12th IMEKO TC4 International Symposium
Electrical Measurements and Instrumentation
September 25-27, 2002, Zagreb, Croatia

A MULTI-CRITERIA ALGORITHM FOR VOLTAGE SAG DETECTION

R. Chiumeo[1], A. Florio[2], A. Mariscotti[3] and M. Mazzucchelli[3]

[1]CESI S.p.A. - Milano - Italy
[2]Ansaldo Ricerche s.r.l. - Genova - Italy
[3]Dipartimento Ingegneria Elettrica, Università di Genova, Genova, Italy

Abstract - A multi-criteria algorithm for voltage sag detection is presented and its performances are evaluated by means of recorded voltage waveforms (at some Medium Voltage/Low Voltage transformers) and simulated voltage/current waveforms. The algorithm is intended to detect voltage sag occurrence and to trigger the disconnection of the faulty supply network and subsequently the connection of a voltage support system. The algorithm is very convenient in terms of memory storage and computational requirements and may be implemented on low cost platforms. The results show that the time for detection is very short and always less than a quarter of the supply voltage period.

Keywords: Industrial power system transients, Power conditioning, Signal detection

1. INTRODUCTION

A voltage sag is a reduction of the voltage at a customer position with a duration of between one cycle and a few seconds [1]. Voltage sags are caused by motor starting, short circuits and fast reclosing of circuit breakers. Voltage sags normally do not cause equipment damage, but can easily disrupt the operation of sensitive loads such as adjustable-speed drives, static converters supplied loads, etc. [2,3,4].

Voltage sags are much more common than voltage interruptions. Even voltage sags lasting only 4 - 5 cycles can cause sensitive equipment to malfunction [5,6,7].

Several solutions have been conceived for sensitive loads, depending on several factors [4,8,9,10]. For the solutions which imply one or more static converters, switched onto the supply network to feed the load in case of voltage sag or voltage interruption, a key role is played by the time for the detection of the voltage sag and the duration of the switching operation. Depending on the characteristics of the sensitive load, the requirements on the intervention time may be very severe. Moreover, the choice of algorithm/techniques for voltage sag detection is highly dependent on the real-time requirements, on the available computational hardware and on the amount of computational effort. Several approaches have been proposed in the literature for voltage sag analysis and detection [11-16]. The algorithms appearing in the literature are based on 1) Short Time Fourier Transform, 2) analog or digital filters banks, 3) wavelet transform using different wavelet kernels, 4) neural network classifiers and 5) fractal base methods.

In the next sections a composite algorithm is presented and its performances are verified against simulated and measured voltage sags.

2. MULTI-CRITERIA ALGORITHM

The proposed algorithm (see Fig. 1) consist of a cluster of simple algorithms (in this implementation limited to two algorithms both operating on the line-to-line voltage), which can be implemented on a low cost microprocessor or DSP board, which operate in parallel; a final block (an OR gate in this implementation) determines the global answer on the basis of the answers received by the three different algorithms.

The use of multiple algorithms is intended to increase the robustness of the voltage-sag detection process, by keeping each algorithm less sensitive to voltage harmonic distortion with correct trimming of algorithm parameters.

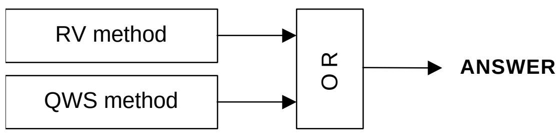


Fig. 1 Block diagram of the Multi-criteria algorithm

The Rectified Voltage (RV) and Quarter Wave Symmetry (QWS) methods are described in the next section. These methods may be classified of category 2, since they are based on the manipulation of the supply voltage signal by means of linear and non-linear filters.

2.1. Rectified Voltage (RV) method

The RV algorithm is based on the comparison of the instantaneous rectified voltage $r(n)$ (which may be obtained with a low power diode bridge or with maximum operation performed at software level) with a reference rectified voltage $rr(n)$, obtained using a moving average filter (Finite Impulse Response filter). The comparison is performed using an adjustable threshold α. The algorithm operates on the rectified voltage only, instead of all the three-phase input voltages, to save computational time and storage memory.

