A Co-Simulation Platform for Microgrid Integration into Transmission System - Power Quality Study

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***Abstract*— Microgrids open up a new arena of power generation, distribution, and consumption. Microgrids have the ability to deliver reliable and clean power. It enhances grid reliability through its ability to isolate from the utility grid under any abnormal conditions and work in standalone mode, then reconnect and synchronize again with the grid without load interruption. The growing installation of renewable energy resources creates higher interactions between transmission and distribution systems, which increases fears of the impact of power electronics devices on the stability and power quality metrics of the utility grid. Such studies require complete modeling and simulation of the power electronics interfacing microgrids with the power system. This paper presents a co-simulation framework for a microgrid connection with a transmission system. The framework uses Power System Simulator for Engineering (PSS/E) as a power system analysis tool and electromagnetic transient simulator (PSCAD) which is used to model the microgrid system and its control. The paper also investigates the impact of a large-scale microgrid on the power quality of the grid network. The total harmonic distortion (THD) in the current and voltage at the point of common coupling (PCC) is investigated and the obtained results are compared with the limits specified by the international standards. The co-simulation results are aimed to show that the inclusion of Distributed Energy Resources (DERs) in the transmission system works within the allowed limits and standards.**

Keywords*— *Microgrid, transmission system, co-simulation, power quality, PSCAD, PSS/E.

I. INTRODUCTION

In recent years, the amalgamation of renewable energy sources with power systems ascends due to various reasons such as the increased awareness of environmental impacts, the need for increased energy security, and economical reasons [1]. The evolution of power grid infrastructure relies on changing the model of centralized power generation to a more distributed and renewable energy-based. A microgrid paradigm consisting of small-scale and distributed generators is able to transform a traditional power system into a smaller and modular network [2]. A microgrid is an active distribution system composed of distributed generation resources, particularly renewable energy generators such as solar photovoltaic (PV) panels and wind turbines, different types of distributed loads, and intermediate energy storage units. Emerging power electronic devices in a microgrid can ensure a better quality of power supply and better efficiency of energy [3]. The microgrid offers a wide range of benefits for both power networks and customers. From a power network perspective, the microgrid supports a flexible and efficient electric grid because it is a controlled unit, and can be exploited as a distributed load. From the customer perspective, the microgrid enhances the resilience of the electric grid with a quick response to power outages, provides higher local reliability, and increases the efficiency of the power grid [4]. Some of the most paramount microgrid advantages include plug and play functionality either in the grid-connected or islanded operation modes, easily filling the gap between the significant increase in demand and supply [5], improving management and control functionalities of the electricity supply, and supporting the high penetration of different distributed renewable energy generation without requiring re-design of the distribution system [6].

Despite the umpteen benefits of microgrids, still, some technical challenges affect their global spread. The main challenges of the deployment of microgrids are protection, security, power quality (PQ), smooth transition between grid-connected and islanded modes, voltage and frequency control, plug-and-play operation, energy management, scalability, and higher-level system stability [7].

The power quality has been identified as one of the most important challenges facing microgrids. The microgrid must guarantee good PQ when operating in both grid-connected and islanded modes. Achieving an acceptable range of PQ needs to maintain the supplied power almost sinusoidal for rated voltage and frequency. Identification of power quality can be done by checking the harmonic level, voltage unbalances, and frequency deviation. Integrating microgrid to the power grid requires controlling the PQ to ensure supplying power to the consumers efficiently during the transition from grid-connected to the islanded mode of operation. This is particularly important at the point of common coupling with the grid [8]. In this direction, several standards have been published to ensure harmonic control, IEEE Std 519-2014 [9], practice for penetration of the photovoltaic (PV) system, IEEE Std 929- 2000 [10], and for monitoring electric PQ in power system and microgrids, IEEE Standard 1159-2019 [11], [12]. The main types of PQ distortions described in EN-50160 have been chosen as the baseline for the proposed model. Furthermore, many studies have been focused on mitigating various PQ issues such as voltage unbalance, harmonic level, and power factor. Additionally, the identification of different types of PQ disturbances from occurring events [13]-[15]. Nevertheless, none of these studies have considered the co-simulation between two different models. One represents the power electronics-based distributed energy resources (DERs) and their control and management behaviors in the microgrid. The other model represents the complexity of the generating power stations and transmission/distribution systems, on which the current PQ assessment is focused. It is important to note that the level of detail required for such hybrid simulations cannot be achieved by a single platform. Therefore, a co-simulation of large-scale power systems with microgrids is investigated in this paper using an electromagnetic transient simulator (PSCAD), and Power

