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# Performance analysis based on real-field data of a method for locating the source of voltage dips

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**Abstract**—Voltage dips are one of the most recurrent types of power quality disturbances detectable in power systems. Root-cause analysis is important to identify opportunities for mitigation. In this paper, a recently proposed practical method to locate the source of voltage dips that requires only basic Power Quality measurements is refined, including, in particular, an improved solution for aggregating dip events and extended to the case of multi-level scenarios. The performance of this method is evaluated under different operating conditions using real-field data in a South African 66 kV/11 kV network.

**Keywords**—Voltage dips, power quality meter, field data platform, power quality

## I. INTRODUCTION

Voltage dips are a common Power Quality (PQ) event that can significantly affect the reliable operation of a power system. Locating the source of a voltage dip supports the root-cause analysis needed to identify opportunities for mitigation that will improve the performance of a specific network. Several research papers proposed different methods to locate voltage dips in power systems, such as [1] and [2].

The term "voltage dip" refers to a sudden drop in the root mean square (RMS) value of the supply voltage at the power frequency to a level between 10% and 90% of the rated voltage, followed by a voltage recovery after a brief period of time, typically 10 ms to 60 s [3]. Voltage dips are caused by various factors in power systems, such as faults, switching operations and load changes.

The instrument for monitoring PQ phenomena such as voltage dips is typically the Power Quality Meter (PQM), which, when installed at different points in the network, can collectively provide important information for grid management. Additional features, such as accurate time synchronisation and detailed waveform data, allow geographically distributed dip event events to be aggregated (clustered) to a single network incident within a database to locate the source of voltage dips. Analysis of all data relevant to such a single network incident then allows the proper context from which the knowledge needed by system operators can be derived.

Such architecture, see [4], allowed a new methodology to locate voltage dips making use of only the basic parameters recorded during a voltage dip, such as residual voltage, event duration and start time. Geographically distributed measurements from both sides of substation transformers were used. Performance was compared, with promising results, against two known methods ([5] and [6]) that also aim to locate voltage dips.

This paper refines, extends, and then validates the method discussed in [4]. In particular:

- To avoid possible errors when aggregating (grouping) events with a similar timestamp assumed to be related to the same network incident (same root-cause), the criterion considered in [4] is integrated by also considering the duration of different dip events and the timestamping accuracy of the PQMs involved.
- The flexibility of the method is extended to a multi-level scenario, where several substations are connected in cascade.
- The performance of the improved method is tested by considering field data within a 66 kV/11 kV South African distribution network. The importance of choosing suitable values for the voltage threshold levels required in the implementation of the method is also discussed.

## II. METHOD FOR IDENTIFYING VOLTAGE DIPS SOURCES

Starting from the approaches proposed in [5] and [6], an improved technique aimed at identifying if a voltage dip originated in the upstream (further referred to as High Voltage (HV)) or downstream (Low Voltage, (LV)) portion of the system has been presented in [4]. It made use of basic dip data as residual voltage, starting time and duration, as in general expected from PQMs. This method merges criteria based on the timestamping and residual voltage of voltage dip events detected at different busbars and in different HV/LV substations, which are electrically close due to sharing the same HV supply, as shown in Fig. 1.

For the sake of simplicity, in what follows, all the considered criteria, i.e. both the proposed method and those chosen for comparison, will be presented by considering only dips detected by two similar PQMs. Implementation can be easily and straightforwardly extended to general cases where a substation has more than one HV/LV transformer and more than two PQMs that are installed in different busbars.

The parameters to be measured during a voltage waveform are unambiguously defined by Standard [7]. By tracking the RMS voltage for each phase in at least a  $\frac{1}{2}$ -cycle resolution, when any phase voltage sags below the dip threshold (normally -10 % of nominal), the duration of the voltage dip is defined as starting at that time instant, lasting until the last phase voltage recovers beyond the dip threshold value incremented by a hysteresis value. The residual voltage of a voltage dip is the lowest RMS value measured on any phase during the event.