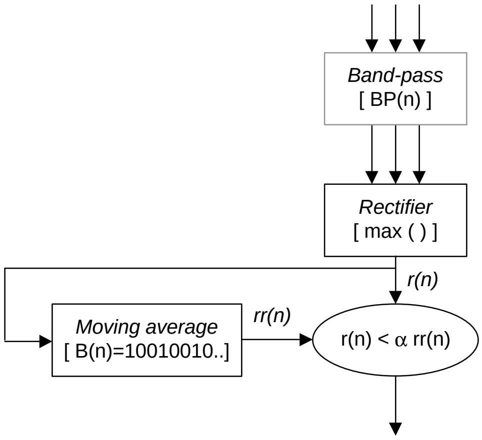


Fig. 2 Block diagram of the RV method

The algorithm may be simplified if the reference signal $rr(n)$ is assigned the rated no-load rectified voltage given by

$$rr(n) = 1.35\,V_{ll,rms} \tag{1}$$

The "moving average" $B(n)$ filter is used to obtain a reference signal $rr(n)$, which is updated by the real average rectified voltage. The filter structure is conceived as a repetitive sequence (M times) of a nonzero coefficient followed by $P-1$ zeros; in this case the depth of the filter is $M(P-1)$ samples, but the multiplications necessary to perform filtering are only those corresponding to the nonzero coefficients. The $B(n)$ filter is a FIR filter with the following general structure

$$B(n) = \begin{cases} 0 & n \neq Pk, \quad k \text{ integer} \\ 1 & n = Pk, \quad k \text{ integer} \end{cases} \tag{2}$$

where

- P is the length of a single averaging cell in number of samples;
- M is the length of the filter impulse response in number of samples.

An ageing factor $1/k$ is also included in the more general version of the filter. In the present implementation of the RV algorithm the sampling frequency is 5 kHz.

2.2. Quarter Wave Symmetry (QWS) method

The QWS algorithm records the samples corresponding to only one fourth of the supply voltage period and estimates the line-to-line rms value $\hat{V}_{ll}$ by assuming even and odd symmetry. The rms value $\hat{V}_{ll}(i)$ at the i-th instant of time is computed using the averaged sum of the square of the last M voltage samples as expressed in (2).

$$\hat{V}_{ll}(i) = \frac{1}{M} \sum_{k=i-M+1}^{i} (v_{ll}(k))^2 \tag{2}$$

The computed rms value $\hat{V}_{ll}(i)$ is compared to the rated value of the rms line-to-line voltage V_{ll} by means of a scaling coefficient δ. The block diagram of the QWS algorithm is reported in Fig. 3; it was found that there is no need for an input band-pass filter to limit the input noise, since this method can work with very low sampling rates (only 20 samples per period, which corresponds to 1000 Hz sampling frequency).

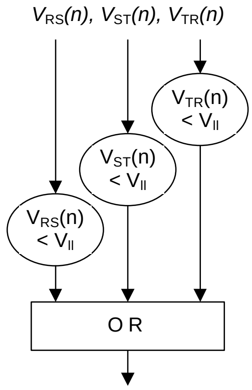


Fig. 3 Block diagram of the QWS method

The QWS algorithm is used as backup solution to ensure a maximum delay for sag detection in case of RV failure.

3. TEST OF THE ALGORITHMS

The tests are performed using:

1. artificial three-phase test signal generated at a specified THD (ranging from 2% up to 8%), with the amplitude of harmonic components proportional to the limits indicated in the standard EN 50160 [17] and random phase with uniform distribution; the voltage sag is of variable amplitude between 10% and 100% (voltage interruption), occurring always at t=50 ms;
2. three-phase voltages recorded at voltage sags occurrence;
3. three phase voltages with fault induced on a prototype system in the laboratory;

3.1. Test with artificial voltage sag waveforms

The results of the test performed on artificial sag waveforms is shown in Fig. 4, where the normalised rms value of the line voltage is shown together with the output "ANSWER" of the composite algorithm.

