PHASOR BASED VOLTAGE SAG MONITORING AND CHARACTERISATION

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INTRODUCTION

This article addresses a wide three-phase voltage sag characterisation, including magnitude, phase-angle jump, and duration. A signal-processing algorithm is proposed to obtain voltage sag characteristics for phase voltages and positive sequence voltage.

The proposed methodology is applied to a set of actual measurements obtained from a power quality monitor and from a synchrophasor measurement unit (PMU). Sag characterisation from both data sources are compared, indicating advantages and drawbacks of each device.

Results show that data from PQ-monitors permit a more complete disturbance characterisation, however results from data obtained by PMUs are promissory for sag characterisation when the recording frequency of the PMU is increased.

BACKGROUND

Voltage sags (dips) are regarded as one of the most relevant issues in power quality due to their high-cost impact in sensitive industrial loads such as adjustable speed drives, frequency converters, and contactors. A voltage event is considered as sag when the rms voltage remains between 0.1 and 0.9 p.u. (per-unit) of nominal voltage and the event duration does not exceed one minute [1]. However, short interruptions where rms voltage is below 0.1 p.u. of nominal voltage, can also be considered as voltage sag events [2].

Although voltage sags are defined as a short duration decrease in the rms voltage, there is no full agreement on their characterisation and severity evaluation. This voltage disturbance has been mainly characterised by its magnitude and duration. Alternatively, research has been developed to simplify voltage sag characterisation to one parameter. Several indices have been proposed: loss of voltage, loss of energy and sag severity. These indices express the sag severity through only one parameter resulting from a combination of magnitude and duration. Moreover, the sensitivity of process has been correlated with some of these parameters, finding that only some of them were successful to represent process sensitivity [3].

On the other hand, for accurate event characterisation and prediction of sensitive equipment behaviour during unbalance three-phase disturbances additional parameters are needed [4]. Symmetrical components have been used to classify three-phase voltage sags, in the so-called ABCD classification [5][6]. This approach has improved the characterisation of three-phase events and the analysis of three-phase equipment sensitivity to unsymmetrical voltage sags.

Despite the fact that three-phase loads are also sensitive to phase-angle jump [7], available standards only estimate equipment sensitivity in terms of event magnitude and duration, using the so-called voltage sag coordination chart or the magnitude-duration chart [8][9].

This article addresses a wider three-phase voltage sag characterisation including magnitude, duration, and phase-angle jump. A signal-processing algorithm is proposed to obtain voltage sag characteristics from phase voltage and positive sequence voltage. Additionally, phase and positive sequence voltage sag characteristics are compared in terms of the accurate representation of event severity.

Actual data, recorded by a power quality monitor (PQ-monitor) and a synchrophasor measurement unit (PMU), are used to evaluate the proposed methodology. PQ-monitor data is a raw set of instantaneous three-phase voltages recorded at 32 samples per cycle, whereas PMU data is the positive sequence voltage, estimated once each cycle. PQ-monitor data permits a complete three-phase characterisation through sag magnitude and phase angle jump, computed 32 times per cycle. Nevertheless, PMU data allows only positive voltage component characterisation through magnitude and phase angle jump estimated once per cycle. Although, some drawbacks of PMU voltage sag assessment can be stated, it is a novel application of this measurement device.

METHODOLOGY AND RESULTS

Power quality monitor raw data was obtained from an equipment installed in the low voltage network (460 V LL three-phase three-wire grid) of a cable factory in Brazil. The PQ-monitor was set to trigger when rms voltage remains below a certain threshold, 0.90 p.u. of nominal voltage. As a consequence, the monitor records the instantaneous voltages during a certain period. The number of points per cycle and the number of cycles recorded are configurable in the monitor used in this research. It has been set to record 54 cycles with 32 points per cycle, being 900 ms the total recorded period. Thus, each recorded event is a set of 5184 instantaneous voltages (Vabc), 1728 voltages for each phase.

