An Improved Detection Technique for Voltage Sag using the Wavelet Transform

Chul-Hwan Kim, Jong-Po Lee, Sang-Pil Ahn and Byung-Chun Kim

Abstract - This paper presents a discrete wavelet transform approach for detecting voltage sags initialized by fault conditions and starting of larger motors. The proposed technique is based on utilizing the summation value of D1(at scale 1) coefficients in multiresolution analysis(MRA) based on the discrete wavelet transform. In this paper, the proposed technique is tested under various cases of voltage sags. It is shown that the voltage sag detection technique based on the wavelet transform is a satisfactory and reliable method for detecting voltage sags in power quality disturbance analysis.
Keywords - Voltage Sag, Power Quality, Wavelet Transform, Multiresolution Analysis

1. Introduction

A voltage sag is defined as a momentary decrease to between 0.1 and 0.9 pu in the RMS voltage magnitude for durations from 0.5 cycle to 1 minute, usually caused by a remote fault somewhere on the power system. As an example, Fig. 1 describes a voltage sag disturbance. Voltage sags are the most important Power Quality(PQ) problems facing many industrial customers. Equipment used in modern industrial plants(process controllers, programmable logic controllers, adjustable speed drives, robotics) is actually becoming more sensitive to voltage sags as the complexity of the equipment increases. Even relays and contactors in motor starters can be sensitive to voltage sags, resulting in shutdown of a process when they drop out. Because of the increased use of sensitive electronic equipment, these disturbances have a greater impact on customers than ever before. As a result, monitoring and assessment of the system performance at both the transmission and distribution voltage levels are becoming increasingly important[1-9].

The first notion of utilization of the wavelet theory in power system is credited to Ribeiro[10]. This theory uses special functions called mother wavelets. There are many mother wavelets and the selection of a wavelet will depend on a particular application. In quality of power, the current state of art is the use of Daubechies wavelets. Daubechies wavelets belong to a special class of mother wavelet and actually they are the most used for detection, localization and classification of disturbances[11-16]. In addition, much of power system analysis is steady state. However, in the area of electric power quality analysis, transients may assume an important role. The MRA technique allows sharp time changes in voltage signal such as voltage sags, interruptions, overvoltages, transients to be detected. Because of this particular attribute, applications of the MRA technique to PQ disturbance detection are being increased[17-19]. Therefore, in this paper, the MRA technique based on the wavelet transform is applied to voltage sags detection.

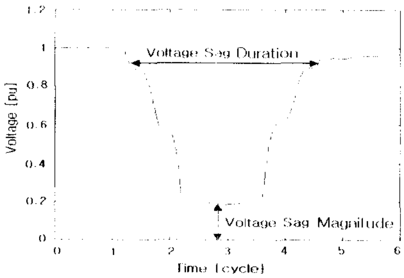

Fig. 1 Description of voltage sag

Firstly, voltage sags caused by remote fault conditions and starting of motors are considered and simulated by the EMTP software. This paper then describes an improved detection technique for voltage sags caused by fault conditions and starting of induction motors; it essentially determines the beginning and end times of voltage sags utilizing the summation value of D1 coefficients via MRA based on the discrete wavelet transform.

The effectiveness of the technique developed herein is

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illustrated by considering the power system model including transmission and distribution lines.

2. Voltage sags

2.1 Voltage sags caused by fault conditions

Voltage sags are typically caused by fault conditions. Fault resulting in voltage sags can occur within the plant or on the utility system. The voltage sag condition lasts until the fault is cleared by a protective device. In the plant, this will typically be a fuse or a plant feeder breaker. On the utility system, the fault could be cleared by a branch fuse or a substation breaker. If reclosing is used by the utility, the voltage sag condition can occur multiple times.

Utility system faults can occur on a distribution system or on a transmission system. Fig. 2 illustrates a typical distribution system configuration with a number of feeders supplied from a common bus. A fault on Feeder F1 will cause an interruption, which will affect the customers on that particular feeder. However, most of the customers on the others three parallel feeders will also experience a voltage sag while the fault is actually on the system.