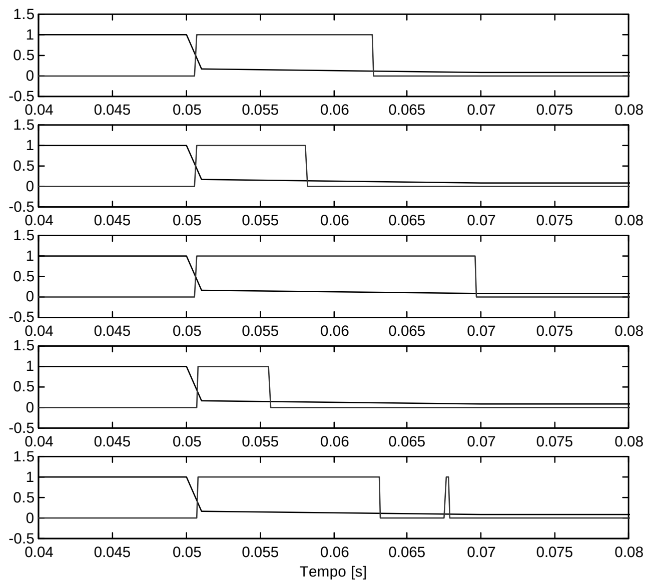
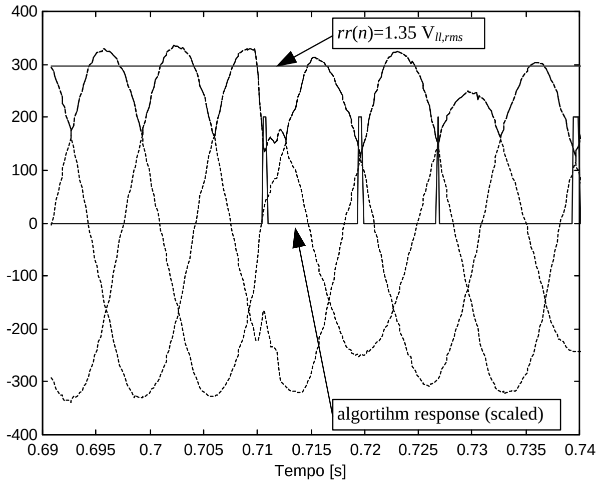


Fig. 4 Response of the RV method: normalised rms value of the line-line voltage (THD=8%) and RV output

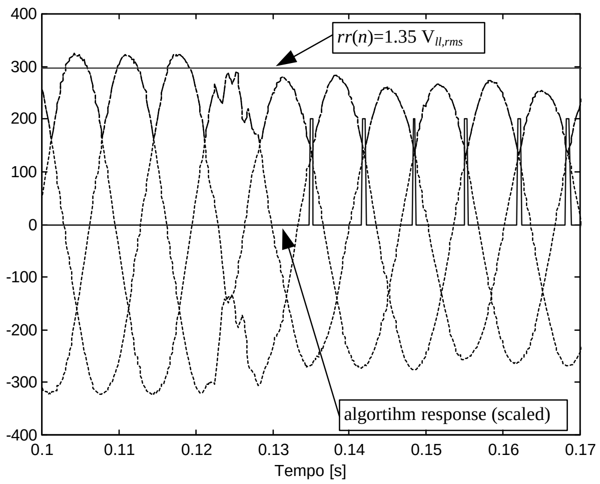
The RV method detects the voltage sag after less than 1 ms for all the choices of the method parameters.

3.2. Test with recorded waveforms

The results of two tests performed with voltage sag waveforms recorded at the secondary winding of a Medium Voltage/Low Voltage transformer are shown in Fig. 5.



(a)



(b)

Fig. 5 Response of the RV method for real cases: (a) repetitive sags of short duration, (b) 85% sag of long duration

The RV method detects the multiple voltage sags after less than 550 µs.