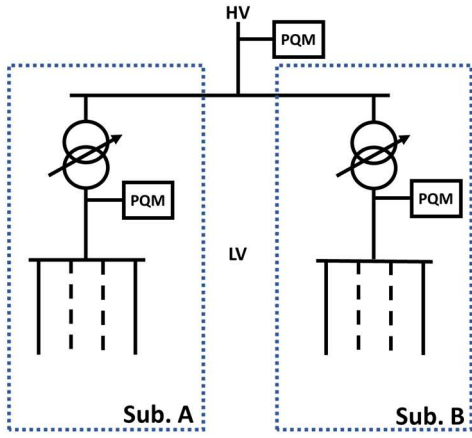


Fig. 1. Two substations (Sub. A and Sub. B) on the same HV line

### A. First step: time aggregation

Voltage dips detected at two different busbars of HV/LV substations sharing the same HV supply are grouped into a single network incident if they occur simultaneously.

In previous approaches [5] and [6], the difference between dip trigger timestamps was considered as a criterion to detect two dip events that occur at the same time:

$$|T_i - T_j| \leq \delta T_{lim} \quad (1)$$

where  $T_i$  and  $T_j$  are the timestamps of the considered voltage dip events recorded by two generic PQMs  $i$  and  $j$  and  $\delta T_{lim}$  is a predetermined threshold. Such approach may fail [3] when two voltage dips detected at different locations, sharing the same root-cause, have a significantly different RMS voltage profile, as shown in Fig. 2. Indeed, the different depths and slopes of the two voltage profiles can lead to situations where the difference ( $T_j - T_i$ ) between the start time of the two events is larger than the established threshold, suggesting that the two voltage dips are unrelated, even if they are actually related to the same incident in the power system.

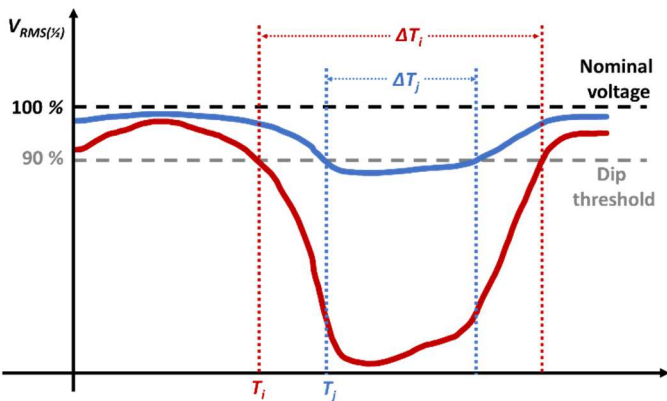


Fig. 2. Example of two RMS voltage profiles corresponding to two simultaneous dip events measured at two remote locations but having different start times ( $T_i$  and  $T_j$ ).

This issue is overcome by integrating criterion (1) with an additional aggregation policy: if the shallowest voltage dip is located within the deepest one (i.e. the start time of the shallowest voltage dip occurs after that of the deepest one, and

the shallowest dip ends before the deepest one), then the two events are related to the same root-cause.

In this process, timestamping uncertainty must be considered. In this paper, such uncertainty is taken into account by introducing an additional term,  $T_u$ .

Finally, the two events are “simultaneous” if either condition (1) or the following composite condition (2) is met:

$$T_j \geq T_i - T_u \quad \text{and} \quad T_j + \Delta T_j \leq T_i + \Delta T_i + T_u \quad (2)$$

where  $\Delta T_i$  and  $\Delta T_j$  are the durations of the considered voltage dips as detected by the respective PQMs.

### B. Second step: comparison of residual voltages

The origin of the voltage dips is attributed to the HV grid if the difference between the residual voltages of the detected dips is lower than a given threshold  $\Delta V_{lim\%}$ .

In this respect, the method can be implemented in two ways, depending on the available instrumentation.

If only measurements taken at the LV side of the substations are available, the criterion to be considered to attribute the origin of the dip to the HV side is as follows:

$$|V^A - V^B| \leq \Delta V_{lim\%} \quad (3)$$

where  $V^A$  and  $V^B$  are the RMS values (in percent) of the residual voltages of the two voltage dips simultaneously recorded in LV busbars of substations A and B, respectively (see Fig. 1). If the voltage difference in (3) is higher than the limit value ( $\Delta V_{lim\%}$ ), then the origin of the voltage dip incident is in the section of the LV grid where the lowest residual voltage value was measured.