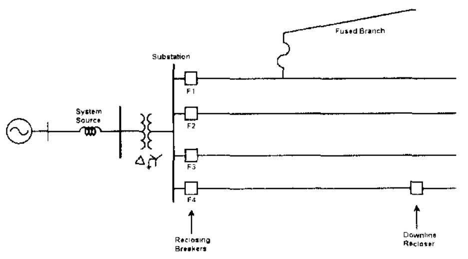

Fig. 2 Typical distribution system configuration

Faults on a transmission system can affect even more customers. Customers miles away from the fault location can still experience voltage sags resulting in equipment maloperation when the fault is on the transmission system.

To quantify sag magnitude in radial systems, the voltage divider model, shown in Fig. 3 can be used. This might appear a rather simplified model, especially for transmission systems. In Fig. 3 we see two impedances: Zs is the source impedance at the point-of-common coupling(PCC); and ZF is the impedance between the PCC and the fault. The point-of-common coupling is the point from which both the fault and the load are fed. In other words, it is the place where the load branches are off from the fault current. In the voltage divider model, the load current before as well as during the fault is neglected. There is thus no voltage drop between the load and the PCC, and thus the voltage at the equipment terminals, can be found from eqn (1).

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} E \tag{1}$$

If we assume that the pre-event voltage is exactly 1 pu, then E = 1. This results in the eqn (2) for the sag magnitude.

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} \tag{2}$$

Any fault impedance should be included in the feeder impedance ZF. We see from eqn (2) that the sag becomes deeper for faults electrically closer to customer(when ZF becomes smaller), and for systems with a smaller fault level (when Zs becomes larger). Note that a single-phase model has been used here, whereas in reality the system is three-phase. That means that this equation strictly speaking only holds for three-phase faults.

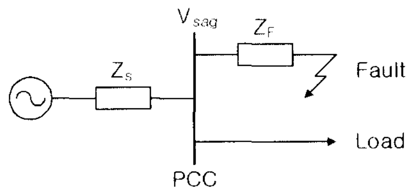

Fig. 3 Voltage divider model for voltage sag

2.2 Voltage sags due to starting of induction motors

Motor starting can also result in undervoltages, but these are typically longer in duration than 30 cycles and associated magnitudes are not as low, generally over 0.8 pu. During start-up an induction motor takes a larger current than normal, typically five to six times as large. This current remains high until the motor reaches its nominal speed, typically between several seconds and one minute. The drop in voltage depends strongly on the system parameters. Consider the system show in Fig. 4, where Zs is the source impedance and ZM is the motor impedance during run-up.

The voltage experienced by a load fed from the same bus as the motor is found from the voltage divider equation as eqn (3).

$$V_{sag} = \frac{Z_M}{Z_S + Z_M} E \tag{3}$$

Like with most previous calculations, a source voltage of 1 pu has been assumed. When a motor of rated power Smotor is fed from a source with short-circuit power Ssource, we can write for the source impedance as eqn (4), and for the motor impedance during starting as eqn (5) with the ratio between the starting current and the nominal current.