System Simulator for Engineering (PSSE). The main objective of the proposed work is to monitor and assess the PQ of a microgrid based on harmonic distortion levels. The proposed assessment complies with IEEE 519 harmonic and the EN 50610 standards for interconnections between distributed resources and power systems. This investigation is a critical step for mitigating the harmonics generated in microgrid integration into the power utility grid. The paper's organization is as follows; Section II represents a detailed model of the microgrid and its control, Section III describes the used IEEE-39 Bus system, and Section IV shows the co-simulation model. Section V presents the comprehensive analysis of microgrid power quality disturbances, and finally, section VI presents the simulation results. The conclusion is given in section VII.

II. Microgrid System Modeling.

The microgrid is an integrated energy system consisting of interconnected loads and distributed energy resources, which can operate in grid-connected mode and islanded modes. It is a combination of distributed generation sources, static and dynamic loads, and energy storage, interfaced through fast-acting interconnections. The interconnection between microgrids and the power grid is usually carried out by switchgear and power electronic interfaces. Such a microgrid should be modeled with its interfacing elements with the grid to perform the proposed study.

TABLE I. Distribution Energy resources

Distribution Unit	Rated voltage (Kv)	Reted frequency (Hz)	Active Power (MW)	Reactive Power (MVAR)
Diesel Engine	13.86	60	2.00	0.8
Wind Turbine	0.69	60	2.50	0.3
Solar PV	0.460	60	0.25	0.1
Solar PV coupled with Battery system	0.600	60	0.25	0.1

The microgrid model is built in PSCAD, where two hybrid renewable energy sources, wind and PV, are used. Since the operation of the battery energy storage system is one of the important elements to include, a detailed model of a Li-ion battery is considered which is coupled with a solar PV. The complete specifications of the grid-connected system are illustrated in Table I

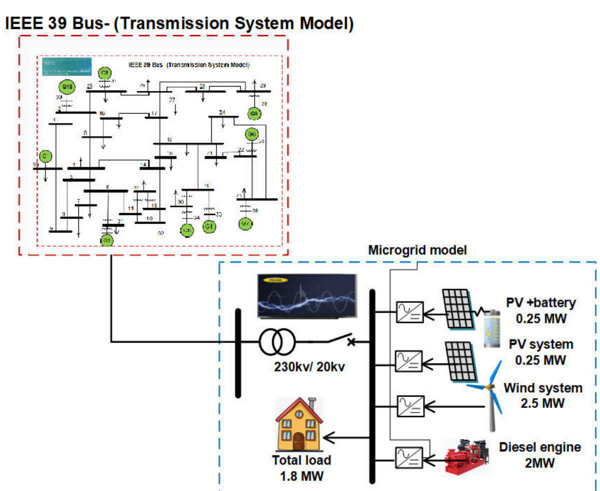

Fig.1 Schematic diagram of the integrated microgrid

The behavior of balanced loads is considered in the proposed microgrid network. Each distributed generation system in the microgrid is rated at 20 kV. The microgrid is connected to the IEEE-39 bus system through a 20/230 kV transformer. The microgrid is composed of a 0.25MW photovoltaic system, a Type 3 DFIG-based Wind farm of 2.5 MW, another solar with a battery system of 0.25MW, and a diesel engine of 2MW to which all the community loads of 1.8 MW are connected as shown in Fig.1.

