A Decisive Evaluation of Parks Transformation Based Commonly Used Voltage Detection Method

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Abstract: **The abc-to-dq0 based voltage detection technique is commonly employed in static transfer switch (STS) applications, which are targeted to protect sensitive loads against variety of disturbances. The technique is quite fast and precise especially in case of balanced disturbances. However balanced events seldom occur as compared to unbalances in supply system. Also there is every possibility that sensitive load may comprise of combination of single phase and three phase loads and therefore to offer a ride through capability during most of events, it is equally important to maintain good power quality at both single-phase and three-phase levels. The effectiveness and the capacity of the detection scheme are analyzed against common disturbances, routine operations of power system, under balanced variations which are within acceptable limits and against unbalances of hybrid nature (simultaneous presence of the sag and swell events). The impact of control elements on the detection process is also discussed.**

1. INTRODUCTION

Due to its lower cost and its ability to provide a ride through capability during disturbances, a STS is among the most preferred solutions used for the improvement of power quality of sensitive loads [1-4]. The protection of sensitive loads through STSs demands a fast and accurate detection of disturbances [5].The power acceptability curves are widely used for estimating the permissible variations in supply voltage and states that most sensitive loads tolerate a maximum loss of power for half a cycle without failure [6]. This implies that a STS must accomplish its duty within this time frame.

To identify the disturbances, the abc-to-dqo conversion based voltage detection method is often employed in a STS unit. The under performance of the scheme against common disturbances is reported in literature [7-11]. In addition to this, variations in control parameters of detection scheme are also suggested. However there are different possibilities and combinations of source unbalances and control settings as well which can affect the detection status of various events. Balanced variations within acceptable limits and shallow unbalances in source voltages are quite common during routine operations of power system. Such variations may have a decisive impact on the detection status as well as on the detection time of various events. Unwanted detections or undetected events both situations are critical for most of the sensitive loads. Due to the growing use of STS applications, the performance evaluation of the commonly used detection process under such variations and typical conditions of hybrid unbalances and also with different settings of control elements of the detection scheme seems to be significant. The impact of various factors including threshold settings, balanced supply variations, hybrid disturbances, filter cut-off frequencies etc. on detection status is investigated. Key observations are presented and some of them are also supplemented with relevant waveforms. Summarized results indicating the detection status and maximum detection times associated with some notable events which consume considerable time in their detection are also presented. These observations also include the effect of filter settings which are quite often used. Next section discusses the operating principle of detection procedure. Simulation and analysis section explains various cases and the associated results.

2. DETAILS OF THE DETECTION MECHANISM

The mostly used detection technique (for STS Application) is based on the abc-to-dq0 transform [7]. The detection scheme is shown in Figure1

The detection scheme consists of a mathematical algorithm (dq0 transform), a filter and a comparator. The (dq0 transform) block transforms the voltage signal to a synchronous rotating frame, the low-pass filter provides protection against voltage spikes and the comparator generates the transfer signal if the value is lower or higher than a preset threshold. The operating principle is based on Park's transformation [11, 12] for electrical machines and consists of converting the system line voltages into a synchronously rotating frame as follows

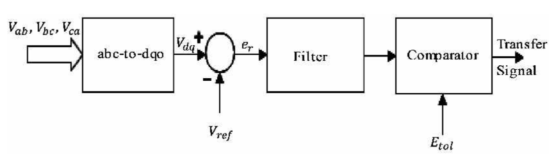

Fig 1: Voltage detection scheme [5]

This change of variables is through Park's transformation matrix as shown by equation (1).

$$V_{dqo_p} = K_s v_{abc_p} \tag{1}$$

Where $(V_{dqo_p})^T = \begin{bmatrix} V_{q_p} & V_{d_p} & V_{o_p} \end{bmatrix}$

$$K_s = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\ \sin(\theta) & \sin(\theta - 120^\circ) & \sin(\theta + 120^\circ) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

$$(V_{abc_p})^T = [V_{ab_p} \quad V_{bc_p} \quad V_{ca_p}]$$

and

$$\theta(t) = \theta(0) + \int^{t} \omega(\xi)\, d\xi \tag{2}$$

Where;

V_{ab_p}, V_{bc_p} and V_{ca_p} are the preferred source line voltages, V_{q_p} V_{d_p} and V_{o_p} are the qdo components of the preferred source voltages in the rotating frame, ω is the rotating frame angular frequency and $\theta(0)$ is the initial value of θ.

$$V_{dq_p} = \sqrt{{V_{d_p}}^2 + {V_{q_p}}^2} \tag{3}$$

From (3) the amplitude of the supply vector is obtained. Later this value is compared with the threshold set by the end-user to start the transfer process when necessary.

