# Prediction of voltage dips characteristics in IEEE 13-bus test grid using harmonic footprint

Aleksandar M. Stanisavljević, *Member, IEEE,* and Vladimir A. Katić, *Senior Member, IEEE*

***Abstract*—In this paper, the method of harmonic footprint (HF), as a significant feature of voltage dip is applied for a dip characterization. The dips are generated using an internationally verified test grid, the IEEE 13-bus test grid. First, the method of the HF is presented and described. Then, the IEEE 13-bus test grid modified by adding the distributed generators (wind or solar power) is described. Faults were simulated in the test network, and the values of the HF parameters were determined. The results were used for the voltage dips characteristics prediction. The results of simulation and prediction were compared and the mutual deviation (error) was determined. It is shown that the HF can be used for the early voltage dips characteristic prediction and further applied for training a deep-learning algorithm. Some limitations have been observed and their mitigation will be a topic of future research.**

***Index Terms*—Electric power quality, Voltage Dips, Harmonic footprint, Test grids**

## I. Introduction

In recent years, power quality issues have become more relevant, and significant attention had been paid to the related topics. In addition to the quality of delivery, the quality of delivered electrical energy is also important, which is often recognized as the quality of voltage. Voltage dips or sags are a consequence of disturbances in the operation of the power system and may have serious negative effects on industrial loads and connected distributed generation (DG) [1]. Particularly inconvenient are outages of industrial plants or the shutdown of small power plants in the distribution network, which can have major financial consequences. For these reasons, great research efforts are focused on the rapid detection and successful characterization of voltage dips [2, 3] and techniques of its compensation [4].

One of the successful methods for the dip's characterization is the application of harmonic footprint [5]. It provides the possibility for early characterization of a voltage dip so that in the first phase of fault its characteristics can be predicted with high probability [5, 6, 7]. For the sake of more accurate categorization and faster response, it is convenient to apply some of the methods of artificial intelligence, i.e., machine learning or deep learning [8, 9]. However, the main problem is the training, i.e., providing a huge number of adequate and different cases of voltage dips. Voltage dips occurrence in real grids is relatively rare, so long-term measurements are needed, which is costly and requires specialized equipment. Therefore, the use of synthetic dips based on mathematical calculations or simulated ones, based on the response from the grid simulation model are possible solutions.

This paper aims to test the application of the harmonic footprint method for the prediction of the voltage dip characteristics and to discuss such an approach for training a deep learning algorithm. The testing is based on recognizable and internationally verified references or test grids [10]. First, the method of harmonic imprinting is presented and described. Then, the IEEE 13-bus test grid is described, which is modified by additional distributed generators (wind and solar power plants). Faults were simulated in the test grid, and the values of the harmonic footprint parameters were determined for the various types of voltage dips thus obtained. The results of modeling and prediction of the voltage dips characteristics were compared and the mutual deviation (error) was determined.

Aleksandar M. Stanisavljević with the University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia (e-mail: acas@uns.ac.rs).

Vladimir A. Katić is with the University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia (e-mail: katav@uns.ac.rs).

## II. Harmonic footprint

It is generally known that voltage dips are a consequence of faults in the network, high-power motor drive starting, or power transformer energizing [1]. During these events, a sudden rise of current may be observed, which distorts the voltage waveform all over a huge area of the grid. If the Fourier transformation is performed, the second and several other low-order harmonics may be noticed [1, 5]. If they are traced as a group, which consists of the 2nd, the 3rd, then 5th, and the 7th harmonics, and monitored throughout a voltage dip, a specific waveform may be observed [5]. It was named harmonic footprint (HF) [5]. Its mathematical representation is:

$$HF = \frac{\sqrt{\sum_{n=2,3,5,7} U_n^2}}{U_1^2} \cdot 100 \quad [\%] \tag{1}$$

where $n$ is harmonic order, and $U_n$ is r.m.s. value of the *n-th* harmonic.

