World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:7, No:8, 2013

An Evaluation of Sag Detection Techniques for Fast Solid-State Electronic Transferring to Alternate Electrical Energy Sources

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Abstract**—**This paper deals with the evaluation of different detection strategies used in power electronic devices as a critical element for an effective mitigation of voltage disturbances. The effectiveness of those detection schemes in the mitigation of disturbances such as voltage sags by a Solid-State Transfer Switch is evaluated through simulations. All critical parameters affecting their performance is analytically described and presented. Moreover, the effect of fast detection of sags on the overall performance of STS is analyzed and investigated.

Keywords**—**Faults (short-circuits), industrial engineering, power electronics, power quality, static transfer switch, voltage sags (or dips).

I. INTRODUCTION

CRITICAL loads connected in industrial power distribution systems require electric power of good quality, i.e. free from voltage disturbances. Several mitigation methods for the consequences of voltage disturbances and other power quality phenomena have been proposed. Modern mitigation methods are based on power electronics technology. The Solid-State or Static Transfer Switch (STS), the Dynamic Voltage Restorer (DVR), the Distribution STAtic COMpensator (DSTATCOM), the Static Var Compensator (SVC) and the Solid State Tap Changer (SSTC) are the most used devices [1]-[3].

The Static Transfer Switch (STS) is one of the most effective solutions among the above to mitigate voltage sags. This device can be used to rapidly connect the sensitive load to an alternate (or backup) source of ac power when the main (or preferred) source fails. Thus, voltage sags experienced by an industrial customer are of minor severity and their critical or sensitive equipment is protected from shut-down, malfunction or even damage.

The STS operation requires an alternate electrical energy source or a new feeder from the existing power grid. This feeder should not be affected by the same disturbances as the main (or preferred) feeder and must be provided at a reasonable cost. For example, a voltage sag due to a short-circuit somewhere in the transmission or distribution system should not affect also the alternate feeder. Obviously, STS is not effective in the event of a utility complete outage and cannot provide power conditioning.

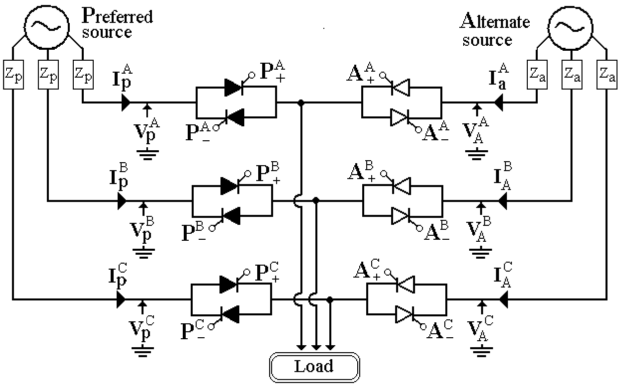

Fig. 1 Static transfer switch

The most critical part of STS and other similar devices is the system that detects the presence of disturbances such as voltage sags. Voltage sags are rapid drops in the rms voltage and are mainly caused by short-circuits in the electric power transmission or distribution system. They are characterized by the remaining (retained or during-fault) voltage magnitude. A voltage magnitude down to 90% and more than 10% is defined as voltage sag (or dip) according to [4] and [5] respectively. Other characteristics of voltage sags include their duration, the phase-angle jump for fault-induced sags, the point-on-wave that the sag initiates and the sag type, which mainly refers to the number of phases sagged. It should also be noted that voltage sags are more frequent than voltage interruptions but less severe.

In this paper, the performance of three different detection systems will be evaluated in case of fault-induced voltage sags. The effect of sag characteristics will be fully investigated through simulations using PSCAD software [6].

II. STATIC TRANSFER SWITCH

The three-phase model of a STS is shown in Fig. 1. It consists of two thyristor blocks at the P(referred) and A(lternate) source, which connect the load to the two alternate

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This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF).

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sources. Each thyristor block is composed of three thyristor modules corresponding to the three phases of the system. In each thyristor module, two sets of thyristor switches are connected in opposite directions, e.g. P_+^A/P_-^A and A_+^A/A_-^A, to allow the load current to flow in both positive and negative directions. The main parts of STS are: the voltage detection system and the control system that provides the commutation and gating of thyristors.

III. VOLTAGE SAG DETECTION

Voltage sags have different characteristics that depend on their source. Voltage magnitude and phase-angle jump during fault-induced sags are the most common factors that affect sag detection procedure. Two more characteristics of sags affect their detection procedure:

1) The during-sag rate of change of voltage. Voltage sags can be distinguished in fast and slow events depending on their cause. Fast and sharp sags are usually due to short-circuits or sudden load variations while slow and mild sags are mainly due to the presence of induction motors.
2) The point-on-wave that the sag initiates. It takes values between 0 and 180^0. In Fig. 2, an example of a fault-induced voltage sag is shown and the point-on-wave sag initiates, which is also the time instant that the fault occurs. Moreover, the subsequent phase-angle jump due to the fault can be observed.