The response of the scheme is mainly determined by the filter cut-off frequency The higher the the faster is the detection circuit and shorter is the detection time. However, increasing makes the logic more sensitive to voltage transients, e.g., capacitor switching's. Usually a low-pass filter is set with a cut-off frequency of 50Hz or 60 Hz. The analysis and results are discussed in next section.

3. SIMULATIONS AND ANALYSIS

The requirement of different threshold settings in accordance to load and the magnitude of the event to be detected are reported [7, 8]. The preciseness of the scheme against balanced disturbances is well recognized. The detection times associated with various disturbances, the criterion of selection of a suitable threshold, the impact of voltage variations (within permissible limits) on detection process and the detection status of hybrid events is considered. The impact of filter settings on detection process is also discussed. Finally the maximum detection times associated with notable events are presented.

During ideal conditions of source, the abc-to-dqo transformation, of input phase voltages results in a vdq vector which is exactly 1.0 p.u. whereas if line voltages are used, the output of transformation block is 1.732 p.u. (times of 1.0 p.u.) and can be scaled to a unity value for comparison purposes. A sampling frequency of 6 kHz is used. Except for the cases which assimilate the impact of filter settings, in all cases a first-order low pass filter with a cut-off frequency of 50 Hz is used. Simulations are carried out with MATLAB software [14].

3.1 Impact of Threshold Settings

Based on the variation of threshold settings, the behavior of detection process is analyzed under three different situations, the detection status of low magnitude events, unwanted detections and delayed detections.

(a) Based on threshold levels there exists certain low magnitude single-phase and double-phase sag/swell events which are not detected as shown in Table1.

Table 1: Detection status of single-phase and double-phase faint disturbances

Event Type	Threshold p.u.	Sag/Swell Magnitude (%)	Detection Status
Single-Phase Sag/Swell	0.07	Up to 15 %	Not Detected
	0.08	Up to 17 %	Not Detected
	0.09	Up to 19 %	Not Detected
	0.10	Up to 21 %	Not Detected
Double-Phase Sag/Swell	0.08	Up to 10 %	Not Detected
	0.09	Up to 11 %	Not Detected
	0.10	Up to 12 %	Not Detected

(b) At a threshold of 0.07 p.u., an unwanted detection occurs even at a 3-ph voltage level of 0.93 p.u., which is within the acceptable limits. Also switching of capacitor at t = 0.1134s causes hunting of transfer signal as shown in Figure 2.

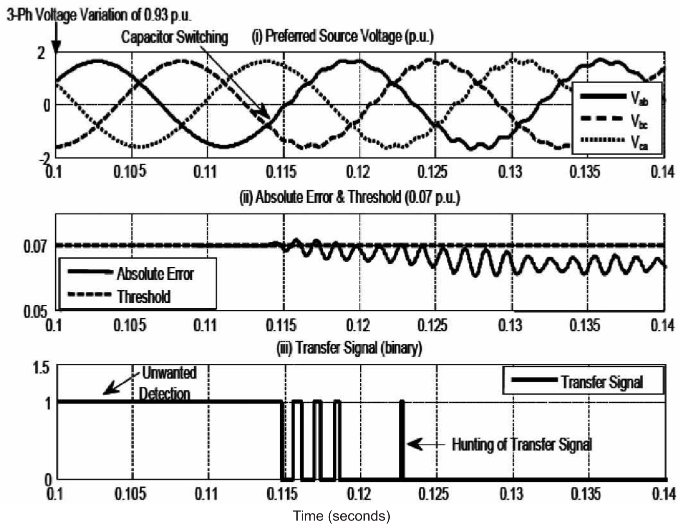

Fig 2: Unwanted detection and hunting of transfer signal at lower thresholds

(c) In certain cases of marginal sag/swells, the threshold settings on higher side have a subsequent effect of delaying the