The harmonic footprint is an important feature of a voltage dip. It appears at each voltage dip transition state, i.e., at the start of the dip and its end. Additionally, the HF may be recorded if the dip progresses from single-ground one to two-phase to ground or if some other voltage transition occurs. It

 ISBN 978-86-7466-930-3

can be obtained in a few milliseconds, so the HF method represents one of the fastest tools [11].

The main parameters of an HF are its initialization (start-up), maximum value (MHF), and width (wHF). They may be used for voltage dip detection (start-up moment) and prediction of voltage dip magnitude (depth), and duration, i.e., for fast and accurate characterization [5, 6, 7]. The HF and its parameters are presented graphically in Fig.1.

The HF method was tested with voltage dips recorded in various real distribution grids, and the configurations of the different distribution grids did not significantly affect the accuracy of the algorithm [5, 6, 7]. Furthermore, it can be noted that stochastic quantities, like fault resistance and fault inception angle, have some influences on the HF, but their effects are combined with the distance from the fault (line impedance between the fault location and voltage dip recording point). Generally, the total impedance has an inversely proportional effect, i.e., if it is higher, the HF is usually of a smaller value. The fault inception angle does not influence the precision of the method, as it is tested with real faults, which had different fault inception angles.

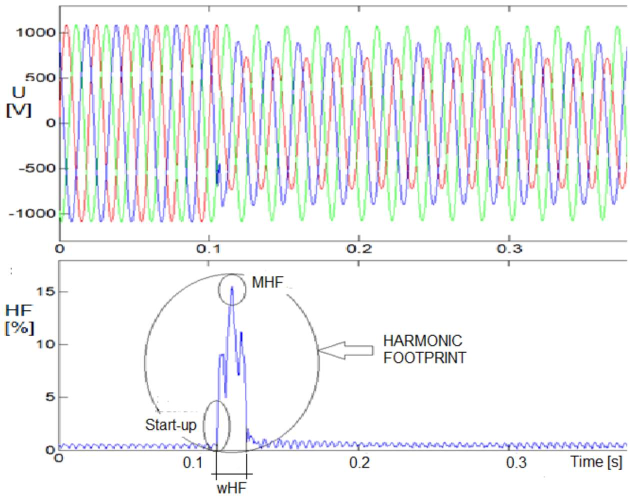


Fig.1.Harmonic footprint characteristics

## III. Modified IEEE 13-bus test grid

There are several different test grids available for the simulations of voltage disturbances in a grid [10]. In this paper, the IEEE 13-bus test grid will be used. It represents a sample of the North American distribution grid consisting of three-phase lines, with two-phase and single-phase ones close to the ends of feeder laterals (load side). The supply voltage is 155 kV, while the distribution voltage is 4.16 kV. The grid is loaded with constant current, constant impedance, and constant power consumers, so that the total load is 3.466 MW. Unity power factor is assumed.

The test grid was modified with the addition of DGs, to make a better representation of a modern distribution grid. The optimal DG size is 2.5 MW connected at bus #633 [12], but in this paper, it will not be concentrated. A 2 MW wind plant was added at bus #633, and a 0.5 MW solar PV system at bus #652. The wind plant consists of four wind generators of 0.5 MW each interconnected with the grid via a power transformer and a one-kilometer-long power line. The solar PV plant is an on-grid solar PV system of 0.5 MW connected to the grid at bus #652 via a power transformer, which is further connected to the mainline at bus #648 via a 2 km line. These plants are dispatchable, but also comply with low-voltage ride-through (LVRT) requirements [13]. Therefore, they can support the grid during the duration of a voltage dip.

The IEEE 13-bus test grid is available as the Matlab/Simulink simulation model in [14]. Its modification is also done in Matlab/Simulink and its one-line diagram is presented in Fig.2.