3.3. Test with real waveforms

The RV algorithm was implemented on a DSP board and tested in the laboratory on the prototype of the Compensation Electronic System (composed of a Voltage Source Inverter and all other apparatus for voltage regulation, system protection and control) of a Superconductive Magnetic Energy Storage system.

The voltage sags were caused either by switching on and off low value resistors on the supply network (test 1) or opening the main circuit breaker (test 2). The results are shown in Fig. 6 and Fig. 7. Two line-to-line voltages are shown and the third (lower) trace is the algorithm response.

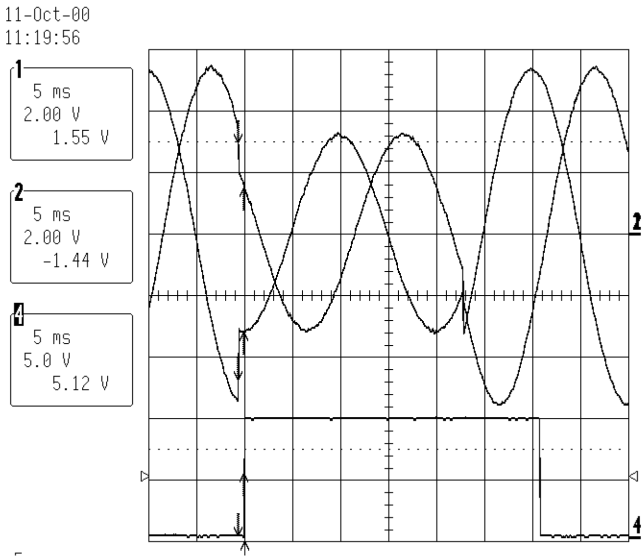


Fig. 6 Response of the RV method for lab test 1

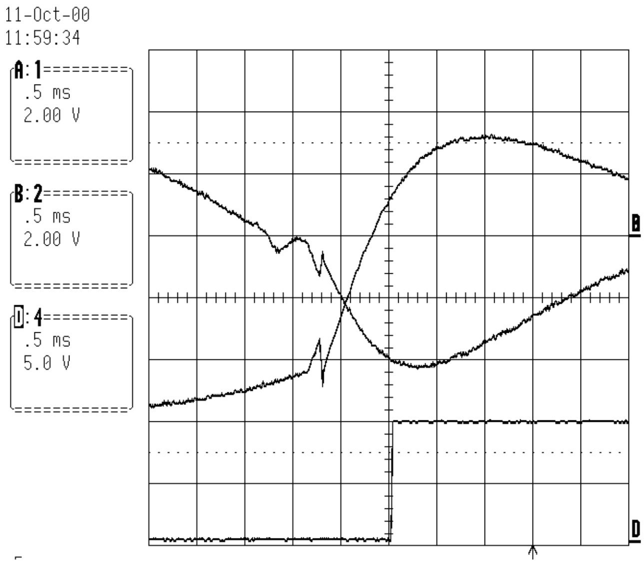


Fig. 7 Response of the RV method for lab test 2

The delay values for sag detection are 0.6 ms and 0.8 ms for Fig. 6 and Fig. 7 respectively.

Tests like those shown in Fig. 6 and Fig. 7 have been repeated for days, switching the Compensation Electronic System on and off from the protected load.

4. CONCLUSIONS

The proposed multi-criteria algorithm has shown to be efficient in voltage sag detection (the time to sag detection is below 1 ms for most of the tests) and the computational effort (that is the algorithm complexity in terms of number of operations and memory storage requirements) is reduced to a minimum.

This algorithm is presently implemented on a prototype of the Compensation Electronic System supplied by a Superconductive Magnetic Energy Storage (SMES) device.

5. REFERENCES

[1] IEEE Recommended Practice for Monitoring Electric Power Quality, ANSI/IEEE Standard 1159, 1995.

[2] J.L. Duran-Gomez, P.N. Enjeti and B.O. Woo "Effect of voltage sags on adjustable-speed drives: A critical evaluation and an approach to improve performance", *IEEE Trans. on Industry Applications*, v. 35, pp. 1440-1449, Nov./Dec. 1999.

