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Fast and precise voltage sag detection method for dynamic voltage restorer (DVR) application

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ABSTRACT

Voltage sag detection method has a significant impact on the performance of dynamic voltage restorer (DVR). This paper proposes a fundamental voltage amplitude detection method which is applicable in both single/three-phase systems for DVR applications. Advantages of the proposed method include application in distorted power grid without any low-pass filter, precise and reliable detection, simple computation and implementation without using a phased locked loop and lookup table. The proposed method has been simulated and implemented experimentally and tested under various conditions considering all possible cases such as different amounts of voltage sag depth (VSD), different amounts of point-on-wave (POW) at which voltage sag occurs, harmonic distortion, line frequency variation, and phase jump (PJ). A detailed procedure to design the threshold band for comparator is presented. According to the achieved results and detailed analysis, maximum ripple of the calculated fundamental voltage amplitude is ±0.3% in normal condition of line frequency and ±1% in the case of ±1 Hz variation of 60 Hz line frequency. In addition, the error between the actual fundamental voltage amplitude and the calculated one is almost zero in normal condition of line frequency and maximum of ±0.25% in the case of line frequency variation with excessive-harmonic distortion. Furthermore, detection time (DT) of the proposed method is analyzed in detail for different amounts of VSD, POW and PJ. The best and worst detection time of the proposed method were measured 1 and 8.8 ms, respectively. Finally, the proposed method has been compared with other methods available in the literature.

1. Introduction

In recent years, the number of sensitive loads such as medical equipment, factory automations, semiconductor-device manufacturer, and paper manufacturer integrated to power grid has been increased. One of the common characteristics of these sensitive loads in modern industrial/commercial applications is their vulnerability to voltage sags. Consequently, the demand for high power quality and voltage stability becomes a pressing issue [1–4]. Both the “Canadian Power Quality Survey” conducted by the Canadian Electrical Associate (CEA) in 1991 on 550 customer sites and the “Distribution System Power Quality Survey” conducted by the Electric Power Research Institute (EPRI) on 222 utility distribution feeders between 1993 and 1995 have shown that voltage sags are the most frequent power quality events [5]. According to an EPRI report, the economic losses due to poor power quality are $400 billion dollars a year in the U.S. alone [6,7].

These disturbances occur due to, e.g., short circuits in upstream power transmission line or parallel power distribution line connected to the point of common coupling (PCC), inrush currents involved with the starting of large machines, sudden changes of loads, energizing of transformers or switching operations in the grid [8,9]. According to the IEEE STD 1159-2009, voltage sag (also called voltage dip in the IEC terminology) is defined as a decrease of 0.1–0.9 p.u. in the voltage at system frequency with the duration of half cycle to 1 min [10–14]. Recently, a new IEEE Std 1564-2014 “Guide for Voltage Sag Indices” has been approved by IEEE Review Committee in March 2014 which identifies appropriate voltage sag indices and characteristics of electrical power and supply systems [12]. Voltage sags are recognized as a serious and frequently occurring power-quality problem with a costly consequence such as sensitive loads tripping and production loss [15–18]. There are several methods for compensating the voltage sag, including static transfer switches, uninterruptible power supplies and dynamic voltage restorer (DVR). For all mentioned compensation methods, voltage sag detection is the first step whose response speed is critical for the performance of these compensation methods [9,18–20].

In literature [6,21–90], several methods have been reported to detect the voltage sag such as peak value monitoring based

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Table 1
List of acronyms.

Acronym	Definition	Acronym	Definition
Low-pass filter	LPF		
Phase locked loop	PLL	Least error square	LES
Voltage sag depth[1]	VSD	S-transform	ST
Point-on-wave[2]	POW	Standard deviation	SD
Phase jump	PJ	Digital signal processor	DSP
Detection time[3]	DT	Calculated fundamental voltage amplitude	CFVA
Dynamic voltage restorer	DVR	Analog to digital converter	ADC
dq-Transformation	DQT	Upper limit	UL
Wavelet transform	WT	Lower limit	LL
Kalman filter	KF	Extended kalman filter	EKF
Calculated fundamental voltage amplitude	CFVA		
Digital signal processor	DSP	S-transform	ST

[1] VSD is amount of voltage drop regarding the nominal value. For example if the voltage decreases to 80% of nominal value, the residual voltage is 80% and VSD is 20%.
[2] POW is the moment at which the voltage sag disturbance happens and it is between 0° and 360° of one line cycle.
[3] In this paper, DT is the period of time from the moment at which the voltages sag happens to the moment that voltage detection method detects it.

on gradient calculation of voltage, root-mean-square (rms), d–q transformation, differential controller, obtaining dc voltage from a rectified voltage, wavelet transform, Kalman filtering, phase-corrected wavelet transform known as S-transform, numerical matrix based methods, or hybrid methods. These methods generally require complex computation, precise phase-locked-loop, excessive look-up table, and/or low-pass filter. In Section 2, reported methods in literature as well as their advantages and disadvantages are reviewed.