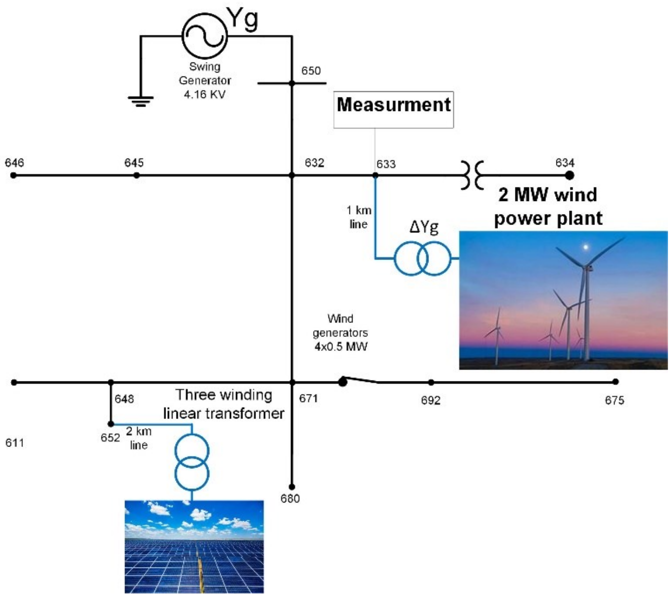


Fig.2. Modified IEEE 13-bus test grid with added DGs

## IV. Voltage dips simulations

The simulated voltage dips are the result of hypothetical faults in the test grid. The faults are generated at buses #692, #633, and #671 with a rated voltage of 4.16 kV. Different faults are simulated: single-phase to the ground (line-to-ground), two-phase faults (line-to-line), and a three-phase to the ground.

The voltage dips are measured (recorded) at bus #633. Two main features are monitored, the magnitude of voltage dip (MoVD) and duration.

The magnitude of a voltage dip represents the voltage during the dip as a percentage of the rated voltage, i.e., it is defined as:

$$MoVD = \frac{U_{rem.}}{U_r} \cdot 100 \ [\%] \tag{2}$$

where $U_{rem}$ is the remaining voltage during the voltage dip at the observing bus and $U_r$ is the rated voltage.

The duration of a voltage dip is defined as a period when the voltage at the observing bus is lower than $0.9U_r$.

 ISBN 978-86-7466-930-3

Fig. 3 shows an example of the single-phase (line-to-ground) voltage dip recorded at bus #633. The fault occurred on line 1 (L1, the blue line) at bus #671. As the result, the voltage at observing bus #633 suddenly decreases from the rated to 5% of the rated, i.e., the MoVD=5%. The voltages of the other two lines (L2, the red one, and L3, the green one) experience voltage swells, i.e., increased by around 15%. The duration of the voltage dip was 0.16 seconds. After that, the fault was cleared and all voltages returned to the rated values. It can be easily observed that significant voltage distortion occurred during the voltage transient states, i.e., when a fault and corresponding voltage dip initiated (started) and when it ended. In these periods the HF appears, and it can be calculated and recorded.

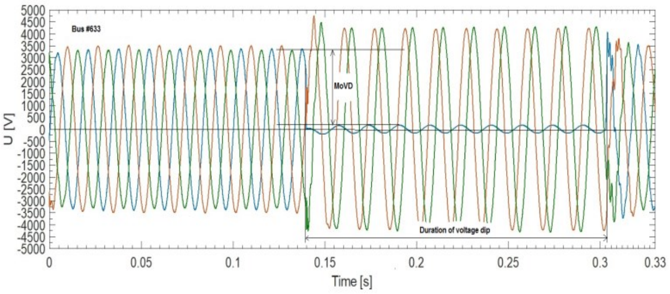


Fig. 3. Single-phase voltage dip recorded at bus #633.

Beside the single-phase to the ground (line-to-ground) fault and corresponding voltage dip presented in Fig. 3, six more cases of different faults were simulated. They are presented in Table I. It can be seen that three single-phase to the ground faults which occurred on the busses #692, #671, and #648 were simulated, together with the additional three phase-to-phase (line-to-line) faults on the same busses and one three-phase to the ground on bus #643. In total, seven faults were tested.

The recorded voltage dips on bus #633 were also summarized in Table I. It shows the main characteristics of the simulated voltage dips, their magnitude (given by MoVD), and their duration. It can be seen that for single-phase to the ground faults the MoVDs are very small, as well as for the three-phase to the ground fault, while in cases of phase-to-phase faults the MoVD values are around 50%.