A. Diesel Generator.

The diesel generator is a controllable energy source that has been modeled in PSCAD. The synchronous generator is driven by a small hydro generator, which is initialized to operate at its rated conditions. The synchronous generator rated 12 MVA, 13.86 kV, 60 Hz, diesel generator model is connected to a 20 kV network through a step-up, Y /Y 3 MVA transformer.

B. Doubly-fed induction generator (DFIG) wind turbines

The wind turbine power generation technologies are intermittent and non-dispatchable because they are variable power sources. The doubly-fed induction generator (DFIG) is considered the most widely used technology, due to its variable-speed operation and independent control of active and reactive power. A variable-speed wind turbine with a doubly-fed wound-rotor induction generator is employed. The wound-rotor induction generator is rated 2.5 MVA and the output line voltage of the generator is 0.69 kV, 60 Hz, which is connected to the step-up transformer rated 0.69/209kV, 5.5MVA, and then supplied to the load. This wind turbine is located 5km away from the microgrid network and is connected through a 20kV transmission line, a three-phase PI section transmission model is introduced as shown in Fig.2.

C. *Solar Power (Photovoltaic Array)*

A photovoltaic (PV) system is composed of panels combined with a maximum power point tracking DC-DC conversion, and an inverter, which converts DC voltage to an AC voltage with a magnitude of approximately 460 V and a frequency of 60 Hz. The voltage is then stepped up using a step-up transformer 460 V/20 kV and linked to the microgrid. The solar irradiation and ambient temperature are included in the PV model as input data.

