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Investigation of the Stochastic Harmonic Distortion Caused by Multiple Converters in Micro-Grid

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Abstract:
The primary emphasis of this inquiry is on the influence of voltage-source converter harmonics on the power quality of a power system. The level of harmonic distortion produced by several VSCs may significantly vary in the presence of uncertainties, making it challenging to predict its behavior due to these fluctuations. These uncertainties may arise due to the selection of design parameters or the adjustment of system characteristics. Therefore, it is essential to use statistical techniques to quantify the levels of VSC harmonic distortion in the presence of uncertainty. The experimental assessment of the UDR's performance was conducted using a practical microgrid lab that included three VSCs. The MCS approach functioned as a benchmark for evaluating the precision of the anticipated UDR results. The UDR consistently achieved the expected results, saving a large amount of time compared to the MCS technique. Furthermore, the UDR findings closely aligned with the MCS strategy.

Keywords: VSCs, MCS, UDR, Power System, Harmonic Distorsion.

1. INTRODUCTION

A microgrid is a system that integrates Renewable Energy Systems (RES) into the Electrical Power System (EPS) to generate sustainable energy, meet consumer energy needs, and conserve finite fossil fuel resources. To achieve the required degree of power management and conversion, these renewable energy systems (RES) are often linked to the grid using power electronic converters, such as Voltage Source Converters. This enables the required degree of adaptability. Voltage Source Converters (VSCs) are capable of producing harmonics in both current and voltage. The presence of these harmonics adversely impacts the Power Quality (PQ) of a microgrid and has the capacity to destroy or disable equipment.

Advancements in state-of-the-art technology and the increasing integration of renewable and sustainable energy generating systems into the electrical grid have given rise to innovative concepts like smart grids and microgrids. The proposed concepts advocate for the integration of Renewable Energy Systems (RES), such as wind turbines and photovoltaics, into the Electrical Power System (EPS) to provide environmentally friendly power, meet the energy demand, and safeguard the depleting fossil fuel resources.

Power electronic converters are often used to provide the necessary degree of regulation and transformation of power in renewable energy systems (RES). These converters are furthermore used to establish a connection between the renewable energy source (RES) and the electrical grid. Power converters, such as Voltage Source Converters (VSCs), have gained popularity and are being used more often due to their enhanced controllability and fast switching capabilities. Nevertheless, the converters produce current and voltage harmonics at their terminals, which then propagate to the rest of the grid as disturbances. These harmonics possess the capacity to induce malfunctions, impairments, or interference in several different electrical and electronic equipment. Examples of potential consequences include damaging or destroying EPS components due to incorrect signals, leading to the activation of fuses and circuit breakers. Harmonics contribute to the occurrence of stray flux losses and the excessive heating of transformer windings, resulting in the generation of copper and iron losses in transformers. High-frequency harmonics may induce electromagnetic interference, leading to disruptions in telecommunication lines and smart metres, resulting in erroneous readings and measurements. However, low-frequency harmonics do not have such effects.

When there are changes in specific factors such as operating conditions (output power) or system parameters, the probability of an EPS encountering significant increases in harmonics and the challenge of accurately predicting those increases both rise significantly (grid voltage background distortion). Furthermore, due to the non-linear nature of harmonics, accurately assessing their collective influence on the Power Quality (PQ) of an EPS becomes challenging, especially when several VSCs are interconnected with the

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system. Due to the inherent randomness of harmonics, it is essential to use statistical techniques to predict the extent of cumulative harmonic distortion induced by power converters in an EPS.

The use of statistical techniques, such as the Monte Carlo Simulation (MCS), has gained significant popularity as a common approach to predict the extent of harmonic distortion generated by power converters. Nevertheless, to get a precise forecast, a substantial number of simulations, numbering in the tens of thousands, are necessary. However, this need diminishes the feasibility of using this approach for systems that include a significant number of VSCs. This study primarily examines the impact of variable speed drives (VSCs) used in renewable energy sources (RES) on the power quality of microgrid. To assess and predict the impact of these parameters on the power quality (PQ) of the microgrid, it examines many aspects that may significantly amplify or reduce the degree of harmonic distortion caused by voltage source converters (VSCs). The objective of this project is to provide a reliable and efficient approach for predicting the power quality (PQ) in microgrid design, operation, and management. This method will be able to make accurate predictions even when only limited information about specific factors is available. This approach may be used in circumstances when the MCS exhibits a limitation. This approach assesses the harmonic distortion levels of the VSC by determining whether they comply with the specified harmonic limitations set by regulatory requirements. Regulatory regulations specify the acceptable limits for harmonics.