Table 1 Detailed parameters of power system model

Transmission system	source	vsource	230 kV	
	source equivalent circuit	SRC bus ~ 230kV bus	$\%Z_1$ = 0.135 + j0.845 $\%Z_0$ = 0.105 + j0.640 surge impedance: 400[Ω]	-mutual coupled R-L circuit -base=100[MVA]
	transmission line	230kV bus ~ REC bus	$\%Z_1$ = 1.72 + j14.33 $\%Z_0$ = 11.9 + j42.53 shut admittance: 30[MVar]	-PI equivalent model -160.9[km]
	capacitor bank	230 kV bus	50[MVar], 230[kV],	-open in steady-state -Y-grounding sys.
Distribution system	distribution lines	44kV bus ~ BUS1 bus	Z = 0.058 + j1.2778[Ω]	-lumped R, L, C
		44kV bus ~ BUS2 bus	Z = 3.678 + j8.0150[Ω]	
		44kV bus ~ BUS3 bus	Z = 0.987 + j2.9810[Ω]	
		44kV bus ~ BUS4 bus	Z = 1.804 + j1.7040[Ω]	
		BUS4 bus ~ BUS5 bus	Z = 3.717 + j7.8410[Ω]	
		BUS5 bus ~ BUS6 bus	Z = 0.620 + j1.3340[Ω]	
	linear loads	44kV bus	500[MVA], 44.0[kV]	
		44kV bus	50[MVA], 44.0[kV]	
		BUS1 bus	4500[kVA], 44.0[kV]	
		BUS2L bus	3100[kVA], 13.0[kV]	
		BUS3L bus	1100[kVA], 12.5[kV]	
		BUS4L bus	1300[kVA], 12.5[kV]	
		BUS5 bus	600[kVA], 44.0[kV]	
		BUS6L bus	2000[kVA], 0.48[kV]	
	non-linear load	BUS6L bus (induction motor)	3-phase, 4-pole, 60[Hz], 500[HP], pf: 0.90, efficiency: 0.92	
	capacitor banks	44kV bus	6000[kVar], 44.0[kV]	-closed in steady-state -Y-grounding sys.
		BUS2L bus	1800[kVar], 13.0[kV]	
		BUS3L bus	1800[kVar]×2, 12.5[kV]	
		BUS4L bus	750[kVar], 12.5[kV]	
	STEP1 Tr.	REC bus ~ 44kV bus	18[MVA], 230/44[kV]	-Δ-Y
	STEP2 Tr.	BUS2 bus ~ BUS2L bus	7.5[MVA], 44/13[kV]	
	STEP3 Tr.	BUS3 bus ~ BUS3L bus	5.0[MVA], 44/12.5[kV]	
	STEP4 Tr.	BUS4 bus ~ BUS4L bus	2.5[MVA], 44/12.5[kV]	
	STEP5 Tr.	BUS6 bus ~ BUS6L bus	7.5[MVA], 44/480[kV]	

$$Z_S = \frac{V^2}{S_{source}} \tag{4}$$

$$Z_M = \frac{V^2}{\beta S_{source}} \tag{5}$$

Eqn (3) can now be written as eqn (6)

$$V_{sag} = \frac{S_{source}}{S_{source} + \beta S_{motor}} \tag{6}$$

Of course one needs to realize that this is only approximation. The value can be used to estimate the sag due to induction motor starting, but for an accurate result one needs a power system analysis package. The latter will also enable the user to incorporate the effect of other motors during starting of the concerned motor. The drop in voltage at the other motor's terminals will slow them down and cause an additional increase in load current and thus an additional drop in voltage.