If synchronous measurements of the same events are also available on the HV side of the power system, e.g. provided by either Phasor Measurement Units (PMUs) or further PQMs, this information can be exploited to improve the performance of the method. In this case, the dip incident is attributed to the HV network if the following criteria are simultaneously fulfilled:

$$|V^{HV} - V^X| \leq \Delta V_{lim\%} \quad (4)$$

where  $V^{HV}$  is the residual RMS voltage (in percent) of the voltage dip recorded in the HV grid; and, in  $V^X$ , the superscript  $X$  can be either  $A$  or  $B$ . If condition (4) is not met for a given busbar  $X$ , then the origin of the voltage dip incident is attributed to the section of the LV grid supplied by the corresponding busbar.

### C. Selection of the thresholds

The implementation of the method is based on the suitable selection of time and voltage thresholds  $\delta T_{lim}$  and  $\Delta V_{lim\%}$ .

In scientific and technical literature, different values have been proposed. For  $\Delta V_{lim\%}$ , values typically ranging from 3 % to 10 % of the nominal voltage value are used. The highest values are introduced to take into account different possible conditions that can lead to voltage differences exceeding 3 %, such as the different positions of the on-load tap-changers in the HV/LV transformers, the contribution of power flows from distributed renewable power generation, and the voltage drop across the impedance between different measurement points.

The time threshold  $\delta T_{lim}$  on the starting time of the dip trigger is usually set to either 60 ms [6] or 70 ms [8].

In any of the cases considered, specific values for voltage and time thresholds should reflect the conditions in the grid under investigation, and therefore their values must be configured according to the specific grid conditions, reflecting the monitoring strategy pertaining to a specific network. In the following section, tests will be performed to underline the effects of possible different choices.

Finally, concerning the value of the term  $T_u$  related to timestamping uncertainty in (2), two contributions can be considered. The first one is related to the dip detection method indicated in IEC 61000-4-30, which is based on zero crossings, and can be set to 20 ms in 50 Hz systems. The second one is related to the quality of PQM synchronisation, and its estimation requires information on the accuracy of the primary time source and the internal clock. As an example, the PQMs considered in this work have a GPS receiver, whose time accuracy during normal conditions is  $\pm 100$  ns, and an internal clock with an accuracy of 1 ppm [9]. Both values are negligible with respect to the 20 ms of the first contribution described above. However, other synchronisation techniques can be used, but with a time source accuracy up to many orders of magnitude greater, e.g. if Network Time Protocol (NTP) is considered.

#### D. Cascade Application

The application of the proposed approach can be suitably extended to situations where the power system involves more than two portions, operated in cascade at either different voltage levels or the same voltage level.

Fig. 3 shows a situation where the secondary busbars, referred to as Medium Voltage (MV), of the HV/MV substations connected to the same HV grid supply both a further distribution network at MV level (busbars  $C_1$  and  $C_2$ ) and an LV portion of the grid (busbars  $D_1$  and  $D_2$ ), fed by proper MV/LV substations.

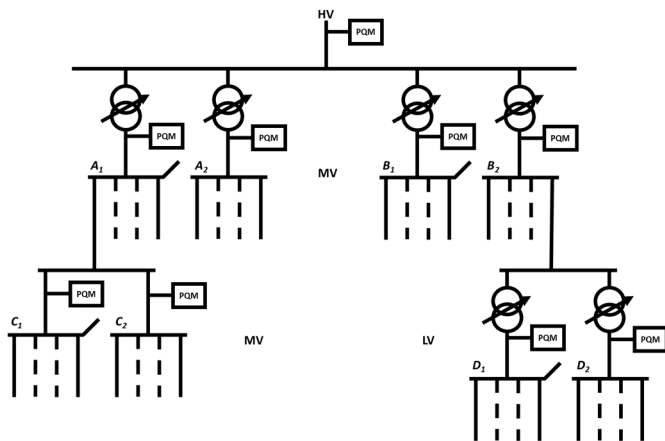


Fig. 3. Power system with High Voltage (HV), Medium Voltage (MV) and Low Voltage (LV) monitored busbars.