II. LITERATURE SURVEY

The following articles were selected for the investigation:

A study conducted by Ahmed, E. M. and colleagues in 2019 [1] introduced a versatile distributed maximum power point (MPPT) controller designed for the purpose of integrating photovoltaic (PV) systems into the electricity grid. The proposed distributed Maximum Power Point Tracking (MPPT) controller utilises a four-leg three-level T-type multilevel inverter, which will be explained in depth in the following sections. The proposed inverter performs many purposes, including distributed Maximum Power Point Tracking (MPPT), correction of neutral current for imbalanced loads, provision of reactive power to the grid, and integration with the grid, among other services. Moreover, the recommended inverter has the ability to overcome the unpredictable nature of both PV productions affected by partial shadow challenges and its operation with imbalanced loads. In addition, the newly proposed controller introduces sinusoidal output currents into the grid with reduced levels of total harmonic distortion (THD) compared to the old controller. The case study, which has undergone extensive testing, examines several operating scenarios for photovoltaic (PV) production and load demand. The results, together with the performance data shown in tables, demonstrate that the proposed multifunctional photovoltaic (PV) system surpasses the competition. The results indicate that the proposed controller is able to efficiently extract distributed maximum power point tracking (MPPT) for all photovoltaic (PV) modules in all tested conditions. In addition, eliminating the neutral current resulting from uneven loads in the system enhances the overall energy efficiency of the system.

In their study, Ala, G., et al. (2019) [2] performed an experimental analysis to determine the degree of harmonic content in the voltages generated by a three-phase, five-stage cascaded H-Bridge Multilevel inverter under the direction of an FPGA-based control board. In addition, they have attempted to assess the efficiency of the FPGA by adopting prevalent modulation approaches and contrasting simulation and experimental outcomes. The VHDL programming language was used to construct the control algorithms. The output voltage waveforms generated by using various PWM techniques in the inverter are compared based on their total harmonic distortion (THD) percentage. The outputs of simulation and experimental are analysed, contrasted, and explained, accordingly.

Al-duaij, E. O. S. (2015) [3] This publication provided an explanation of the significance, origins, and causes of harmonics in the power system. Additionally, there are the effects of harmonics on the electrical power supply. The team calculated and analysed the harmonics. The researchers examined the influence of harmonics on the electrical power supply. In the fourth segment of their presentation, they also showcased techniques for mitigating harmonics in the power system. In order to comprehend and investigate the origins and effects of harmonics in the public electric supply system, they conducted a thorough literature review and performed experiments to achieve their objective. The findings of their investigation were published in a publication that undergoes rigorous evaluation by experts in the field.

Alhafadhi, L., et al. (2020) [4] introduced a novel approach to decrease the total harmonic distortion (THD) of photovoltaic (PV) systems. This was achieved by using an adaptive filter that relies on a predictive model. Instead of incrementally lowering the total harmonic distortion (THD) at each level of the photovoltaic (PV) system, a single-step approach is done at the final stage. The connection topology of the adaptive filter is similar to that of active and passive filters. The ability to modify the filtering coefficients distinguishes it from other options. In order to assess the accuracy of the proposed method, it is implemented on a standalone photovoltaic system with a single phase. The algorithms used for this evaluation are LMS, NLMS, and leaky LMS. By using all of the above strategies, the recommended strategy has the potential to significantly reduce Total Harmonic Distortion (THD) in the current signal of the Photovoltaic (PV) system. Optimal THD reduction is achieved by using minuscule increments and employing filters of considerable length. NLMS minimizes total harmonic distortion (THD) to the maximum extent, whereas LMS obtains the peak current in the shortest amount of time.

