting the criteria for Tier 5. However, despite the high percentage of Tier 5 quality, early failures were still found. Some of these failures were caused by PQ issues [4]. This highlights that the parameter of voltage variation is insufficient to evaluate the system's overall PQ, hence it is unable to comprehensively capture PQ problems. Furthermore, the limited availability of data for the MTF assessment—restricted to monthly voltage measurements at the supply feeder [4], which is typical in such contexts— further contributes to its inability to fully capture the PQ problems.

On the other hand, reflecting on the base level of QAF to MTF, while QAF offers more definite criteria to classify the system's service level, its lowest defined service level corresponds only to Tiers 4 and 5 in the MTF. This implies that systems with quality attributes below Tier 4 are considered unsafe and do not fulfill the minimum PQ requirement. Furthermore, QAF lacks specific classifications for systems that do not meet the base level of service, potentially leaving a gap in addressing lower-tier systems.

Both MTF and QAF necessitate measurement and monitoring to properly implement them. Therefore, incorporating a monitoring system is essential as an 'enabler'. Power analyzer is one of the measurement devices that is typically used to evaluate PQ, however, its bulky design and expensive price might not be suitable for system monitoring in remote areas. On the other hand, multimeter are relatively cheap and most likely to be available on site, but those are not

TABLE I. COMPARISON OF MTF ON HOUSEHOLD SUPPLY [1] AND QAF [2]

	Multi-Tier Framework (MTF) on household supply	**Quality Assurance Framework for Mini-Grids (QAF)**
Purpose	To assess capabilities of household energy systems.	To provide guidelines to ensure the mini-grid meets a specified level of service.
Evaluated parameters	7 attributes: capacity, availability, reliability, quality, affordability, legality, and health and safety.	- Service level framework: quality, availablity, reliability. - Accountability framework: customer and utility accountability.
Classifications	Tier 0–5 for all attributes.	- Quality and reliabiltiy: base, standard, high. - Capacity: level 1–6. - Availability: level 1–3 or 4.
Overlap	Attributes: capacity, availability, reliability, quality.	Level of services: availablity (this includes capacity), reliability, quality.
	Quality attribute	
Indicators	Tier 5: voltage is stable and within parameters specified in prevalent grid code, appliances can operate properly, little to moderate impact in terms of financial losses or productivity or service delivery reduction, and no brightness issues perceived by user. Otherwise, Tier 0.	A limit value is set for base, standard, and high service level for the following indicators, - AC: voltage imbalance, transients, voltage and frequency variations, voltage drop. - DC: voltage drop, ripple, switching noise, faults per day.
Assessment method	Except for the voltage indicator which require measurements, the other indicators can be obtained by reviewing design documents, operation and maintenance plans, or site observations.	Mostly require measurements and monitoring except for transients and DC ripple, which can be done through reviewing design document or site observation.
Note	Narrowly defined but more practical.	- Only mapped Tier 5 in MTF. - More comprehensive, better PQ evaluation, but less practical.

Fig 1. MTF evaluation in Maluku and North Maluku, Indonesia [4]

equipped with the capability for data recording, which is essential in monitoring. Although metering system such as a power and energy meter is usually installed on site and capable to measure an record the required parameters, it is not easy to install and usually only available at the feeder supply. Therefore, neither MTF nor QAF can be effectively implemented with those typical measurement devices.

Given the constraints of limited resources, the measurement and monitoring tools must be cost-effective, durable, and easy to install. One example of such remote monitoring tools is developed in [15], which aims to provide alternative between high-end power analyzers and low-cost multimeters. The PQ sensor is capable of monitoring root-mean-square voltage and current, frequency, phase angle, power factor, active power, reactive power, and detecting events such as voltage sags and swells. The recorded data then sent to the serve, which can be accessed remotely. Moreover, its compact, plug-and-play design makes the PQ sensor particularly suitable for supporting the implementation of MTF or QAF in evaluating quality attributes in remote areas.

Fig. 2 shows an example of monitored voltage using the PQ sensor, highlighting a similar trend across the grid but with different voltage levels and localized fluctuations due to appliance usage, which is one of the important observation that can be further processed for system analysis. This study proposes the integration of such a monitoring tool that is capable of remotely detecting, measuring, and monitoring indicators specified in QAF, including additional indicators such as harmonics and transients. However, rather than incorporating the presence of the monitoring tool as another indicator for classifying service levels or tiers, it should be considered a mandatory requirement as it is needed to perform the assessment. This enables the implementation of practical frameworks such as MTF and QAF, with extended capability of assessing more PQ parameters that are recommended by existing standards.

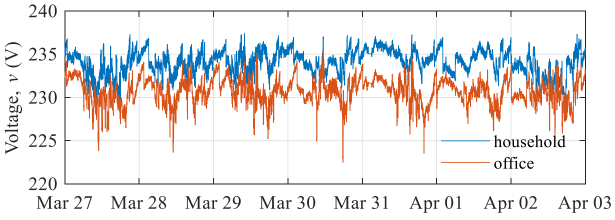

Fig 2. Measured voltage in a household and an office building connected to the same grid in the Netherlands.

Similar to MTF or QAF, which require trained personnel for in-site assessments, the monitoring tool also needs to be overseen by skilled personnel (or computer and processing). However, this can be done remotely because the device is designed for easy plug-and-play use by the general public, hence anyone can get it started. The measured data will then automatically sent to the cloud, allowing remote access for processing. Unlike MTF and QAF, which are one-time evaluations that overlook system dynamics, the monitoring tool provides real-time measurements, allowing for timely intervention if performance deterioration is detected. For instance, it allows for the detection of increasing harmonics, more frequent voltage variations, or higher voltage imbalances, which could indicate a need for maintenance or upgrades to maintain the desired service level. This bridges the gap between the standardized measurements and the very pragmatic approach introduced in MTF or QAF, enabling an actual and real-time in-situ evaluation.

V. CONCLUSION

Ideally, maintaining good PQ prevents appliances connected to the microgrid from malfunctioning. Good PQ can be achieved by ensuring that the system design complies with applicable standards. However, standards provide a comprehensive and detailed assessment of PQ, which unfortunately often not applicable in the context of energy access. Alternatively, there are two more pragmatic approaches that offer practicality in measuring the level of energy access i.e., MTF and QAF. Although the MTF is indirectly related to PQ, it cannot adequately assess PQ. While the QAF does measure PQ, it should incorporate monitoring practices. Compared to MTF, QAF evaluates more PQ parameters, thus providing a better system evaluation. However, it compromises the QAF's practicality.

Nevertheless, both MTF and QAF are considered more relevant for the energy access context compared to the existing standards.

Despite the practicality offered by both MTF and QAF, their implementation still necessitates PQ measurements and monitoring. This can be challenging in remote areas where the required measurement tools may not be readily available. To address this issue, this study proposes to add cost-effective monitoring tools as a mandatory requirement in the design of remote microgrids. This is an essential enabler for conducting proper PQ assessments that are suggested by MTF and QAF, which also enables extended capabilities for evaluating additional parameters such as transients and harmonics defined in existing standards. Furthermore, properly monitoring PQ parameters facilitates timely interventions minimizing the possibility of deteriorating system performance, which is important to ensure the microgrid's reliability.

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