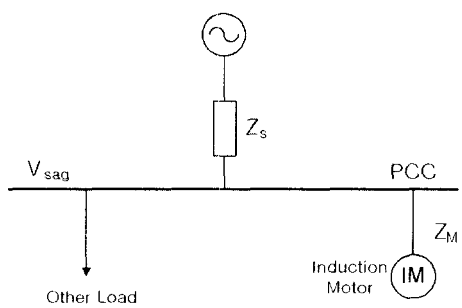

Fig. 4 Equivalent circuit for voltage sag due to induction motor starting

Table 2 Data cases of voltage sags

Case #	Beginning time [msec]	End time [msec]	Duration time [cycle]	Fault type	Faulted bus	Bus measured for data
1	62.5000	512.5000	27.0000	SLG(0°)	BUS1A	BUS6LA
2	80.5600	147.2200	4.0000	SLG(30°)	BUS1A	BUS6LA
3	181.9400	523.0500	20.4666	SLG(60°)	BUS1A	BUS6LA
4	508.3000	737.8055	13.7703	SLG(90°)	BUS1A	BUS6LA
5	147.0833	347.0833	12.0000	SLG(27°)	230kVA	BUS6LA
6	92.0963	211.8055	7.1825	SLG(80°)	44kVA	BUS6LA
7	231.7128	498.2960	15.9950	SLG(55°)	BUS2LA	BUS6LA
8	195.8333	629.1666	26.0000	SLG(0°)	BUS5A	BUS6LA
9	124.9667	541.6333	25.0000	SLG(90°)	BUS2A	BUS6LA
10	96.2960	301.0523	12.2854	SLG(10°)	BUS3A	BUS6LA
11	98.6109	155.8143	3.4320	DLG(60°)	BUS3A- BUS3B	BUS6LA-BUS6LB
12	58.3000	411.3231	21.1813	DLG(90°)	44kVA- 44kVB	BUS6LB-BUS6LC
13	564.3518	821.0000	15.3989	DLG(30°)	BUS1A- BUS1B	BUS6LC-BUS6LA
14	215.0461	629.1666	24.8472	DLL(55°)	RECA- RECB	BUS6LA-BUS6LB
15	80.5600	512.5000	25.9163	DLL(30°)	BUS3LA- BUS3LB	BUS6LA-BUS6LB
16	695.0521	923.1121	13.6836	DLL(0°)	BUS2A-BUS2B	BUS6LC-BUS6LA
17	320.8365	632.3327	18.6897	DLL(20°)	44kVA-44kVB	BUS6LC-BUS6LA
18	416.6667	652.7579	14.1654	3G(90°)	BUS3A-BUS3B-BUS3C	BUS6LA-BUS6LB
19	150.9259	257.0785	6.3691	3G(70°)	BUS3LA-BUS3LB-BUS3LC	BUS6LB-BUS6LC
20	50.2572	683.5937	38.0001	starting of induction motor(3-phase)	BUS6L	BUS6LA

3. Detection technique of voltage sags using the wavelet transform

3.1 System model studied

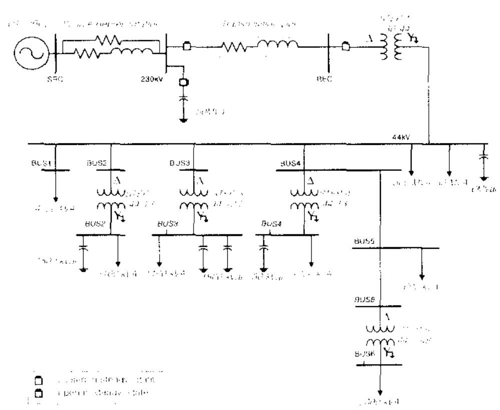

Fig. 5 Power system model studied

For illustration purposes, the power system model has been adopted as depicted in Fig. 5. This system consists of five step-down transformers, six capacitor banks, and seven linear loads. It includes both transmission and distribution systems, which sectioned off by the point of step 1 transformer. The detailed parameters are listed in Table 1. Modeling of voltage sags is implemented by simulating fault in various bus points, which are listed in Table 2. As described in Table 2, various fault conditions such as single line-to-ground fault(SLG), double line-to-ground fault(DLG), line-to-line fault(DLL), 3-phase fault(3G) are considered in the power system model. To simulate voltage sags by starting of induction motor, linear load of 2000 kVA in BUS6L is replaced by induction motor of 500 HP instead.

3.2 Characteristics of voltage sags

Fig. 6 shows the magnitude of voltage sags at each bus caused by faults(SLG, DLL) on transmission lines. Section A(transmission system) has 0.23, 0.20 pu in SLG, DLL faults respectively. Likewise, section B(distribution system) has 0.46, 0.33 pu and section C(sub-distribution) has 0.78, 0.75, correspondingly. By faults on distribution lines, each magnitude of voltage sags in section A, B, C is 0.85, 0.16, 0.54 respectively for SLG fault, and 0.78, 0.15, 0.45, correspondingly for DLL fault, as depicted in Fig. 7. From these results as mentioned above, it can be seen that the magnitude of voltage sags is in reverse proportion to fault location.