Moreover, as shown in Figure 1, a voltage disturbance is noticed because voltage amplitude is highly reduced in the period from 115 to 165 ms. However, to estimate voltage sag characteristics, rms voltages must be computed.
Estimation of rms values
Instantaneous voltages are used to estimate the rms voltages according to equation (1). The previous cycle of instantaneous voltages is used to obtain the new rms value. The estimation is performed each 0.52 ms (32 times per cycle). A one-cycle window is employed to avoid the oscillation produced by second harmonics when half-cycle window is used.

\[ V_{\text{rms}}(k) = \sqrt{\frac{1}{N} \sum_{i=-N}^{N+1} v_i^2} \]  

(1)

Where \( N \) is the number of points per cycle and \( v_i \) the instantaneous sampled voltage at time \( i \).

The rms voltages (phase to ground voltages) of the event presented in Figure 1 are shown in Figure 2. It can be seen that it is a three-phase unbalance voltage sag, where the sag differs in magnitude and duration in each one of the three phases. Most common characterisation considers the magnitude of the deepest sag and the duration of the overall disturbance. Therefore, this event is characterised by magnitude of 24 V (0.09 p.u.) and duration of 50 ms.

Estimation of fundamental voltages
It is often useful to compute the fundamental voltages, i.e. the 50 or 60 Hz voltage component. Discrete Fourier Transform (DFT) is the standard tool for estimating these voltages. The main advantage of performing this computation is that both voltage magnitude and angle are easily obtained, facilitating further characterisation such as phase-angle jump and symmetrical component analysis.

As shown in Figure 3 the magnitude of the fundamental voltage as a function of time is almost the same as the rms voltage as a function of time. This is accurate when voltage harmonic level is below the recommended limits. Consequently, voltage sag magnitude estimated as the lowest rms voltage or as the lowest value of the fundamental voltage gives similar result.

Phase-angle jump estimation
Once the fundamental voltages are obtained by Discrete Fourier Transform algorithm, the phase-angle jump is also estimated. Considering pre-event phase angle as the reference, phase-angle jump is computed as the difference between the instantaneous and pre-event angle. Phase-angle jump for the voltage sag presented above is shown in Figure 4. It can be observed that for this three-phase unbalanced sag the phase-angle jump experienced by each phase is different. In the disturbance presented, one phase experiences a positive phase-angle jump of 22 degrees, while the other two phases experience phase-angle jumps of –45 and –30 degrees respectively. Which value to be used to characterise the three-phase event is a controversial issue, considering that there is not any IEEE or IEC standard where phase-angle jump is defined for three-phase voltage sags.
Phasor measurement unit for voltage sag characterisation

Phasor measurement unit (PMU) data available is not as complete as data available from PQ-monitor devices. Normally a PMU only delivers magnitude and phase-angle of the positive sequence voltage. In order to explore its possibilities for power quality monitoring, first, a PMU is simulated using the data available from the PQ-monitor. Thus, for the same event presented in Figure 1, the results that would be obtained from a PMU are estimated, considering two recording speeds: 32 times per cycle (continuous line) and once per cycle (star points). Positive sequence voltage magnitude and phase-angle are shown in Figure 5 and Figure 6, respectively.

Positive sequence Voltage - V1

Voltage [V]

Time [ms]

Figure 5 – Positive sequence voltage magnitude estimated by fictitious PMU

As observed in Figures 5 and 6, a considerable difference may be obtained in the values used for event characterisation, signalled by the arrows. While voltage sag magnitude coincidentally gives similar results, phase-angle jump presents a huge difference as shown by the two arrows on Figure 6. The estimation performed once per cycle gives one result (-8 degrees) that is almost half the phase-angle jump estimated by the algorithm derived 32 times per cycle (-14 degrees).