In this case, a first application of the method on the HV and MV sides allows the origin of the dip to be attributed to one of two levels. If the event is attributed to the feeders supplied by a specific MV busbar, a second application on that limited part of the network allows a more detailed identification of the event's origin. If, for instance, the root cause of the event is found to be located downstream of busbar  $B_2$  in the first round, a second round allows the operator to

identify if this cause is either in the MV portion of the grid supplied by that busbar or in one of the LV feeders supplied by one of the MV/LV transformers (e.g., through busbars  $D_1$  or  $D_2$  in Fig. 3).

As a general final remark, the method has been presented and discussed here by considering that all involved busbars are monitored. The presence of possible non-monitored busbars does not affect the possibility of locating the source of voltage dips originating in other (monitored) portions of the grid, but, of course, it does not allow for possible events originating in the portion supplied by that specific non-monitored busbar to be identified correctly.

### III. MEASUREMENT ARCHITECTURE

A brief presentation of the elements that compose the considered measurement architecture is reported in what follows.

#### a) Data Platform

The data platform responsible for collecting data from devices installed at different nodes of the network is Osprey PRO [10]. Osprey PRO is used to store the recorded data from the PQMs, which can be accessed in near real-time via a user-friendly web interface. The data platform is specifically designed for PQ analysis and can report on the behaviour of the electric network through waveform graphs and RMS profiles of voltages and currents. Power frequency and the state of the instruments installed in the network (synchronisation status, device fault, etc.) are also included in the monitored quantities. In addition, system operators can add information to the events recorded in the platform, such as the origin of a fault or voltage dip. Knowing the real causes behind them allows the events to be analysed in detail.

#### b) Measurement Devices

The PQM used to generate field data is CT Lab's Vecto 3 [9]. It complies with power quality standard [7] (Class A, Edition 3, on both voltage and current) and features a built-in GPS receiver with a timing accuracy of  $\pm 100$  ns. With a sampling rate up to 500 kHz, it can acquire waveforms and track the RMS voltage profile with a 1/6 cycle resolution, exceeding the minimum requirement of [7] (a 1/2 cycle resolution). A cloud database hosts, administrates, analyses and reports on instruments geographically distributed within the context of network connectivity, such as a specific distribution network under consideration.

#### c) Monitored Network

The considered South African network covers an area of 800 km<sup>2</sup>, serving residential, industrial and commercial loads. Network performance is monitored by 42 PQMs located at strategic points in this network.

A simplified generic scheme of this network is presented in Fig. 3. Several substations share the same 66 kV grid (indicated as HV in Fig. 3). Each substation hosts one, two or three 66 kV/11 kV transformers. These 66 kV substations can be connected in cascade with other distribution substations supporting downstream loading requirements.

### IV. TEST AND RESULTS

The performance of the proposed approach has been verified on several test cases based on real-field voltage events that have been detected between 2021 and 2023.

The test cases focus on different scenarios that involve different substations and PQMs installed at different voltage levels so that different formulations of the approach, as defined by equations (3) and (4), can be analysed.

#### A) Case Study 1

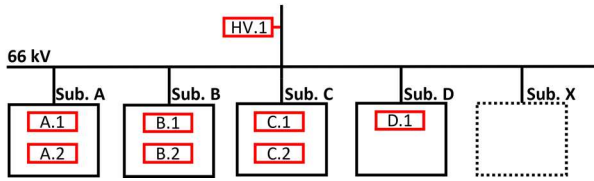


Fig. 4. Portion of 66 kV/11 kV network with substations monitored by PQMs (in red) considered for case studies 1 and 2.