In their study, Awais et al. (2016) [5] introduced a new issue formulation as a restricted optimisation problem and applied it specifically to balanced three-phase systems. They claim that reducing total harmonic distortion (THD) in single-phase CMLIs requires a different approach compared to three-phase systems. This is because single-phase systems include triple-n harmonics that are not accounted for in balanced three-phase systems. This research expands upon the previously proposed novel problem formulation for minimizing total harmonic distortion (THD) in current-mode logic inverters (CMLIs) by applying it to single-phase systems. The initial suggestion was made specifically for multiphase systems. Computational investigations demonstrate that single-phase systems have a higher number of solutions (switching angles) and a bigger amount of total harmonic distortion (THD) compared to three-phase systems. Circuit simulations are used to validate the precision of the computational results.

Bajaj, M., et al. (2020) [6] presented a comprehensive analysis of power quality issues resulting from the growing utilisation of grid-integrated renewable energy systems. They also conducted a brief review of the latest solutions published in the literature to address these concerns. Furthermore, the text thoroughly examines the possibility of doing future research on strategies to reduce or prevent the negative impacts.

Basit, M. A., et al. (2020) [7] provided a thorough examination of renewable energy sources. The use of Energy Storage Systems (ESSs) in renewable energy systems, along with the developmental stage of these systems, has been investigated. An analysis has been conducted on the significance of Energy Storage Systems (ESSs) in enhancing the longevity, optimizing efficacy, and augmenting the energy density of power systems reliant on renewable energy sources. In addition, many approaches to address significant issues in photovoltaic (PV) systems, such as low efficiency, harmonics, and inertia reduction, have been provided. This study is the first to investigate the impact of FACTS technology on power systems that use renewable energy and utilise multitype flexible AC transmission system (FACTS) controllers. This is different from most of the existing review studies. Three simulation models have been developed in MATLAB/Simulink, using the OpenCL library. According to the results, FACTS devices enhance the stability of RES's integrated power system by improving its efficiency. Their study is expected to have the capacity to aid researchers from both industry and academia in acquiring a more comprehensive comprehension of the obstacles and methods for resolving renewable energy-based power systems. Additionally, it may contribute to identifying future research directions in this field via collaborative efforts.

Basta, B., and Morsi, W. G. (2021) [8] Investigated the harmonic emissions produced by fast-charging stations over a range of low-order and high-order harmonics. The use of Energy Storage Systems (ESSs) in renewable energy systems, along with the developmental stage of these systems, has been investigated. An analysis has been conducted on the significance of Energy Storage Systems (ESSs) in enhancing the longevity, optimising effectiveness, and augmenting the energy density of power systems reliant on renewable energy sources. In addition, many approaches to address significant issues in photovoltaic (PV) systems, such as low efficiency, harmonics, and inertia reduction, have been provided. This research investigates the impact of FACTS technology on power systems that use renewable energy and utilise multitype flexible AC transmission system (FACTS) controllers. This is a unique study since it differs from other existing review studies. Three simulation models have been developed in MATLAB/Simulink, using the OpenCL library. According to the results, FACTS devices enhance the stability of RES's integrated power system by improving its efficiency. Their study is expected to have the capacity to aid researchers from both the industry and academia in gaining a more comprehensive grasp of the issues and solution strategies for renewable energy-based power systems. Additionally, it may contribute to identifying future research directions in this field via cooperation.

Belega, D. and Petri, D. (2021) [9] suggested a method to determine the frequency, amplitude, and phase of sine waves that are influenced by either wideband noise or both noise and harmonic distortion. Straightforward techniques for real-time applications. The innovative Corrected Interpolated Discrete Fourier transform (IpDFTc) approach calculates signal parameters by adjusting for the impact of spectral interference from the fundamental image component and harmonics on the classic IpDFT parameter estimations. Subsequently, a linear sine-fit methodology is used to enhance the noise resistance of the estimators, which is compromised by the implementation of signal windowing to reduce spectral leakage. The Hann window is used in the research because of its superior noise endurance and ability to minimize long-range spectral leakage. Both proposed methods effectively achieve the Cramér-Rao Lower Bounds for unbiased estimators when detecting at least 1.5 sine-wave cycles. This enables windowing to effectively adjust for interfering tones on IpDFTc estimates. The performances of these techniques are assessed using computer simulations and experiments.