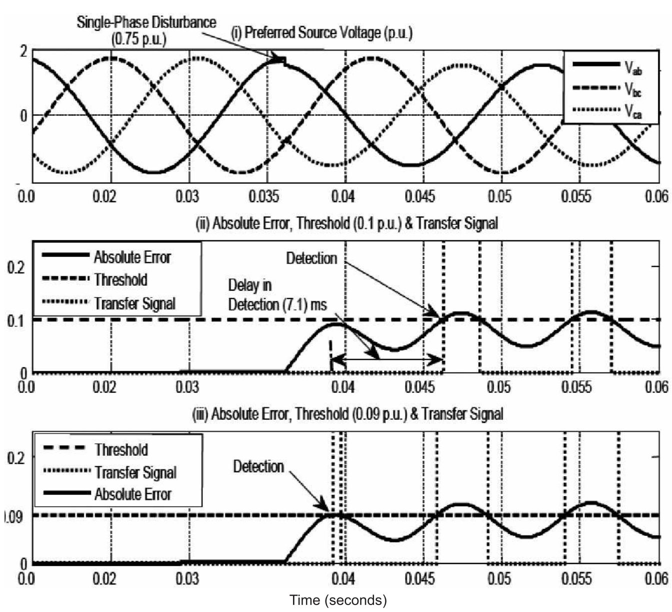

Fig 3: Delayed detection at higher thresholds

detection. A typical case is shown in which, the detection of single-phase sag of 0.75p.u. is delayed by 7.1 ms (see Figure 3) when the threshold of 0.09p.u. is increased to 0.1 p.u.

From the above discussion it is observed that thresholds on higher side (close to 0.1) leads to a precise and stable detection whereas thresholds on lower side may result in unwanted detections even during normal conditions of the supply and also the detection process is much sensitive towards routine switching operations of power system. This may lead to frequent and unnecessary switching of load from one source to the other. Hence to arrive on an optimum threshold in addition to load routine conditions of the source and the presence of other switching equipment should also be considered.

3.2 Impact of Point-on-Wave (POW) of Initiation

Figures 4 to 6 show the respective variations in detection times of various events (single-phase, double-phase and faults events) with respect to point-on-wave of initiation. Single-phase variations are created in phase 'a'; phase 'a' and phase 'b' are involved in double-phase events; L-G fault involves phase 'a' and the LL and LL-G faults involve phases 'a' and 'b'. The characteristics are similar irrespective of the phase(s) involved. Balanced disturbances except close to 10 % (sag/swell) are detected very accurately and in a negligible time therefore are not included in this discussion. Each of the characteristic are obtained at a threshold of 0.1 p.u. and for a first-order low pass filter with cut-off frequency of 50 Hz.

It is seen that based on the point-on-wave of initiation there is a significant variation in the detection time of faults and unbalanced events. In most cases, the detection time is either close to or more than 5 ms. In case of balanced disturbances, as the changes in Vdq (see Figure 4) vector are instantaneous and detection time is almost independent of point-on-wave. In later case the response of the detection scheme is almost governed by the filter settings.

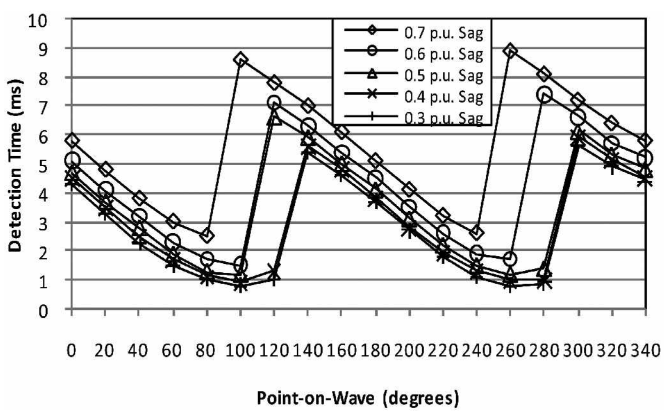

Fig 4: Variation in detection time of single-phase sag events (phase 'a') w.r.t point-on-wave.