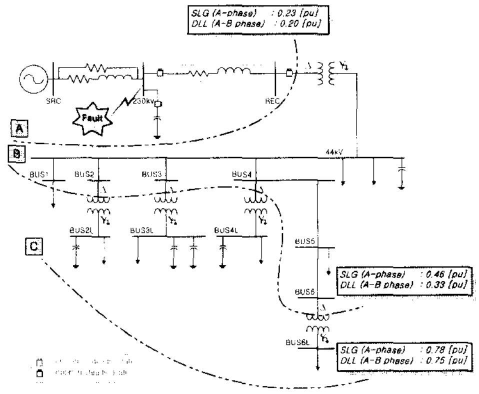

Fig. 6 The magnitude of voltage sags at each bus due to faults on 230kV bus

Fig. 8 shows waveforms of voltage sag in the case study #8 as in Table 2. As depicted in Fig. 8, the voltage sag caused by fault conditions has the magnitude of 0.45 pu and the duration of 26 cycles. But, the voltage sag initialized by starting of induction motor in the case study #20 as in Table 2 has the magnitude of 0.89 pu(over 0.8 pu) and the duration of 38 cycles(over 30 cycles), as shown in Fig. 9. Therefore, improved detection technique should consider the case of voltage sags caused by starting large motors.

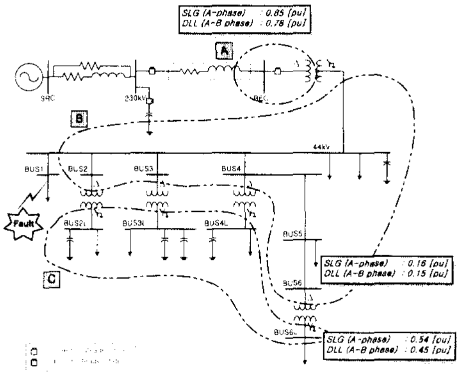

Fig. 7 The magnitude of voltage sags at each bus due to faults on BUS1 bus

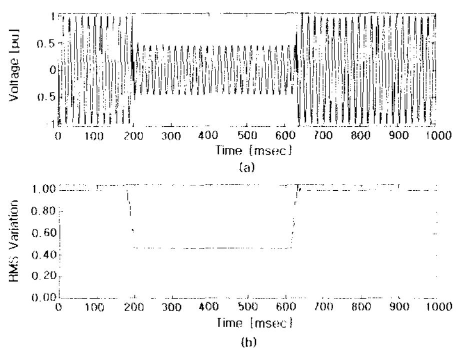

Fig. 8 Waveforms of voltage sag caused by fault conditions
(a) Waveform of voltage sag
(b) RMS variation of voltage sag

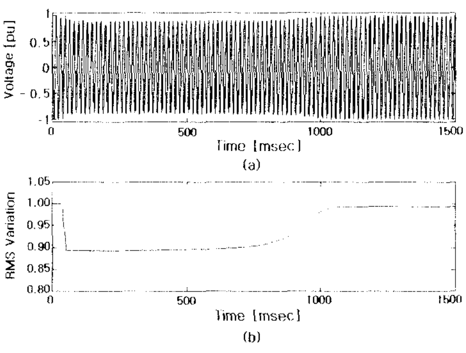

Fig. 9 Waveforms of voltage sag caused by starting of induction motor
(a) Waveform of voltage sag
(b) RMS variation of voltage sag

3.3 Improved detection techniques using summation value of D1 coefficients based on the wavelet transform

Improved detection algorithm technique for voltage sags using summation value of D1 coefficients based on the wavelet transform is described in Fig. 10. Those summation values are calculated over a 1-cycle period and the sampling rate employed is 3840 Hz i.e., 64 samples/cycle at 60 Hz. The whole process is based on a