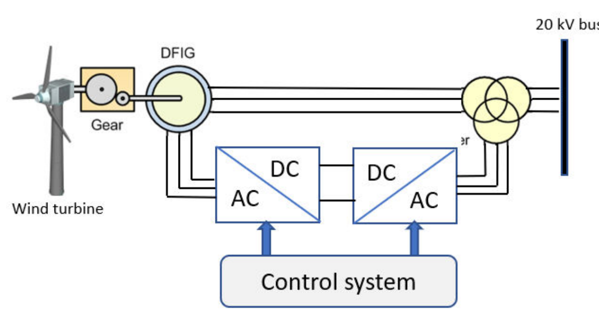

Fig.2 Wind turbine

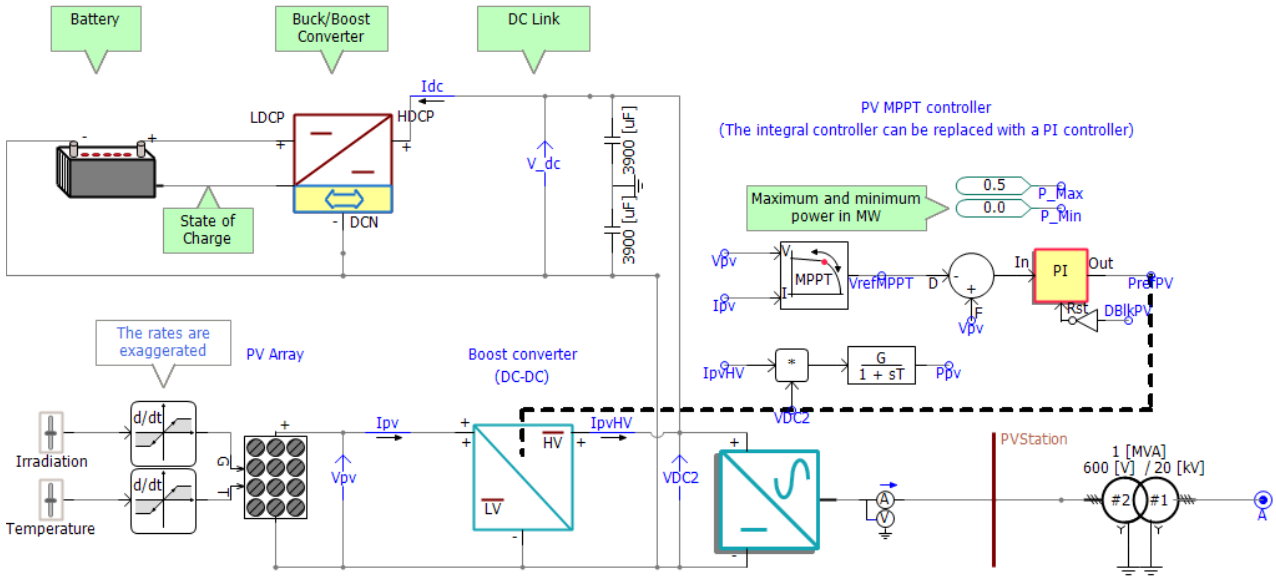

Fig.3 Solar photovoltaic with a battery storage

D. *Photovoltaic Array with Battery System*

The integration of different types of energy generation systems, as well as battery systems, is defined as a hybrid energy system. The model consists of a photovoltaic array along with a Lithium-ion (Li-Ion) battery. The PV array is used for charging the battery. A Li-Ion battery is used to effectively store the extra power produced by the PV. The generating power is delivered to the load. The control of the battery system is connected with a DC-DC converter (Buck/Boost converter), which switched modes based on the status of charge for the battery. Then connected to the DC-AC converter via a DC link system of 3900μF capacitors as shown in Fig. 3. The output AC voltage level with a magnitude of approximately 600V and a frequency of 60Hz is established on electrical interconnection points. The voltage is then stepped up using a 600 V/20 kV step-up transformer and sent to the system.

III. Transmission System Network Model

The IEEE 39 bus system is coupled with the microgrid and is analyzed under both operation modes, i.e., islanding and grid-connected. The system consists of 10 generators and 46 transmission lines, 12 transformers, and 10 loads. The transmission system network has been built with detailed machine models for dynamic analysis. Fig. 4 depicts the model of the IEEE 39-bus system using the PSS/E software. PSCAD is used as a simulation tool for the microgrid system and also the power electronics interference, while PSS/E is used as the power system simulation modeling tool to simulate electrical power transmission networks. The software E-TRAN is utilized to provide interfacing between PSCAD and PSS/E. The analysis of the transmission system and the microgrid is typically performed separately as two decoupled systems.