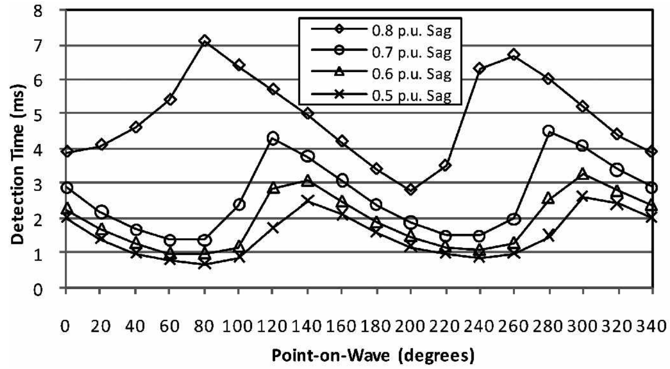

Fig 5: Variation in detection time of double-phase sag events (phases 'a' & 'b') w.r.t. point-on-wave

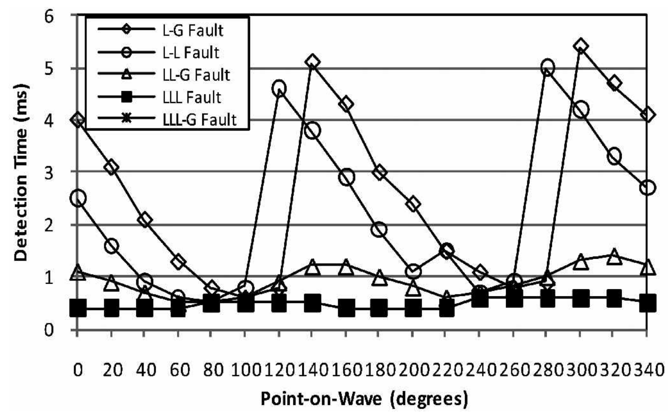

Fig 6: Variation in detection time of faults w.r.t. point-on-wave

3.3 Impact of Type and Severity of Disturbance

Point-on-wave characteristics also indicate that the type and severity of event have a considerable impact on detection status as well as on detection time too. LLL and LLL-G faults are detected in almost same time and are detected quite earlier in comparison to other type of faults. Double-phase events are detected earlier than single phase events and in most of the disturbances cases, it is noted that higher the severity level of an event, lesser is the detection time.

3.4 Impact of Marginal Voltage Deviations

There exist situations during which the source voltages may deviate from ideal values of 1.0 p.u., but are still within acceptable limits (0.91 p.u. to1.09 p.u.). Such variations in undisturbed phases may be quite decisive in detection of single-phase and double-phase events in remaining phases. Based on the analysis, following observations are made:

(a) Single-phase sag/swell events, comprising of 26 % change (increase/decrease), are not identified when the voltage of undisturbed phase is varied from 0.91p.u. to 1.09 p.u. In presence of a 9% reduced voltage of phase 'a', at t = 0.032 s, a swell of 26 % is introduced in phase 'b'. Recovery of the source takes place at t = 0.052s which is followed by another disturbance of 26 % sag in phase 'b' (in presence of 1.09 p.u. voltage of phase 'a') at t = 0.062s. Associated plots are shown in Figure 7.Other results are given in Table 2.

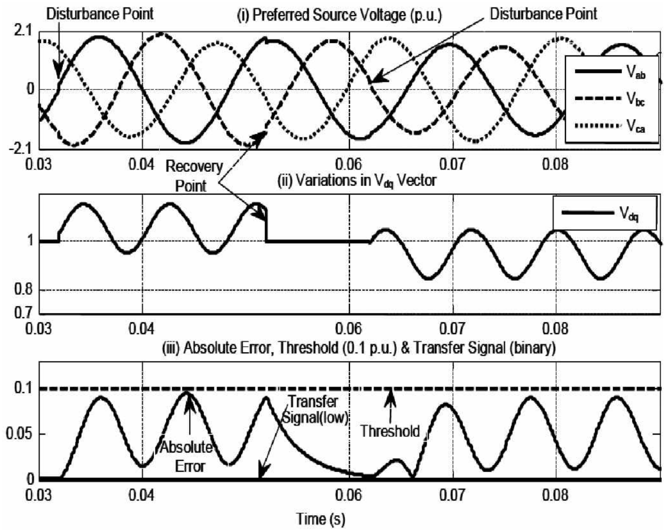

Fig 7: Marginal voltage variation and detection status of single-phase sag/swells