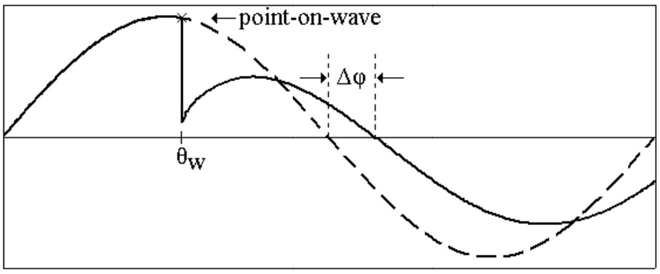


Fig. 2 Point-on-wave and phase-angle jump

The detection time of voltage sags depends on its characteristics and the detection technique used. In this paper, we focus on the fault-induced sags as faults are the most frequent type of sags. Three detection techniques are compared through simulations using PSCAD simulation software [6]. The basic principle of those techniques is the comparison of the voltage deviation from a reference voltage for a tolerance limit. A reference value of 1 pu is assumed and, as tolerance limits, values of 0.1 or 0.15 pu can be used for the voltage detection system of a Static Transfer Switch.

A. 1st Detection Technique-Park (dqo) Transformation

One technique commonly mentioned and used for the detection of fast voltage variations is the Park or abc-to-dqo transformation [7], [10]. The detection is based on the calculation of V_p^p according to the following equation:

$$V_p^p = \sqrt{(V_p^d)^2 + (V_p^q)^2} \qquad (1)$$

The detection system structure is shown in Fig. 3 (a). A filter is required to limit the waving. Moreover, a small time delay t_d is necessary as voltage V_p^p responds very rapidly to voltage variations and may give a false detection signal. Due to this delay, the voltage variation should last at least a time period equal to t_d in order to generate the detection signal.

B. 2nd Detection Technique-Fast Fourier Transformation

This technique is based on the comparison between each phase voltage $\widetilde{V}_p^A(t)$, $\widetilde{V}_p^B(t)$ and $\widetilde{V}_p^C(t)$ (Fig. 1) with a reference waveform of constant amplitude and frequency as shown in Fig. 3 (b). This waveform is implemented by calculating the angle of the three phase voltages of the previous time period (cycle) using a Fast Fourier Transformation (FFT). Based on this angle, a sinusoidal waveform is created of a 1 pu amplitude and of nominal frequency (e.g. 50 Hz) per phase, that is, three new reference waveforms $\widetilde{V}_{p,FFT}^A(t)$, $\widetilde{V}_{p,FFT}^B(t)$ and $\widetilde{V}_{p,FFT}^C(t)$ are implemented. The maximum deviation of the three reference (FFT) waveforms from the actual ones is compared to a tolerance of 0.1 or 0.15 pu. A time delay is again required to avoid false detection signals due to waveform distortion caused e.g. by voltage harmonics or notching.

C. 3rd Detection Technique-Minimum rms Voltage

This technique is based on the calculation of the minimum rms value among the three phase voltages $\widetilde{V}_p^A(t)$, $\widetilde{V}_p^B(t)$ and $\widetilde{V}_p^C(t)$ (Fig. 1) of the preferred source, which corresponds to the definition of sag magnitude. A filter is required in order to reduce the waving in the rms meters. The deviation of that minimum reference value is compared to the tolerance limit as shown in Fig. 3 (c). When this limit is violated, the transfer procedure to the alternate source is activated.

D. Simulation Results

The comparison among the three detection methods will be based on the sag type and magnitude, and the point-on-wave that the sag is initiated (or the fault occurs). Only fault-induced sags will be considered. Sag type corresponds to the number of phases sagged. Thus, in one-phase (1ph) sags only one phase is sagged, in two-phase (2ph) sags two phases are sagged and in three-phase (3ph) sags all the three phases are sagged.

Moreover, three sag magnitudes (remaining or during-fault voltage) are considered: 0.5, 0.6 and 0.7 pu. For the point-on-wave, ten values are used in the range 0-180^0, thus in steps of 18^0. Tolerance limits of 0.1 or 0.15 pu are studied, that is, when the reference voltage goes below 0.9 pu, which corresponds to the definition of sag magnitude, and 0.85 pu. Those two limits are commonly used in the literature for STS applications [7]-[9].