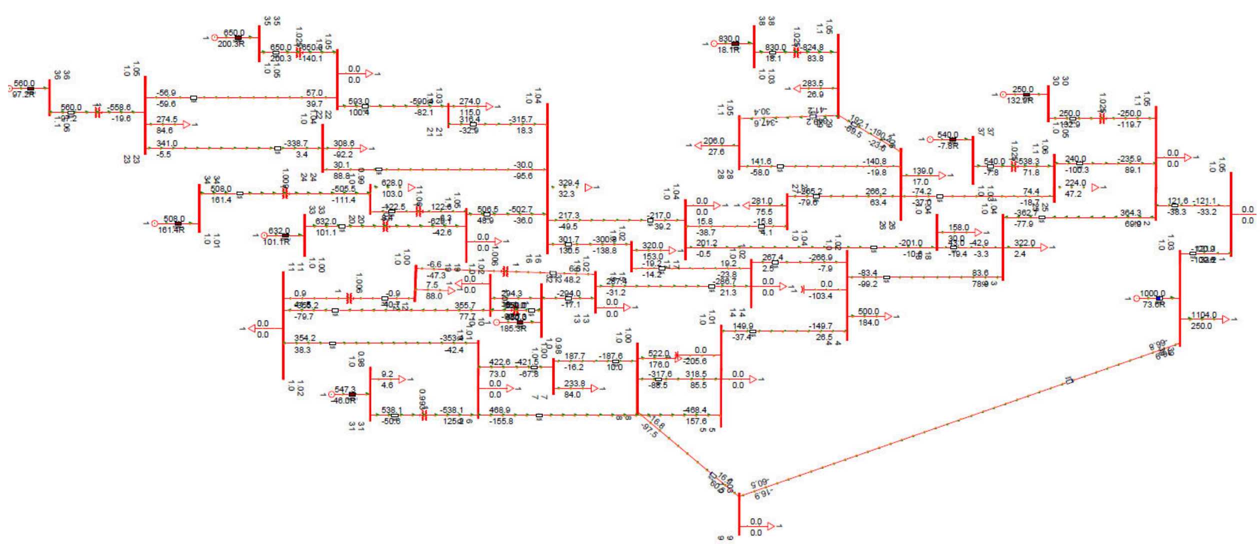

Fig.4 Transmission system network model

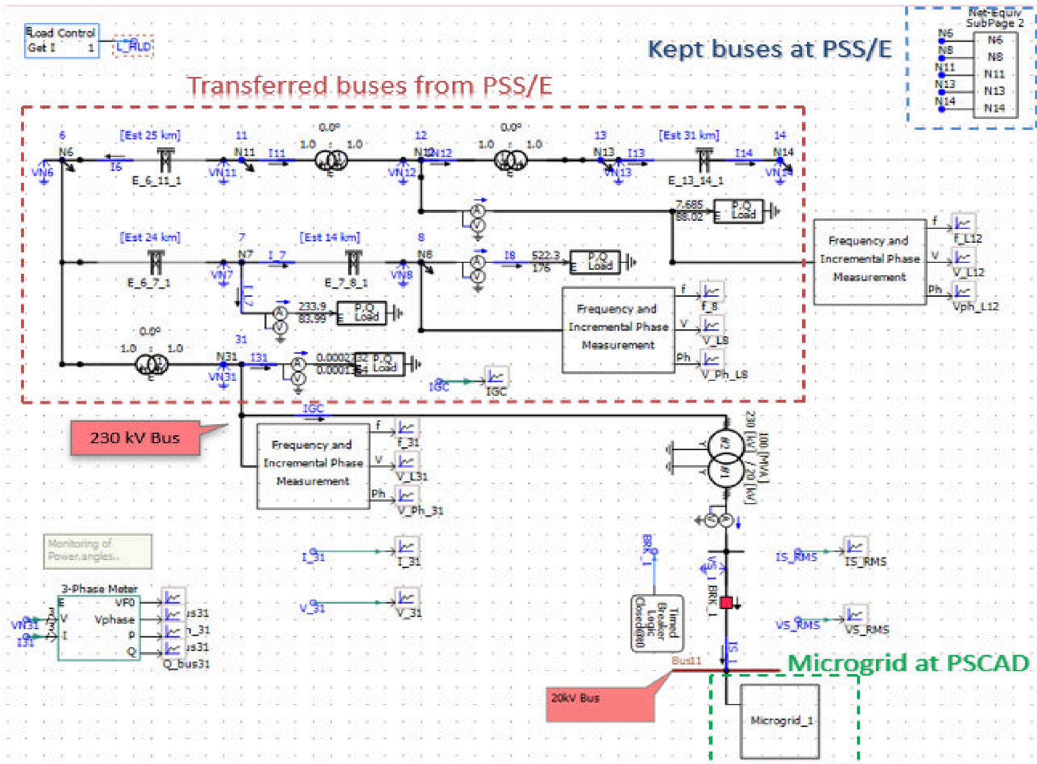

Fig.5 Transmission-Microgrid Co-Simulation Model

IV. Co-Simulation Model

The developed test system can be used to study transmission and microgrid interactions. PSS/E-PSCAD co-simulation module is a hybrid simulation interface between PSCAD and PSS®E programs [17]. This work presents the development of a co-simulation framework to allow microgrid network equivalents in PSCAD to communicate with a PSS/E simulation. During the simulation, the PSCAD system equivalent, which simulates the detailed distributed generating units gets updated from the PSS/E voltage, angle, and frequency for the transmission system model (IEEE-39 bus test system), and the PSS®E system gets updated from what happens in PSCAD. Once the hybrid simulation is set up, both programs run in parallel, communicating and updating each other. The IEEE 39-bus transmission system is connected through a 230/20 kV step-down transformer to the microgrid at the point of common coupling (PCC) of the designed microgrid as shown in Fig. 5.