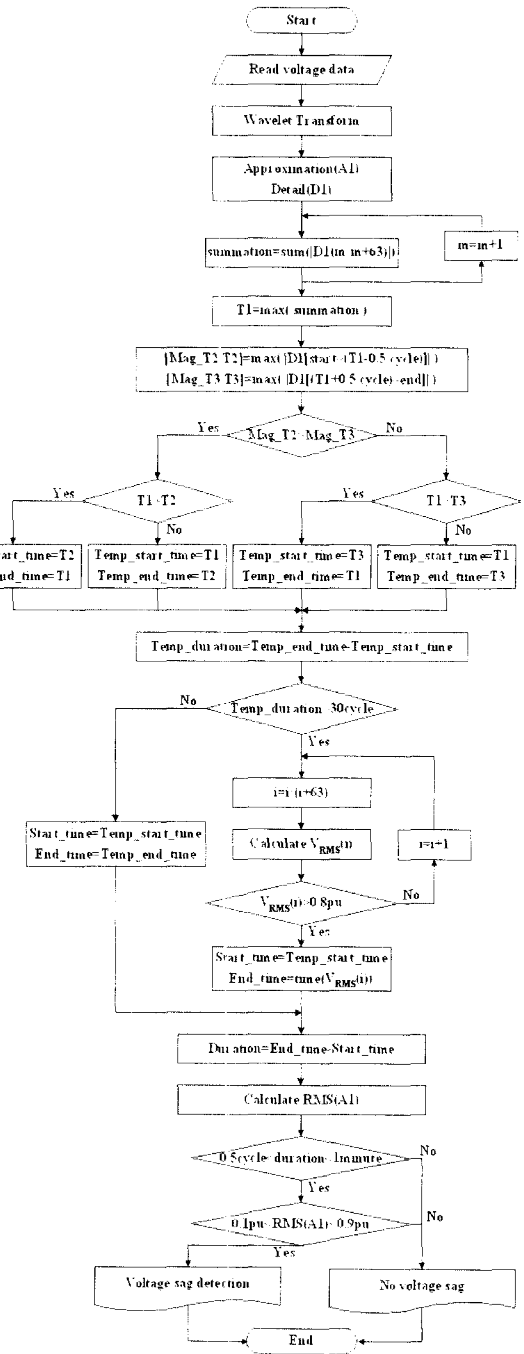

Fig. 10 Detection technique using summation value of D1 coefficients

moving window approach whereby the 1-cycle window is moved continuously by 1 sample. Then, to determine the beginning and end times, maximum values of summation values are utilized.

4. Simulation results

The input voltage waveforms including voltage sags are modified by the capacitor voltage transformer(CVT), anti-aliasing lowpass filters and A/D conversion processes. It should be noted that although not shown herein, response/limitations due to CVTs, relay hardware(such as voltage interface module comprising anti-aliasing filters and analog-to-digital converters), etc have been taken into account in the simulation so that the performance of the detection technique attained pertains closely to that expected in reality.

Fig. 11 shows the results of 4 levels of multiresolution analysis by db4 mother wavelet, Fig. 11a being the input waveform of voltage sag in the case study #11 as in Table 2. Fig 11b is the A1 coefficient and Figs 11c, 11d, 11e, 11f are D1, D2, D3, D4 coefficients, respectively. Among D1, D2, D3, D4 coefficients, D1 coefficient has a better performance in the detection process than the D2 coefficient, which is unable to detect approximately 10% of voltage sags. Also with respect to the speed of multiresolution analysis, D1 coefficient in level 1 is superior. Thus maximum values using D1 coefficients are applied in the detection technique of voltage sags.

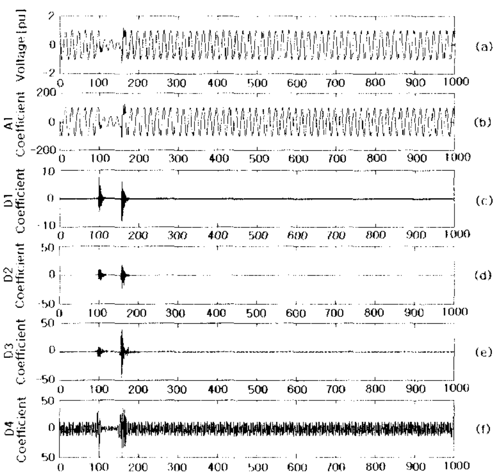

Fig. 11 Results of 4 level of MRA by db4 mother wavelet
(a) Waveform of voltage sag
(b) A1 coefficient
(c) D1 coefficient
(d) D2 coefficient
(e) D3 coefficient
(f) D4 coefficient

Fig. 12a shows D1 coefficients in multiresolution analysis by db4 mother wavelet and Fig. 12b shows summation value of D1 coefficients. In Fig. 12, the estimated start and end times are 98.4 msec and 155.7 msec, respectively. Estimated duration is 3.437 cycles. Table 3 shows the results of detection using summation value of D1 coefficients based on the wavelet transform, where all voltage sags can be detected, and average errors are slightly lower than those attained when method mentioned above are employed. Average errors of estimated start and end times are 0.0340 cycle, 0.0203 cycle respectively.