Biswas et al. (2017) [10] introduced a strategy using a differential evolution (DE) algorithm known as L-SHADE to optimise the parameters of a Hybrid Active Power Filter (HAPF). SHADE is a history-based parameter adaptation approach used in Differential Evolution (DE) for optimizing a constrained multimodal nonlinear objective function. L-SHADE improves the performance of SHADE by reducing the population size across successive generations. The study discusses two widely used HAPF topologies for the purpose of parameter estimation. In a system with non-linear sources and non-linear loads, the reduction of harmonic pollution (HP) is achieved by using a single target function that combines the total harmonic distortion of voltage (VTHD) and the total harmonic distortion of current (ITHD). An in-depth analysis is conducted on an industrial plant. Prior studies have conducted a comparative analysis of the output of the L-SHADE algorithm and that of other well recognized evolutionary algorithms.

Busatto, T., et al. (2020) [11] examined the disparity between the outcomes obtained from the widely used model and the real harmonic distortion seen in a low-voltage setup. Several indices are provided to quantify the nonlinear interaction between the two variables. These indices may be used to measure the extent to which the commonly used model can accurately forecast harmonic voltages and currents in a modern low-voltage system. Measurements from several combinations of PV inverters and LED bulbs with various technologies offer experimental support for the proposed model, which is then analysed mathematically. The results indicate that the extent of deviation is influenced by the specific technology used, the impedance of the network, and the waveform of the source voltage. Additional findings reveal that nonlinear interaction mostly takes place at lower harmonic orders and that the effects are particularly pronounced at the phase angle of the harmonics. These findings are being analysed to identify potential causes for them.

Chen, F., Ruijie, L., and Guanhua, L. (2019) [12] Constructed a comprehensive charger model to investigate the impact of charger quantity, charger power, and starting state of charge (SOC) on harmonics. Subsequently, an Active Power Filter (APF) is used in order to mitigate harmonics. The control technique employs a hybrid control strategy that incorporates both PI control and repeated control features. The simulations validate the efficacy of the provided technique. The proliferation of electric automobiles on the road is leading to an increasingly substantial issue of harmonic pollution stemming from electric car charging stations. Ensuring the assessment and control of the harmonics generated during the charging procedure of electric vehicles is crucial for safety purposes.

Elkholy, M. M., et al. (2018) [13] discussed the use of passive filters in both grid-connected and isolated hybrid renewable microgrids. Single-tuned filters are used to ensure that total demand distortions remain within the maximum allowable thresholds. The recommended passive filters aim to lower both the total cost and THD simultaneously, while adhering to specific operational inequality restrictions. These reductions are seen as modified bi-objectives. This study employs a Multi-Objective Grasshopper Optimisation Algorithm (MOGOA). The selection of the optimal Pareto solutions is conducted meticulously via the use of the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) approach. Prior to and subsequent to the installation of passive filters, harmonic analysis is used to verify critical frequencies. Their research investigates the influence of harmonics on the torque of motors and wind generators. The system's power factor is improved. Multiple grid functioning scenarios are examined, including the unpredictability of renewable energy sources. The torque fluctuations of the induction motor and wind turbine generator are minimised. The results of the MOGOA algorithm for filter cost and THD are very competitive and persuasive when compared to the well-structured multi-objective genetic algorithm.

Etesami et al. (2018) [14] conducted a comparison of stochastic approaches often used for pulse width modulation techniques, namely for Sinusoidal Harmonic Elimination (SHE) and Modified Sinusoidal Harmonic Elimination (MSHE). The problem is defined as the pursuit of local optima in the operational parameters of cascaded H-bridge converters. The research specifically examines significant indicators of low-order harmonic components, as well as the weighted total harmonic distortion. Both SHE and MSHE use a floating fundamental component to enhance the flexibility of optimisation techniques, resulting in significant benefits. Ultimately, a refined modulation method is provided to effectively manage the voltage fluctuations on the dc-link circuit. To illustrate the concept, simulation and empirical results are shown.