(b) Similarly when two phases experience a variation of 0.91 p.u./1.09 p.u., a 30 % sag/swell event in remaining phase is not detected. Results are given in Table 2. It is shown that trivial voltage variations in one/two phases, not categorized as power quality issue, may be decisive for identification of some disturbances in the remaining phase(s). Such undetected disturbances may be quite critical for a STS application.

Table 2: Impact of marginal voltage deviations on detection process

Phase(s) Involved in Marginal Voltage Deviation	Change in Voltage Magnitude	Magnitude & Type of Disturbance	Detection Status
Phase 'a'	0.91 p.u.	26 % Swell in Phase 'b'	Not Detected
Phase 'a'	0.95 p.u.	24 % Swell in	Not Detected
Phase 'a'	1.05 p.u.	24 % Sag in Phase 'b'	Not Detected
Phase 'a'	1.09 p.u.	26 % Sag in Phase 'b'	Not Detected
Phases 'a' & ' b'	0.91 p.u. & 0.91 p.u.	1.3 p.u. Swell in Phase 'c'	Not Detected
Phases 'a' & ' b'	0.95 p.u. & 0.95 p.u.	1.26 p.u. Swell in Phase 'c'	Not Detected
Phases 'b' & ' c'	1.05 p.u. & 1.05 p.u.	0.72 p.u. Sag in Phase 'a'	Not Detected
Phases 'b' & ' c'	1.09 p.u. & 1.09 p.u.	0.67 p.u. Sag in Phase 'a'	Not Detected

3.5 Detection Status of Hybrid Disturbances

Research work has shown that there exists an entire series of events of hybrid nature which is not detected. A hybrid disturbance is the simultaneous presence of events of opposite nature. The situation can arise when two or more phases are involved with the conditions of unbalance. It is quite common that during certain faults (severe sag condition) the voltage of unfaulted phase(s) experience swells. Unbalance disturbances of similar nature are detected quite successfully whereas in case of unbalances of hybrid nature, a variety of disturbances remain undetected. As the prediction of all such cases is quite difficult task, a few selected cases of relevance are presented in Table3.

Table 3: Detection status of multiphase hybrid events

Case No.	Phases Involved in Disturbance	Type of Disturbance	Disturbance Magnitude (p.u.)	Detection Status
1.	Phases 'a' & ' b'	Sag in Phase 'a'& Swell in Phase 'b'	0.8 p.u. & 1.2 p.u.	Not Detected
2.	Phases 'a' & ' b'	Sag in Phase 'a'& Swell in Phase 'b'	0.7 p.u. & 1.3 p.u.	Not Detected
3.	Phases 'a' & ' b'	Sag in Phase 'a'& Swell in Phase 'b'	0.65 p.u. & 1.35 p.u.	Not Detected
4.	Phases 'a', 'b' & 'c'	Swell in Phase 'c' & Sag in two Phases ('a' & 'b')	1.1 p.u. & 0.8 p.u., 0.9 p.u.	Not Detected
5.	Phases 'a', ' b' & 'c'	Sag in two Phases (a & b) & Swell in Phase 'c'	0.8 p.u., 0.8 p.u. & 1.33 p.u.	Not Detected

Two cases (case no.3 and case no.5 of Table 5) are illustrated with help of Figure 8. A three phase disturbance is initiated at t = 0.032 s (case no.5). The source recovers at t = 0.052 s and is followed by another two-phase disturbance (case no.3) which occurs at t = 0.062 s. Both the events are of practical importance and of considerable level too but remain undetected. During case no.5 even all the three phases are under an effective unbalance condition but the event is not identified.

3.6 Impact of Filter Order and Cut-off Frequency

Observations made from the study indicate that the choice of a filter order and precise cutoff frequency is very critical as it has considerable impact on the detection time as well as on the accuracy of detection. The impact of filter is studied by using different filter arrangements.