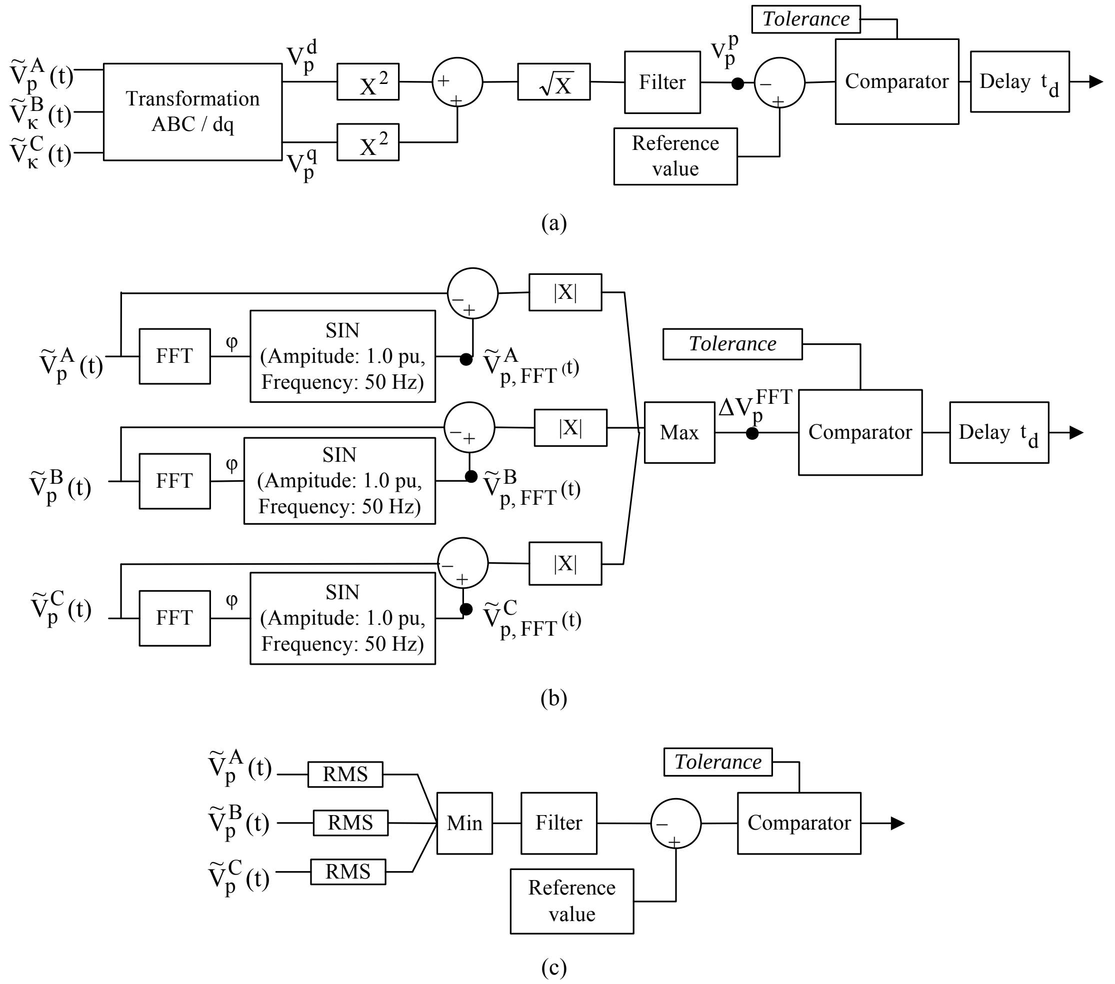


Fig. 3 Detection schemes based on: (a) Park transformation, (b) Fast Fourier Transformation, (c) Minimum rms voltage

The detection time in each case is calculated by repetitive simulations in PSCAD software using the multirun module [6]. The sag type influences the detection time, that is, 3ph sags are expected to be detected faster than 1ph sags for the same sag magnitude and point-on-wave. Furthermore, a high sag magnitude (shallow voltage sag) is expected to give a longer detection time. However, the effect of the point-on-wave on the detection time cannot be safely predicted from the beginning, therefore simulations are required.