## V. Harmonic footprint parameters determination

The harmonic analysis of the tested voltage dips resulting in their harmonic footprint was performed. An example of the HF for the case of the voltage dip presented in Fig. 3 (fault No.2 in Table I) is shown in Fig. 4. It can be seen that there are two HFs, one at the beginning of the dip and the other at its end. For further analysis, the first one will be considered. Specific parameters of the harmonic footprint can be distinguished, its MHF and wHF. For the voltage dip characterization, the MHF is important. It can be seen that the MHF value in this case (single-phase to the ground fault) is 36%.

A similar analysis is done for all other recorded voltage dips cases. Due to limited space, the HF diagrams for the other cases will not be shown here. The results for the MHF are presented in Table I (column to the right). It can be seen that in the cases of the low MoVD values (deep voltage dips) the MHF values are above 30%, while for the higher MoVDs the MHF is lower.

TABLE I
SIMULATED VOLTAGE DIPS CHARACTERISTICS

| No. | Type of faults / Voltage dip characteristics | MoVD [%] | Duration [s] | MHF [%] |
|---|---|---|---|---|
| 1 | Single-phase to the ground at bus #692 | 7 | 0.18 | 37 |
| 2 | Single phase to ground at bus #671 | 5 | 0.16 | 36 |
| 3 | Single-phase to the ground at bus #648 | 8 | 0.20 | 35 |
| 4 | Phase A and B at bus #692 | 48 | 0.30 | 24 |
| 5 | Phase A and C at bus #671 | 49 | 0.33 | 25 |
| 6 | Phase C and B at bus #648 | 62 | 0.50 | 18 |
| 7 | Three-phase to ground at bus #643 | 9 | 0.80 | 32 |

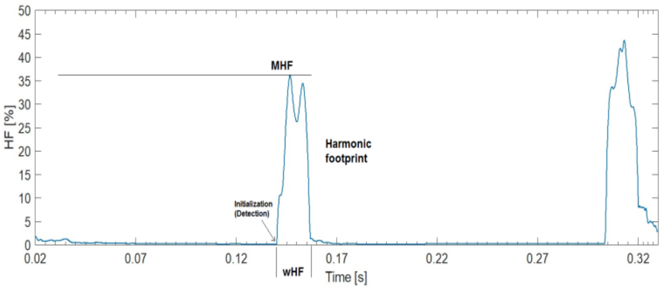


Fig. 4. The HF for the case of the single-phase voltage dip recorded at bus #633 for fault No. 2 in Table I

## VI. Estimation of the voltage dips characteristics

The obtained HF parameters can be used for the early prediction of the voltage dip characteristics, its magnitude (MoVD), and its duration. These characteristics can be predicted using the maximum value of the HF (MHF) according to the expressions given in [6, 7].

The prediction function calculates voltage magnitude as a function of the maximum value of the HF:

$$MoVD^* = f(MHF) \tag{3}$$

where *MoVD** is the predicted value of the voltage dip magnitude, and *MHF* is a global maximum of the HF during the first transient stage. The voltage dip magnitude can be calculated using the following expression [6]:

$$\begin{aligned} log_{10}(MoVD^*) = 1.913 + 0.00284 \cdot MHF + \\ + 0.000036 \cdot MHF^2 - 0.000024 \cdot MHF^3 \end{aligned} \tag{4}$$

The results of the calculations are presented in Table II. For the generated faults (Table I) the values of the predicted MoVD* are presented in the second column of Table II. For comparison, the simulated (recorded) MoVD values are given in the third column (repeated from Table I). It can be seen that predicted values are close to the actual (simulated) ones. The absolute errors of prediction are given in the third column of Table II. It can be seen that these errors are below 9 percent. The average absolute error of the prediction is 4.2%, while r.m.s. error is 5.12%. It can be concluded that the prediction can be successfully performed with an acceptable error of prediction.