Fang, J., Deng, H., and Goetz, S. M. (2020) [15] A technique for estimating impedance that is particularly suitable for grid-forming converters was suggested. The technique consists of four operational modes, each of which is useful in voltage and power control applications, respectively. When it comes to voltage regulation, the voltage's amplitude perturbation or phase angle information is used to regulate the voltage. Subsequently, the grid's inductance and resistance are determined by the use of power measurement. Conversely, in

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the power control scenario, the active or reactive power data is used to forecast the impedance of the grid. The proposed method has the benefit of being easily implemented and devoid of harmonic distortion, safety issues, and reliance on control configurations. Moreover, the strategy is unobtrusive in most situations. Additionally, it is advisable to use a distinctive Kalman filtering methodology to provide supplementary motivations. Ultimately, the outcomes of simulations and tests unequivocally establish the efficacy and simplicity of the proposed technique.

Our project will focus on a practical microgrid that utilises established technology in the VSC architectural interface, its switching strategy, and control techniques. The main objective is to design a model that guarantees high power quality in the microgrid. An examination and research will be conducted to assess the power quality of a microgrid, taking into account the predicted harmonic distortion level of the converters utilised and the impact of various factors on the generated harmonics. This tool will enable researchers and design engineers to analyse the power quality of a microgrid and construct or run an EPS within predetermined boundaries to ensure optimal power quality.

III. METHODOLOGY

The following section presents a concise summary of the primary phases involved in using the UDR technique to gauge the degrees of harmonic distortion at the Point of Common Coupling in a microgrid.

Step i): Determine all stochastic functions inside the system (e.g., power and impedance) and compute their respective probability distribution functions.

Step ii): To minimize variability, calculate the standard deviation (sigma) and assign weights to the points using the Univariate Dimension of UT-reduced Gaussian quadrature.

Step iii): Populate the empty spaces with information obtained from a compact grid. The system has sigma points and weights.

Derived from step ii.

Step iv): Utilise microgrid simulation to get statistical data for output analysis.

Step v): Compute the output variables by means of statistical analysis, using the designated output values and UDR weights.

The requested information includes the current rate/voltage total harmonic distortion (THD) and interharmonic distortion (IHD), the standard deviation of THD/IHD for current/voltage, and the standard deviation of voltage THD/IHD.

Step vi): Obtain mathematical knowledge on the output variables.

The efficacy of the Univariate Dimension Reduction (UDR) method in predicting harmonic distortion levels of several voltage source converters (VSCs) in a real-world microgrid is evaluated via a series of distinct tests. By randomly generating power values using uniform and Gaussian distributions, we then input these values into the VSCs, therefore predicting the resulting harmonic distortions.

IV. FINDINGS AND ANALYSIS

Previous research has shown that variations in output power may impact the overall level of total harmonic distortion (THD). The objective of this inquiry is to forecast the net harmonics generated by three VSCs while the output power fluctuates uniformly and independently within a range of 2.5kW to 10.0kW.

To replicate the approach used by MCS, the VSCs were first exposed to several random power input values. Subsequently, the whole set of net harmonics is measured and documented. Subsequently, the Unscented Kalman Filter (UKF) employs the Unscented Transform (UT) to compute the sigma points and weights. This is achieved by leveraging the statistical properties of the distribution, including the range, mean, and standard deviation. Subsequently, the sigma points that were generated are fed into the VSCs, which function as the power inputs, and the net harmonics are identified at point B. (as seen in Figure 1). Subsequently, the results of both the MCS-type method and the UDR are subjected to statistical analysis and subsequently compared to assess the effectiveness of the UDR procedure. The obtained empirical findings are shown in Table 3 through Table 4 and

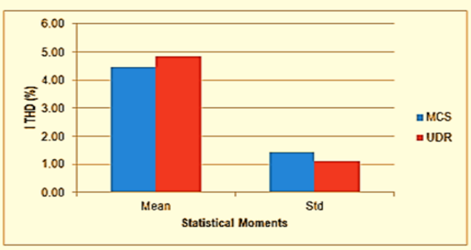

Fig.2: Laboratory Results of ITHD Predicted Statistical Moments (3pts UDR).