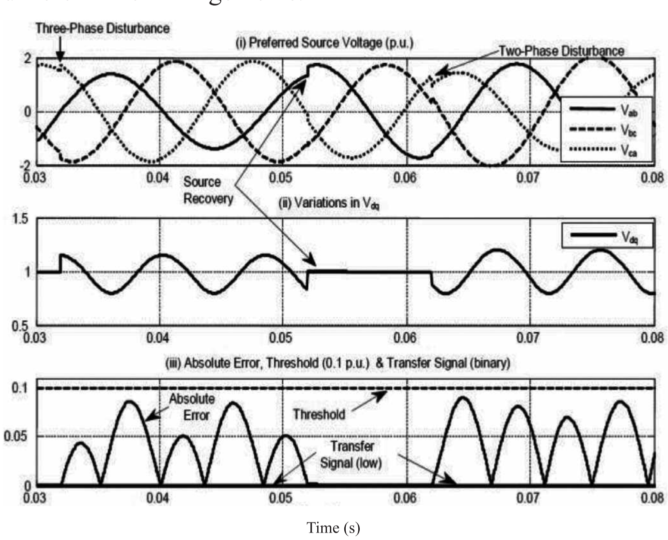

Fig 8: Detection status of hybrid disturbances

To assimilate the impact of filters all events of each category are programmed at same instant. A typical case of much significance (as shown in Figure 9) is selected and is discussed with relevant waveforms. A near medium threshold of 0.085 is assumed and three different filter arrangements including a first-order filter with different cut-off frequencies of 200 Hz and 50 Hz and a second-order filter with cut-off frequency of 50 Hz are used. In all the cases of disturbances, results show that the first-order filters when used with higher cut-off frequencies provides shorter detection times.

Case: In presence of three-phase balance variation of 0.92 p.u. in the source voltage, a capacitor is switched at t = 0.1139 s. Particularly a 1st order filter with cut-off frequency of 200 Hz results in an unwanted detection. Also severe transitions in transfer signal, lasting up to 21.1 ms from the instant of first transition are observed (see first plot of Figure 9).

To detect faint unbalances, the use of lower threshold of 0.08 p.u. is recommended. Also to obtain faster detection a first-order filter with a cut-off frequency of 200 Hz is used [8]. Anyhow the results obtained in this case do not agree with the use of higher cut-off frequencies. It is seen that use of higher cut-off frequencies particularly at lower thresholds, leads to a detection process which is much prone to switching transients. To avoid hunting of transfer signal and at the same time to have a faster detection under such conditions, first-order filters should be preferably used with cut-off frequencies in the range of 40-60 Hz.

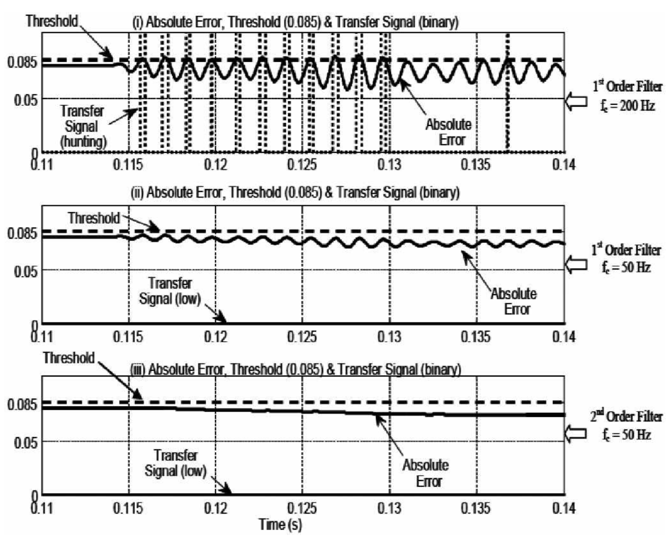

Fig 9: Impact of filter-order and cut-off frequency on detection status

3.7 Maximum Detection Times

Disturbances with magnitudes 10% or higher and lasting for a duration of 1/4 cycle to 30 cycles are categorized as sag/swell [15]. Further in case of sensitive loads it is required to restore good quality power at the earliest. To determine the discontinuity of supply to the load, in addition to detection time an additional component, the transfer time is equally important. Therefore it is essential to estimate the maximum detection times offered by the detection process against various disturbance conditions. Table 4 presents the summarized and decisive information of the detection status and maximum detection times of the single-phase, double-phase events and faults.