For prediction of the voltage dip duration, the method presented in [7] is used. The method uses the *MHF* values to calculate the probability function *f(MHF)* [7]:

$$f(MHF) = (1 + e^{9.15 - 0.23202 MHF})^{-1} \quad (5)$$

The probability function determines the probability of the voltage dip duration being predicted as momentary or temporary. It is a sigmoid function, so two zones (momentary or temporary) can be distinguished easily. If the *f(MHF)* is less than 0.4, which corresponds to MHF<37.7% the voltage dip is momentary, i.e., less than 3 seconds. If the *f(MHF)* is above 0.6 (MHF>41.2%) then the voltage dip is temporary, i.e., longer than 3 s. In between is uncertainty or border zone, where both solutions are possible.

The probability function is calculated for the obtained MHF values and presented in Table III. It can be seen that for all observed cases of the voltage dips predicted duration was "momentary", i.e., less than 3 s, which is in accordance with the actual duration. Therefore, the prediction was true.

TABLE II
VOLTAGE DIPS MAGNITUDE PREDICTION AND PREDICTION ERROR

| Fault No. | Predicted MoVD* [%] | Simulated MoVD [%] | Absolute Error [%] |
|---|---|---|---|
| 1 | 7.11 | 7 | 0.11 |
| 2 | 8.75 | 5 | 3.75 |
| 3 | 10.65 | 8 | 2.65 |
| 4 | 46.79 | 48 | 1.21 |
| 5 | 42.81 | 49 | 6.19 |
| 6 | 68.52 | 62 | 6.52 |
| 7 | 17.96 | 9 | 8.96 |
| The average absolute error of prediction | | | 4.20 |
| Root mean squared error | | | 5.12 |

TABLE III
VOLTAGE DIPS DURATION PREDICTION AND PREDICTION ACCURACY

| Fault No. | Probability function *f(MHF)* | Predicted VD DURATION [s] | Simulated VD DURATION [s] | Prediction accuracy |
|---|---|---|---|---|
| 1 | 0.362 | Momentary (<3s) | 0.18 | TRUE |
| 2 | 0.311 | Momentary (<3s) | 0.16 | TRUE |
| 3 | 0.263 | Momentary (<3s) | 0.20 | TRUE |
| 4 | 0.027 | Momentary (<3s) | 0.30 | TRUE |
| 5 | 0.034 | Momentary (<3s) | 0.33 | TRUE |
| 6 | 0.001 | Momentary (<3s) | 0.50 | TRUE |
| 7 | 0.101 | Momentary (<3s) | 0.80 | TRUE |

## VII. DISCUSSION

The harmonic footprint presents a unique feature of a voltage dip, which may be used for the prediction of its characteristics. Moreover, it offers the possibility of dip detection and obtaining its early characterization. The presented results show that the simulated voltage dips have been analyzed adequately and that the predicted characteristics are true and acceptable regarding prediction error.

The predicted dip magnitudes correspond to the simulated ones with the r.m.s. error of 5.12%, which is acceptable in engineering practice. The predicted dip durations were true, but the prediction was limited to only two options – momentary (less than 3 s) and temporary (more than 3 s). Additional problem is that the HF is not able to predict the exact duration of voltage sag, so the whole period of voltage sag should be recorded. In that case, the two HFs should be calculated (at the beginning and the end of a voltage dip) and their detection times compared (see Fig.4). Other possible solutions will be sawn in future research.

The results also show that simulated voltage dips may be used for creating a database for the training of a deep learning algorithm. Available reference or test grids (IEEE or others) are adequate and suitable, so many different cases may be simulated.

Still, the number of simulated cases is limited, as for the deep-learning algorithm or any other machine learning one high number of input data is needed. One solution is to use the test grids with more buses (feeders) where there are more options to generate the faults and obtain voltage dips. There are other options and they will be the topic of future research.

## VIII. CONCLUSION

The voltage dips characterization is an important task for modern industrial or other loads, as well as for distributed generation and protection of the distribution network. The use of artificial intelligence and deep-learning algorithms for solving this task proved a good solution but require a huge database for the algorithm training process.

In previous papers, the authors have presented that the harmonic footprint, as a voltage dip feature, can be successfully implemented for the prediction of voltage dip characteristics. These results were based on the measurement results obtained in the real grid.