V. Power Quality Analysis

Among the consequences of using microgrids, power quality has gotten the most attention during coupling microgrids to the main grid. PQ issues have recently become more important, given the higher utilization of MGs and the importance of reliable power to meet the needs of customers. Assessing the power quality considering the microgrid coupling is essential for system stability.

The most common types of PQ problems are voltage sag (dip), voltage swell, voltage unbalance, voltage spike, and harmonics [18]. The switching techniques that are used in converter technology in DG units are the main reason for harmonics in a microgrid. For transmission systems which already being injected with harmonics via the non-linear loads in the system. Connecting the two systems could add stress to the power quality of the whole power grid.

The proposed co-simulation framework is created to investigate this aspect and is validated with the consideration of the IEEE 39 bus transmission line system model. The used microgrid is connected to bus number (31) at the transmission line system as illustrated in Fig. 5. The power quality is investigated to assess the power quality based on THD analysis at the (PCC) point. THD is a measurement of the distortion of a voltage or current due to harmonics in the signal. When comes to the interconnection of DERs with electric power systems, some metrics should be achieved to maintain acceptable PQ levels. Regulating standards IEEE Std 519-2014 and the EN 50610 standards are used as references for this study. Based on the standards, the harmonics phenomenon is evaluated for voltage and current and the THD and TRD indexes are used, respectively. Eq. (1), and (2) depict the used expressions.

$$THD_V = \frac{\sqrt{\sum_{h>1}^{50} V_h^2}}{V_1} \times 100\% \qquad (1)$$

$$TRD = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_{rated}} \times 100\% \qquad (2)$$

VI. Simulation results

To calculate the THD, both current and voltage are measured at the PCC point, the point at which the microgrid

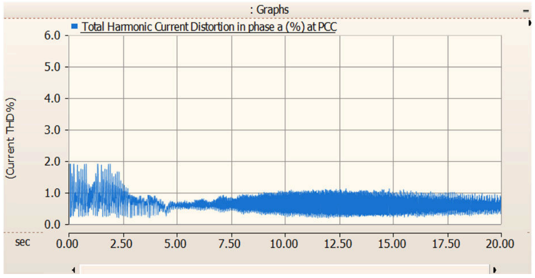

Fig.6 THD (%) of the current in phase a at PCC

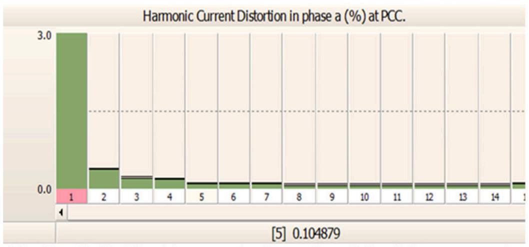

Fig.7 Individual harmonic distortion (%) of the current in phase a at PCC

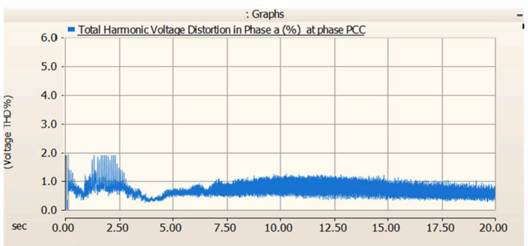

Fig.8 THD (%) of the voltage in phase a at PCC

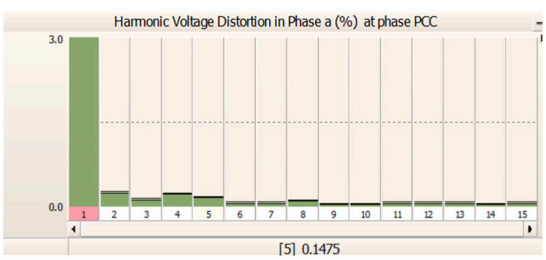

Fig.9 Individual harmonic distortion (%) of the voltage in phase "A" at PCC.