As the issue of impact of marginal deviations in source voltage on the performance of detection process is already been considered and discussed separately, the results obtained in this part of study does not account for the same. Particularly notable events which are either not detected or the detection time is very near to or more than 5 ms are reported. A threshold of 0.1 p.u. is used in this section.

Table 4: Detection status & maximum detection time

Event Type	Event Magnitude (%)	Detection Status & Maximum Detection Time (ms)		Detection Status & Maximum Detection Time (ms)
		1st Order Filter f_c= 50 Hz	1st Order Filter f_c= 200 Hz	2nd Order Filter f_c= 50 Hz
Single-Phase Sag/ Swell	10%	Not Detected	Not Detected	Not Detected
	15%	Not Detected	Not Detected	Not Detected
	20%	Not Detected	Detected 7.8 ms	Not Detected
	30%	Detected 8.9 ms	Detected 6.0 ms	Detected 10.1 ms
	40%	Detected 7.5 ms	Detected 5.4 ms	Detected 8.8 ms
	50%	Detected 6.6 ms	Detected 5.4 ms	Detected 7.8 ms
	60%	Detected 6.0 ms	Detected 5.2 ms	Detected 7.3 ms
	70%	Detected 5.8 ms	Detected 4.4 ms	Detected 6.9 ms
Double-Phase Sag/ Swell	10%	Not Detected	Not Detected	Not Detected
	15%	Detected 10.2 ms	Detected 6.1 ms	Detected 13.1 ms
	20%	Detected 7.2 ms	Detected 4.5 ms	Detected 7.9 ms
	30%	Detected 4.4 ms	Detected 2.1 ms	Detected 5.9 ms
L-G fault	-	5.1 ms	3.5 ms	6.2 ms

Single-phase faint disturbances of 20% or lower are not detected or the detection process is quite time consuming. For remaining cases the detection time is either close to or higher than 5 ms. Double-phase events with disturbances magnitudes greater than 30% are well identified within duration of 5 ms and hence are not listed here. It is also noted that in case of an L-G fault which is comparatively quite frequent, the maximum detection time touches 5 ms duration. Detection of an L-L fault takes around 4 ms. Remaining faults are detected within 2 ms. Results shown in Table 4 clears the fact that the detection scheme under performs in case of most single-phase disturbances and also in some cases of double-phase disturbances and faults. All balanced disturbances of higher magnitudes except marginal sag/swells of the range of 10% to 15%, are identified within 0.3 ms.

4. CONCLUSION

A decisive evaluation of abc-to-dqo based voltage detection scheme which is commonly used with STS systems, is carried out under various operating scenarios and disturbance conditions. The ability of the scheme is also investigated against the variations in control elements of the detection process. It is concluded that to arrive on an optimum threshold value, in addition to load requirements the routine conditions of the source and the presence of switching equipment is also decisive and cannot be neglected. The analysis results indicate the deceased capacity of the method against unbalance events and also against all types of faint disturbances. In addition to low magnitude disturbances which are not detected there exist variety of events where the detection process is quite time consuming and takes either close to or higher than 5 ms. It is noted that marginal variations in source voltages may lead to unwanted detections even when these variations are within acceptable limits. It is found that there exist cases of significant unbalance of source voltage in two or more phases, which remain undetected. Such undetected hybrid events of considerable unbalance are critical for most sensitive loads and in some cases it may happen that the STS installation may even be disqualified. Use of higher cut-off frequencies improves the detection time but at the same time the detection process is more sensitive towards the transient disturbances particularly at lower thresholds and may lead to transitions in transfer signal. Such transitions may cause frequent and unnecessary switching of load from one source to another thereby adversely affecting the performance of sensitive loads. In lieu of the projected applications of STS device under the smart grid technology demands comparatively more precise, faster and stable detection method.

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