The first test case refers to a voltage dip recorded by different PQMs installed in different electrical substations at different voltage levels (Fig. 4). The results, which Table I summarises, show that the recorded events have similar durations between 407 and 438 ms. The difference between the timestamps of all reported events is within 60 ms, thus meeting the threshold chosen for criterion (1). The lowest residual voltage (32.76 %) is recorded by PQM B.2, installed at the 11 kV busbars of one of the transformers existing in substation B. PQM B.1 is installed in the same substation and recorded a residual voltage value comparable to those reported by instruments installed in neighbouring substations. In this case, the proposed method allows the correct identification of the source (Substation B, Feeder 2 monitored by the PQM B.2) with both its possible implementations, that is, either by only using measurements taken downstream of transformers, criterion (3), or exploiting the measurements available in the upstream side, criterion (4).

TABLE I  
CASE STUDY 1: EVENT DATA AND RESULTS OF THE LOCALIZATION METHOD

PQMs and voltage levels	Residual voltage [%]	Duration [ms]	Crit. (3) (Only LV)	Crit. (4) (LV and HV)
A.1 (11 kV)	88.9	407	Origin: LV Sub. B Feeder B.2	Origin: LV Sub. B Feeder B.2
A.2 (11 kV)	88.0	407		
B.1 (11 kV)	89.0	407		
B.2 (11 kV)	32.8	438		
C.1 (11 kV)	87.9	407		
C.2 (11 kV)	88.9	407		
D.1 (11 kV)	87.3	411		
HV.1 (66 kV)	87.6	411		

#### B) Case Study 2

Case study 2 shows the importance of choosing a correct threshold  $\Delta V_{lim\%}$  for criteria (3) and (4).

Table II refers in particular, for the sake of brevity, to the method applied through criterion (3), which means considering only the downstream measurements shown in Fig. 4. It is possible to observe differences of 3.15 % and 3.23 % between the residual voltage measured by PQM D.1 in substation D and those measured by PQMs A.1 and A.2, respectively, both in substation A. This means that if a threshold of 3 % was applied, as considered in other methods for locating voltage dips (see, for instance, [8]), the method would incorrectly attribute the origin of this event to the LV

grid fed by substation D. On the other hand, a higher threshold (10 %) allows the correct identification of the voltage dip source, originated in the HV level.

As a general consideration, a suitable threshold should be chosen after an in-depth analysis of the monitored network. To this purpose, when available, supervised learning techniques or simulated events could be used.

TABLE II  
CASE STUDY 2: EVENT DATA AND RESULTS OF THE LOCALIZATION METHOD

PQMs and voltage levels	Residual voltage [%]	Duration [ms]	Crit. (3) (Only LV) $\Delta V_{lim\%} = 3\%$	Crit. (3) (Only LV) $\Delta V_{lim\%} = 10\%$
A.1 (11 kV)	54.9	107	Origin: LV Sub D	Origin: HV
A.2 (11 kV)	55.0	107		
B.1 (11 kV)	54.2	107		
B.2 (11 kV)	54.5	100		
C.1 (11 kV)	52.8	100		
C.2 (11 kV)	52.9	100		
D.1 (11 kV)	51.7	110		

#### C) Case Study 3

This case study emphasizes the need to use a proper technique, such as the time aggregation defined in criterion (2), to assess if events indeed occurred simultaneously, such as the events presented in section II.A. The measurements obtained from 2 substations (subs A and B) and from the PQM installed at 66 kV (PQM HV.1) are considered below.

Observe the LV measurements recorded by PQM A.1 and PQM A.2 and presented in Fig. 5. The dip event detected by the former is the deepest, with a residual voltage of 16.4 %, while the latter has a residual voltage of 89.9 %. When evaluated according to [7], the starting time of the two events indicated a time difference of more than 60 ms (3 cycles of the fundamental frequency waveform). Therefore, if the approach of [5] and [6] was used, as defined in criterion (1), these two dip events would have been classified as separate dip events not sharing the same root cause. On the contrary, the improved grouping methodology defined by criterion (2) allows the two dips to be considered as the consequence of the same root cause.