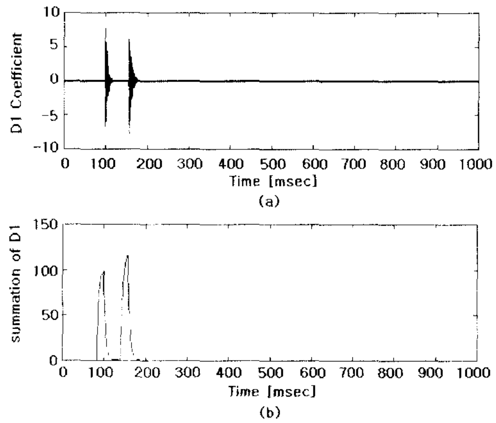

Fig. 12 Waveforms of D1 coefficient and summation value of it
(a) D1 coefficient
(b) summation value of D1 coefficients

Table 3 Results of detection using summation value of D1 coefficients

Case #	Beginning time		End time		RMS of A1 coeffs. [pu]	Duration time [cycle]
	Estimated time[msec]	Error [cycle]	Estimated time[msec]	Error [cycle]		
1	63.0	0.0312	512.5	0.0000	0.5357	26.9682
2	80.2	0.0211	146.9	0.0207	0.5558	3.9999
3	182.3	0.0211	522.9	0.0080	0.5608	20.4371
4	507.8	0.0293	737.5	0.0183	0.5318	13.7810
5	147.4	0.0187	346.9	0.0125	0.7755	11.9685
6	91.1	0.0570	211.5	0.0208	0.5007	7.2186
7	230.7	0.0590	499.0	0.0397	0.8034	16.0934
8	195.0	0.0468	628.4	0.0469	0.5395	25.9995
9	124.5	0.0292	541.7	0.0020	0.7083	25.0307
10	95.8	0.0322	301.0	0.0006	0.5991	12.3122
11	98.4	0.0104	155.7	0.0051	0.3644	3.4374
12	57.3	0.0605	410.9	0.0231	0.5811	21.2183
13	564.1	0.0104	820.8	0.0100	0.3897	15.4059
14	214.1	0.0590	629.2	0.0000	0.8419	24.9058
15	79.9	0.0367	512.5	0.0000	0.7557	25.9526
16	694.0	0.0625	922.9	0.0483	0.7053	13.7341
17	320.1	0.0471	632.3	0.0025	0.5451	18.7340
18	416.1	0.0313	652.3	0.0248	0.2645	14.1716
19	150.3	0.0399	257.6	0.0284	0.7395	6.4374
20	50.5	0.0158	685.2	0.0938	0.8849	38.0774
	avg. error	0.0340	avg. error	0.0203		

With respect to the start time, total average errors in summation value of D1 coefficients is 0.0340 cycle and in the case of the end time, total average errors in summation value of D1 coefficients is 0.0203 cycle. Therefore, it is thus apparent that in all the results considered, the detection algorithm for voltage sags using summation value of D1 coefficients based on the wavelet transform has the best performance and the highest accuracy.

5. Conclusions

In this paper, an improved detection technique for voltage sags using the wavelet transform has been proposed. The proposed technique is tested under various cases of voltage sags. Its validity is demonstrated with simulation studies in relation to the power system model including modeling of voltage sags caused by various fault conditions and starting of large motors in the EMTP software.

Results from the simulation studies show that the analysis and the technique developed are accurate and effective compared with the more traditional approaches, under various voltage sags. Furthermore sub-algorithm to detect voltage sags caused by starting of induction motor also can be implemented in suggested techniques.

In future research, the classification of various voltage sags by its causes will be conducted as soon as possible.

Acknowledgments

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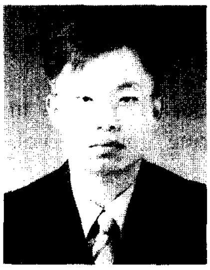

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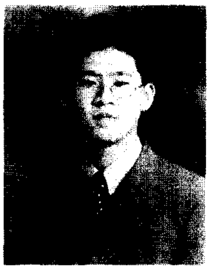

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