Fig.3: Laboratory Results of VTHD Predicted Statistical Moments (3pts UDR).

Fig.2 to Fig.3 correspondingly.

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The findings obtained from the Monte Carlo simulation (MCS) and the Uncertainty and Data Reconciliation (UDR) method for the average value exhibit a high degree of similarity, as seen by the data presented in Table 3. The standard deviation results for the VTHD were expected to be 57 percent lower than those obtained using the MCS approach.

Table 3: Laboratory Results Showing Predicted Moments of ITHD and VTHD using MCS and 3pts UDR

	I_{THD}		V_{THD}	
	Mean	**Std**	**Mean**	**Std**
MCS	4.46	1.44	1.93	0.52
UDR	4.84	1.11	1.94	0.22
Error (%)	8.52	-22.9	0.52	-57.7
Diff	0.38	-0.33	0.01	-0.30

The statistical moments of the ITHD and VTHD, calculated using a 3-point UDR, are shown in Fig. 2 and 3, in that order.

Table 4: Laboratory Results Showing Predicted Moments of ITHD and VTHD using MCS and 5pts UDR

	I_{THD}		V_{THD}	
	Mean	**Std**	**Mean**	**Std**
MCS	4.46	1.44	1.93	0.52
UDR	5.07	1.67	2.06	0.60
Error (%)	13.68	15.97	6.74	15.38
Diff	0.61	0.23	0.13	0.08

The laboratory test findings may be seen in Table 4, which displays the calculated statistical moments of ITHD and VTHD. Table 4 clearly demonstrates that the 3pts UDR method yielded a more precise estimation of the mean and standard deviation, as seen by its lower proportion of errors.

Fig.4: Laboratory Results of ITHD Predicted Statistical Moments (5pts UDR).

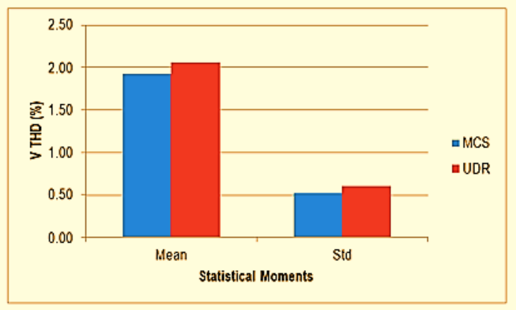

Fig.5: Laboratory Results of VTHD Predicted Statistical Moments (5pts UDR).

The outcomes of using the 5pts UDR are shown in Figure. 4 and 5 show the calculated mean and standard deviation of ITHD and VTHD, respectively.

5. CONCLUSION

The study demonstrated that several design specification elements, including the converter topology, switching frequency, and amplitude modulation, had an impact on the harmonics generated by the Voltage Source Converter (VSC) in an Electric Power System (EPS). The kind of filter and the specific values of the filter parameter may greatly influence the harmonics of a VSC, since this is the main technique used to reduce the effect of harmonics generated by harmonic systems, such as VSCs. Furthermore, the characteristics of the microgrid or EPS, such as the line impedance of the EPS, the harmonic distortion of the EPS background voltage, or the output power of the VSCs, may significantly influence the harmonics generated by the VSCs. Certain parameters, namely those related to the VSCs (variable speed drives) of renewable energy sources (RES), may only be determined within certain constraints. The power generated by renewable energy sources (RES), such as wind turbines and photovoltaics, depends on the wind speed profile and sun irradiation, respectively. These two parameters are apt illustrations to showcase this variety. Consequently, the EPS exhibits an element of uncertainty since there are no guarantees about the quantity of electricity that will be produced by RES. Moreover, in the case of a microgrid when a significant number of Renewable Energy Sources (RES) Voltage Source Converters (VSCs) are interconnected, it becomes infeasible to predict the combined harmonic distortions produced by these VSCs. This phenomenon occurs because the harmonics produced by each Voltage Source Converter (VSC) do not combine linearly.

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