is tied with the transmission system. In the PSCAD model, PCC lies between the transformer and the microgrid at the medium voltage (MV) side, 20 kV. To determine the harmonics change with time for both signals current and voltage at PCC in the three ohases (a,b and c), the Fast Fourier Transform (FFT) block in PSCAD has been used. Then it's output signal fed to the Harmonic Distortion block to get both the total and individual harmonic distortion in percentage (%). FFT block was configured to output the magnitude of 15 harmonics with the fundamental frequency at 60 Hz. The current harmonics had a high impact on the interconnection of the microgrid since its value increased significantly. The IEEE Std 519-2014 specifies less than 5% of the fundamental current frequency. For the individual harmonics, all even harmonics should be less than 25 % of the odd harmonic limits. The current distortion limits as a percentage of the fundamental current frequency for odd harmonics should be less than 4% for (3rd) to (9th), and less than 2 % for (11th) to

TABLE II. THE MAGNITUDE OF INDIVIDUAL HARMONIC DISTORTION (%) OF THE CURRENT IN PHASE A AT PCC.

Harmonics order	The magnitude of individual THD (%) for current	Current distortion limits as recommended in IEEE Std 519-1992 limits
Odd (3rd to 9th)		**< 4.0%**
3rd	0.20645	< 4.0%
5th	0.10487	< 4.0%
7th	0.07691	< 4.0%
9th	0.06034	< 4.0%
Odd (11th to 15th)		**< 2.0%**
11th	0.05912	< 2.0%
13th	0.05819	< 2.0%
15th	0.09917	< 2.0%
Even harmonics		**< 25.0%**
2nd	0.36276	< 25.0%
4th	0.17431	< 25.0%

(15th). Fig. 6 shows the THD as apercentage from the fundamental of the current in phase (a) at PCC. The percentage of THD is oscillating around 2% (within the limits which is up to 5%) based on the standard). Fig. 7 presents the individual harmonic distortion as a percentage from the fundamental within index (1-15) for the current in phase (a) at PCC. The results shows that the % of each current harmonic within the specified standard range. Table. II shows the measured values for the voltage magnitude of 15 harmonics as a percentage of the fundamental frequency at 60 Hz. The voltage harmonics had a low impact on the interconnection of the microgrid to the distribution system compared to the current harmonic [19]. The European standard EN 50160 specifies 8 % as the limit for the total harmonic voltage distortion (THD %) on MV substations [20]. The THD % of the voltage in phase (a) at PCC is measured on the MV bus (20 kV), which is plotted as a percentage that varies with time as shown in Fig. 8. It is clear that the THD of the voltage is oscillating around 2%, which is less than the 8% limit established by the EN 50160 limit for MV. Fig. 9. shows the individual harmonic distortion of the voltage in phase a at PCC which is visualized using a polymeter in PSCAD that associates the harmonic distortion (%) with its harmonic index (1 to 15). Table. II shows the measured values for the voltage magnitude of 15 harmonics as % from the fundamental frequency at 60 Hz. It is noticed that the THD works within the allowed limits since the maximum THD percentage of 0.20% stays below the EN 50160 limit of 8 %.

VII. CONCLUSION

In this paper, the impacts of integrating different renewable energy sources in a microgrid into a transmission line system on power quality are discussed. The power quality analysis is performed at the point of common coupling using the PSS/E-PSCAD Co-Simulation framework by measuring the percentage of THD and comparing the results with standard limits. It is proven that the inclusion of DER units in the transmission system work within the allowed limits since the maximum THD percentage is 0.2% and stays under the EN 50160 limit of 8% for the MV side. The current harmonics had a high impact on the interconnection of the microgrid to the transmission system compared to the voltage harmonics. It is found that none of the current harmonics violate the specified limits for the IEEE Std 519-1992. This is an indication that the microgrid has a better response to quality perturbation when connected directly with the transmission system.

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