[3] H.G. Sarmiento and E. Estrada "A voltage sag study in an industry with adjustable speed drives", *IEEE Industry Applications Magazine*, v. 2, Jan./Feb. 1996, pp. 16-19.

[4] M. Samotyi "Solutions to Voltage Sag problems", EPRI Journal, July/Aug. 1995, pp. 42-45.

[5] IEEE Recommended Practice for Emergency and Standby Power for Industrial and Commercial Applications, ANSI/IEEE Standard 446, 1987, pp. 74-75.

[6] J. Lamoree, J.C. Smith, P. Vinett, T. Duffy and M. Klein "The impact of voltage sags on industrial plant loads", First Intern. Conf. on Power Quality, Paris, France, Oct. 14-16, 1991

[7] L. Conrad, K. Little and C. Grigg "Predicting and preventing problems associated with remote fault-clearing voltage dips", *IEEE Trans. on Industry Applications*, v. 27, pp. 167-172, Jan. 1991.

[8] C.A. Luongo "Superconducting storage systems: an overview", *IEEE Trans. on Magnetics*, v.32, n.4, July 1996, pp. 2214-2223.

[9] R.C. Degeneff, R. Barss, D. Carnovale and S. Raedy "Reducing the effect of sags and momentary interruptions: a total owning cost prospective", 9th Intern. Conf. on Harmonics and Quality of Power ICHQP 2000, v. 2, pp. 397-403.

[10] L.M. Tolbert, H.D. Hollis and P.S. Hale "Evaluation of harmonic suppression devices", 1996 IEEE Industry Applications Annual Meeting, v. 4, pp. 2340-2347.

[11] S.J. Huang, C.T. Hsieh and C.L. Huang "Application of wavelets to classify power system disturbances", *Electric Power System Research*, v. 47, 1998, pp. 87-93.

[12] P. Pillay and A. Bhattacharjee "Application of wavelets to model short-term power system disturbances", *IEEE Trans. on Power Systems*, v. 11, n. 4, Nov. 1996, pp. 2031-2037.

[13] W.A. Wilkinson and M.D. Cox "Discrete wavelet analysis of power system transients", *IEEE Trans. on Power Systems*, v. 11, n. 4, Nov. 1996, pp. 2038-2044.

[14] S.J. Huang and C.T. Hsieh "Feasibility of fractal-based methods for visualization of power system disturbances", *Electric Power System Research*, v. 23, 2001, pp. 31-36.

[15] H.S. Song and K. Nam "Instantaneous phase-angle estimation algorithm under unbalanced voltage-sag conditions", *IEE Proc. Generation Transmission and Distribution*, v. 147, n. 6, Nov. 2000, pp. 409-415.

[16] C. Hochgraf and R.H. Lasseter "Statcom controls for operation with unbalanced voltages", *IEEE Trans. on Power Delivery*, v. 13, n. 2, Feb. 1998, pp. 538-544.

[17] EN 50160, *Voltage characteristics of electricity supplied by public distribution systems*, 1999-07

Authors:

Riccardo Chiumeo, CESI S.p.A., Via Rubattino, 54 – 20134 Milano – Italy, Tel. +39 02 2125 5765, Fax: +39 02 21255440 chiumeo@cesi.it;

Andrea Florio, Ansaldo Ricerche s.r.l., Corso Perrone – Genova – Italy Tel. +39 010 655 8664, Fax: +39 010 7490875 florio@ansaldo.it;

Andrea Mariscotti, Dipartimento Ingegneria Elettrica, Università di Genova, Via all'Opera Pia, 11A – 16145 Genova – Italy Tel. +39 010 3532169, Fax: +39 010 3532700 mari@die.unige.it;

Maurizio Mazzucchelli, Dipartimento Ingegneria Elettrica, Università di Genova, Via all'Opera Pia, 11A – 16145 Genova – Italy Tel. +39 010 3532714, Fax: +39 010 3532700 mazzucchelli@die.unige.it