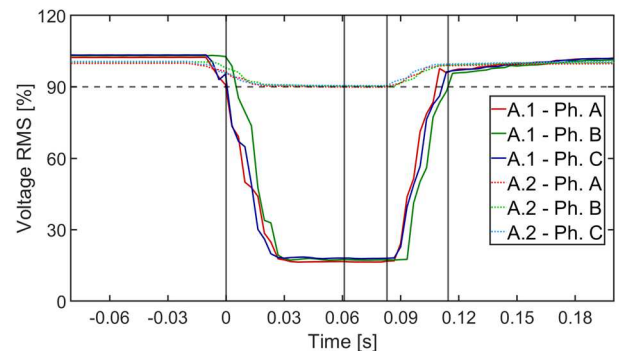


Fig. 5. Voltage RMS profiles from PQMs A.1 and A.2.

Once the issue of dip aggregation has been successfully addressed, the full methodology can be applied to obtain the results listed in Table III.

TABLE III  
CASE STUDY 3: EVENT DATA AND RESULTS OF THE LOCALIZATION METHOD

PQMs and voltage levels	Residual voltage [%]	Duration [ms]	Crit. (3) (Only LV)	Crit.(4) (LV and HV)
A.1 (11 kV)	16.4	117	Origin: LV Sub A Feeder A.1	Origin: LV Sub A Feeder A.1
A.2 (11 kV)	89.9	33		
B.1 (11 kV)	89.7	50		
B.2 (11 kV)	90.0	23		
HV.1 (66 kV)	90.27	20		

#### D) Case Study 4

The last case study evaluates the performance of the proposed method across several substations in cascade, shown in Fig. 6. As an example, Table IV lists voltage dip events recorded by several PQMs at different 66 kV and 11 kV nodes (11 kV is referred to as MV in this case). Substation A feeds substation AA in a cascade connection. MV feeders from the secondary substation (Sub. AA) are monitored by 3 PQMs (AA.1, AA.2 and AA.3). Timestamps of the event starting times are within 60 ms, meeting the threshold chosen for criterion (1).

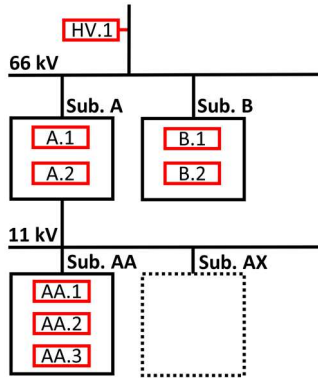


Fig. 6. A portion of the 66kV/11kV network with substations monitored by PQMs (in red) considered for the case study 4.

The lowest residual voltage is detected by the MV PQMs of substation A and in the interconnected substation AA. For the same event, the remainder of PQMs in substation B have detected much higher residual voltages between 88.76 % and 89.55 % of the nominal voltage.

According to subsection II.D, the first step of the methodology, which means the application of criterion (4) to the substations directly connected to the 66 kV line, attributes the source of the event downstream substation A.

The second step defined in II.D, i.e. the application of the proposed method to the MV substations, allows attributing the root cause of this voltage dip incident to the branches downstream substation A, not being monitored.

The above results conformed to the results obtained by the electrical utility, which had access to the operational data as recorded during this network incident, namely an underground cable fault in an unmonitored feeder, supplied by substation A as shown in Fig.6, indicated as “substation AX”.

TABLE IV  
CASE STUDY 2: EVENT DATA AND RESULTS OF THE LOCALIZATION METHOD

PQMs and voltage levels	Residual voltage [%]	Duration [ms]	Crit. (3)	Crit. (4)
A.1 (11 kV)	36.3	442	Origin: MV Upstream Sub AA	Origin: MV Upstream Sub. AA
A.2 (11 kV)	36.3	442		
AA.1(11 kV)	36.2	442		
AA.2(11 kV)	35.9	439		
AA.3(11 kV)	36.0	439		
B.1(11 kV)	88.8	319		
B.2(11 kV)	89.8	279		
HV.1 (66kV)	89.6	319		

## V. CONCLUSIONS

Identifying the location of the voltage dip is crucial to increase the resilience of a power system. In this paper, a method that makes use of basic dip data produced by PQMs was improved to increase the aggregation performance of different dip events recorded at different geographical and electrical locations of a distribution network.

Four case studies validated this method which can be used in different grid architectures, making use of PQ metering devices located both upstream and downstream of transformers between different distribution voltage networks.

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