The result of this paper shows that simulation in the referenced test grids can be also used for that purpose. The harmonic footprint has been successfully applied for a voltage dip early characterization. It proves that such an approach can be also applied for the generation of an artificial (simulated) set of voltage dip cases (characteristics) and used for deep-learning algorithm training. Some limitations of this method have been observed, so future work will focus on their mitigation.

## ACKNOWLEDGMENT

This work was supported by the Republic of Serbia, Ministry of Education, Science, and Technological Development, through the Integrated and Interdisciplinary Research project entitled "Innovative Scientific and Artistic Research from the Faculty of Technical Sciences Activity

Domain" under Grant No. 451-03-68/2022-14/200156.

## REFERENCES


[1] M.H.J. Bollen, *Understanding Power Quality Problems – Voltage Sags and Interruptions*, IEEE Press - Series on Power Engineering, New York, USA., 2000.

[2] P. Khetarpal and M.M. Tripathi, "A critical and comprehensive review on power quality disturbance detection and classification, "*Sustainable Computing: Informatics and Systems*, Vol.28, Paper #100417,2020.

[3] A.E.L. Rivas and T. Abrao, "Faults in smart grid systems: Monitoring, detection, and classification," *Electric Power Systems Research*, Vol.189, Paper #106602, pp.1-26, 2020.

[4] A.H. Soomro, A.S. Larik, M.A. Mahar, A.A. Sahito, A.M. Soomro, and G.S. Kaloi, "Dynamic Voltage Restorer - A comprehensive review", *Energy Reports*, Vol. 7, pp. 6786-68905, 2021.

[5] V.A. Katić and A.M. Stanisavljević, "Smart Detection of Voltage Dips Using Voltage Harmonics Footprint," *IEEE Trans. Ind. Applications,* vol. 54, no. 5, pp. 5331–5342, 2018.

[6] A.M. Stanisavljević and V.A. Katić, "Magnitude of Voltage Sags Prediction Based on the Harmonic Footprint for Application in DG Control System," *IEEE Trans. Ind. Electronics*, vol. 66, no. 11, pp.8902–8912, 2019.

[7] A.M. Stanisavljević, V.A. Katić, and S.Lj. Milićević, "A method for real-time prediction of the probability of voltage sag duration based on harmonic footprint," *IEEE Access*, Vol.10, pp.23757-23774, 2022.

[8] A.K. Ozcanli, F. Yaprakdal, and M. Baysal, "Deep learning methods and applications for electrical power systems: A comprehensive review," *Int. Journal of Energy Research*, Vol.44, pp.7136-7157, 2020.

[9] R. Turović, D. Dragan, G. Gojić, V.B. Petrović, D.B. Gajić, A.M. Stanisavljević, and V.A. Katić, "An End-to-end Deep Learning Method for Voltage Sag Classification," *Energies*, Vol.15, Paper #2898, pp.1-22, 2022.

[10] A.M. Stanisavljević, V.A. Katić, B.P. Dumnić, and B.P. Popadić, "A brief overview of the distribution test grids with a distributed generation inclusion case study," *Serbian Journal of Electrical Engineering*, Vol.15, No.1, pp.115-129, 2018.

[11] A. Usman and M.A. Choudhry, "An Efficient and High-Speed Disturbance Detection Algorithm Design with Emphasis on Operation of Static Transfer Switch," *Advances in Electrical and Computer Engineering*, Vol. 21, No. 2, pp.87-98, 2021.

[12] M. Shaaban and J.O. Petinrin, "Sizing and sitting of distributed generation in distribution systems for voltage improvement and loss reduction," *Intern. Journal of Smart Grid and Clean Energy*, Vol.2, No.3, pp.350-356, Oct. 2013.

[13] R. Hiremath and T. Moger, "Comprehensive review on low voltage ride-through capability of wind turbine generators," *Int. Trans. on Electrical Energy Systems*, Vol.30, Paper #e12524, pp.1-26, 2020.

[14] https://www.mathworks.com/help/physmod/sps/ug/ieee-13-node-test-feeder.html;jsessionid=0abf70e84f19a1618f96de0a91e3


 ISBN 978-86-7466-930-3