Positive sequence Voltage - V1

Voltage [pu]

Time [s]

Figure 7 – Positive sequence voltage magnitude obtained from real PMU

Phase-angle jump of V1

Angle [Deg]

Time [ms]

Figure 6 – Positive sequence voltage phase-angle estimated by fictitious PMU

Then, actual data from a PMU is analysed. These measurements were taken in the island Oland in Sweden, during a LG fault in the 50 kV network. Oland network is interconnected to mainland with a 130 kV submarine cable. There is a second connection with a 50 kV cable that is normally used for reactive power compensation in the island. The PMU is connected to the substation voltage and current transformers. The quantities recorded are positive sequence phasors (magnitude and phase angle) of the measured voltages and currents, frequency and rate of change of frequency. The speed of recording is settable to once every cycle, once every 2\textsuperscript{nd} cycle or once every 4\textsuperscript{th} cycle. For this research recording speed is set to once per cycle. The PMU sends data to a PC, which zips and stores it on a hard disk.

Positive sequence voltage estimated by a PMU needs to be analysed. For instance, phase-angle is measured using the GPS signal as time reference. As actual frequency is not exactly nominal the phasor recorded seems to be rotating with a relative frequency given by the difference between actual frequency and nominal one. In order to obtain a static phasor the recorded phasor is decomposed in a new coordinate system that is rotating at the pre-event relative frequency. Thus, a new positive sequence voltage is obtained keeping the former phasor magnitude but with a new angle which is zero for pre-event situation. So far, positive sequence voltage magnitude and phase-angle are presented in Figure 7 and Figure 8 respectively, where the star points show the estimated phasor values once per cycle.

Positive sequence Voltage - V1

Voltage [pu]

Time [s]

Figure 7 – Positive sequence voltage magnitude obtained from real PMU

Phase-angle jump of V1

Angle [Deg]

Time [s]

Figure 8 – Positive sequence voltage phase-angle obtained from real PMU

The continuous line, seen in Figures 7 and 8, is just a
The low frequency of PMU estimation is the main limitation when the goal is the voltage sag characterisation. This limitation can be easily overcome if PMUs are capable of perform more phasors estimation per cycle. It is considered that 16 recordings per cycle are satisfactory for voltage sag characterisation.

CONCLUSION

Here, a three-phase voltage sag characterisation has been addressed through the sag parameters that are considered the most hazardous for sensitive loads. This characterisation includes voltage sag magnitude, phase-angle jump and event duration. Actual raw data obtained from PQ-monitor measurements at a low-voltage industrial grid in Brazil and from PMU measurements at high-voltage grid in Oland (Sweden) have been used for sag characterisation.

Raw data (instantaneous voltages) obtained from PQ-monitoring were used to test the signal-processing algorithm that estimates rms voltages and fundamentals. Results show that rms voltage and the magnitude of fundamental voltage present similar behaviour. Hence, voltage sag magnitude and duration can be accurately estimated from either rms or fundamental voltages. Phase-angle jump has also been estimated from fundamental voltages, and it is defined as the difference between pre-event phasor angle and the actual phasor angle during the event. The three phases experience different phase-angle jumps during unbalanced voltage sags. One way to define the event phase-angle jump is to choose the highest absolute deviation. Further research and discussion in this issue is needed, as it is not standardised yet.

Phasor measurements units give an interesting but incomplete insight on voltage dip characterisation. Data available from PMUs include positive sequence voltage magnitude and phase angle estimated with GPS as time reference. The proposed signal-processing algorithm estimates the phasor in new rotating coordinates, so pre-event phasor angle is steady zero. Voltage sag magnitude is estimated as the smallest positive sequence voltage magnitude and the phase-angle jump as the highest phase-angle deviation. The algorithm considers linear interpolation between the actual known values. This is the weakness of PMU as power quality monitoring device for voltage dip estimation. If PMU functionality is extended to record three-phase voltages with higher frequency and intelligent threshold recording, it can be considered an excellent device for power quality measurements.

ACKNOWLEDGEMENT

CAPES from Ministerio da Eduacao do Brasil supports this research.

REFERENCES


BIOGRAPHIES

Roberto Chouhy Leborgne was born in Montevideo, Uruguay, in 1972. He received his E.E. Degree and MSc. E.E from Universidade Federal de Itajuba, Brazil, in 1998 and 2003, respectively. His employment experience includes ABB-Daimler Benz Transportation Brazil and Teyma Abengoa Uruguay. He is currently a PhD candidate at Chalmers University of Technology, Sweden. His research field of interest is voltage sags (dips).

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