Due to the high number of acronyms in this paper, a list of acronyms is illustrated in Table 1. The rest of paper is organized as follows. In Section 2, available voltage sag detection methods are briefly reviewed and their pros and cons are provided. In Section 3, important criteria which should be considered in design and evaluation of any voltage sag detection method are discussed in detail. A voltage sag detection method, based on half-cycle Fourier series, with the advantages of precise and fast detection, simple computation and implementation without using a PLL, lookup table and LPF, is presented in Section 4. Moreover, performance of the proposed method under line-frequency variation condition is analytically investigated in Section 4, whose outcomes are matched exactly with simulation results. The presented method is simulated in PSCAD and PSIM and experimentally implemented in DSP F28335 and its performance is analyzed in detail considering all important criteria mentioned in Section 3 and some of the obtained simulation and experimental results are presented in Sections 5 and 6, respectively. It is worth mentioning that no paper has been found to investigate a half-cycle Fourier series based voltage sag detection method analytically and through detailed simulation and experimental tests considering all possible cases such as different amounts of VSD, POW, PJ, harmonic distortion and line frequency variation. Moreover, the DT of proposed method is obtained in detail for different amounts of VSD, POW and PJ and compared with other methods available in literature in Section 7.

2. Brief review of voltage sag detection methods

2.1. Peak value monitoring (PVM)

The PVM is the simplest conceptual method that calculates the peak value at the moment at which the gradient of voltage is zero [21]. The drawback of this method is that it may take up to half cycle to detect the voltage sag as well as the high sensitivity of differential function to noise. Moreover, this method is not very practical since the grid voltage is usually harmonically distorted; therefore, there may be several points with the zero gradient in one cycle of fundamental line-frequency [21]. In Ref. [22], a method was proposed to phase shift the measured voltage by 90° to obtain the in-quadrature component of the measured voltage. Then, summing the square of the measured voltage and its in-quadrature component and performing square root of the summation to calculate the grid voltage. However, this method has the delay of quarter of line-cycle and it is not suitable for harmonically distorted grid voltage [6,22].

2.2. RMS calculation

The most common and traditional method used for voltage measurement in power system is calculation of the rms voltage and its performance is analyzed in Refs. [23–26] and investigated in detail regarding the frequency variation, synchronized and desynchronized calculation in Ref. [27]. The rms values can be computed each time a new sample is obtained. If the rms value is updated whenever a new sample is obtained, the calculated rms is called continuous; otherwise, it is called discrete [25].

Simplicity is the main advantage of this method; in contrary, its performance depends on the window length of rms calculation and the time interval for updating the values. The DT of this method is up to one cycle of fundamental line-frequency, without any LPF, for less severe voltage sags. This DT may increase up to two cycles if the LPF is utilized for highly distorted grid voltage. In Ref. [28], a new method based on rms calculation has been proposed. This method calculates the ratio of new coming sample, $V(t_n)$, with the previous cycle samples, $V(t_n - T)$ (T is the period of line cycle), continuously and if this ratio for three continuous samples is less than one, it assumes the voltage decreased with the same calculated ratio. This method has been tested just for 50% VSD while the threshold of voltage sag detection is set to 80% instead of 90%.

2.3. d-q Transformation (DQT)

Since DQT is a powerful tool in three-phase systems, the voltage sag detection based on DQT has been proposed and analyzed in Refs. [21,29–41]. It is worth mentioning that DQT based voltage sag detection works perfectly with a great DT, i.e., less than 1 ms, for balanced three-phase voltage sag, i.e., the drop of voltage in all three phase are the same, in the cases of pure sinusoidal voltages.

However, the grid voltage is not pure sinusoidal in practice and in fact, it is harmonically distorted; in such cases, the components with the frequency of $6k \times 60$ Hz (i.e., 360, 720, 1080 . . . Hz) will be added to d/q components where k is integer number. To filter out these undesired components, a LPF can be added to this process at cost of increasing the DT. Another significant concern is the performance of this method in the case of single-phase voltage sag which constitutes more than 90% of voltage sags in power grid [42–45]. In this paper, the terminology “single-phase voltage sag” refers to the voltage sag that happens in only one of the phases in three-phase system. In these cases, another sinusoidal component at twice of the line frequency with considerable amplitude will be added to d/q components.

Three solutions have been reported in literature to solve this problem [35–41]. The first solution is to add a LPF with a small cut-off frequency to cancel out the component at twice of the line-frequency resulting in a significant increase of DT. The second solution is to add a differentiator to the DQT based voltage sag detection which has been reported and analyzed in Refs. [35–40]. And the last one is constructing the virtual three-phase voltages