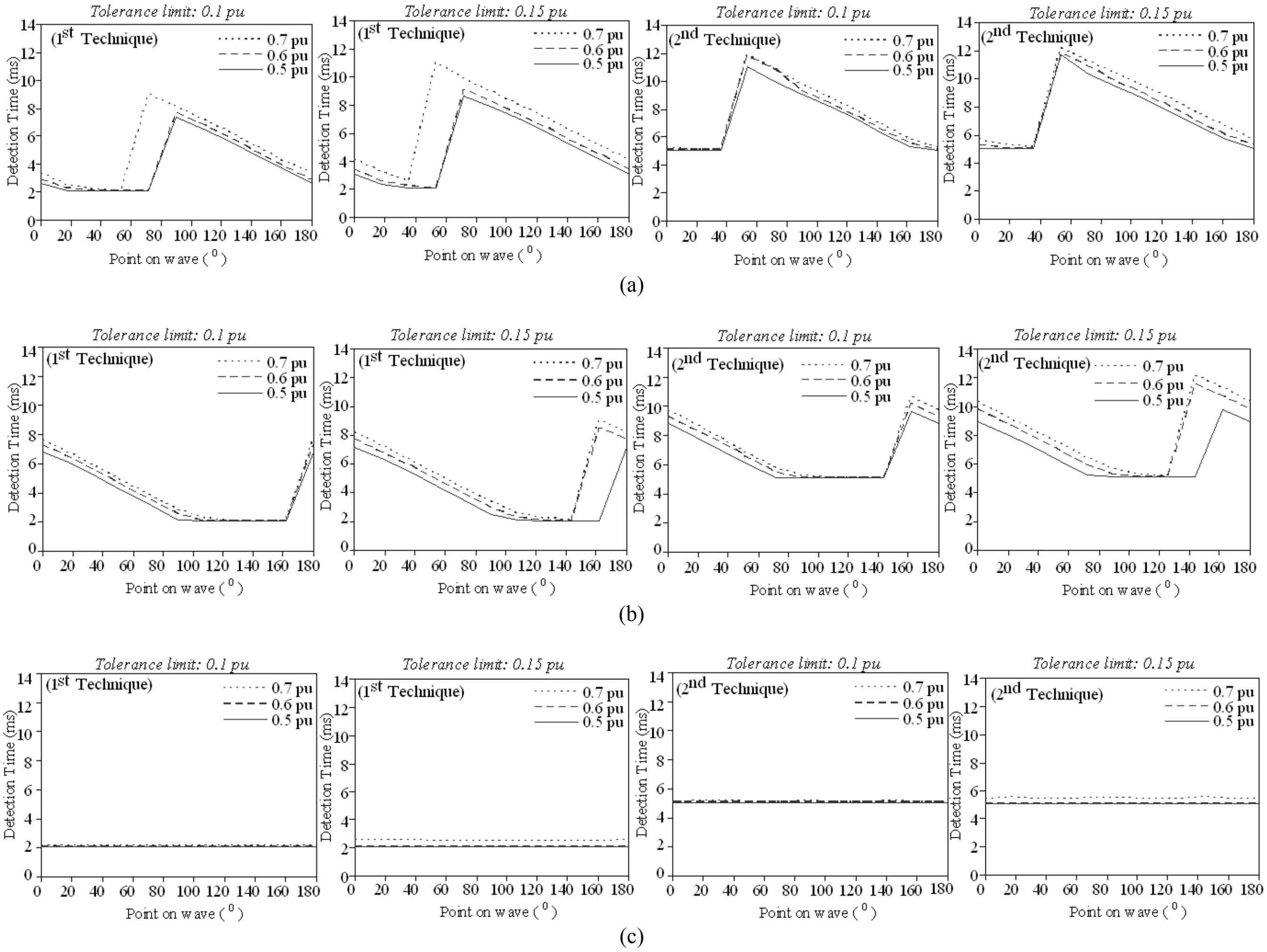
Fig. 4 (a) presents the results for the detection time versus the point-on-wave for three sag magnitudes when the 1st technique is used. A second order filter is used for the 100 Hz frequency with a damping ratio of 0.1 and a time delay $t_d = 2$ ms. It can be seen in Fig. 4 (a) that for 1ph and 2ph sags, the detection time is not constant and takes minimum or maximum values in specific ranges of the point-on-wave values. On the other hand, 3ph sags result in a fast and constant detection of 2 ms, which is also the time delay used. Moreover, the detection time becomes considerably longer for higher sag magnitudes only in cases of 1ph sags.

In Fig. 4 (b), the simulation results for the 2nd technique are presented. A time delay of 5 ms is used to avoid false signals due to phase-angle jump and significant waveform distortion. It can be seen that this technique gives similar characteristics as regard the effects of sag type and magnitude on the detection time. Again, 1ph and 2ph sags give variable detection times and 3ph sags give a constant value equal to the time delay used.

In Fig. 5, the simulation results are presented for the 3rd detection technique. Specifically, the first and the third column of graphs present the detection time and the other columns the transfer time, which will be discussed in the next Section. It can be seen that there are similar characteristics with the other detection techniques as 1ph and 2ph sags give variable detection times, and 3ph sags almost constant values. The only difference from the other techniques is that the detection is clearly and considerably increased as the sag magnitude increases.

IV. TRANSFER PROCEDURE

Apart from the detection system, the control system of a Static Transfer Switch contains a system that controls the transfer procedure from the one source to the other. This system takes as inputs the three phase voltages and currents of both the preferred and alternate power sources and generates the appropriate sequence of gating pulses for the thyristors.



(a)

(b)

(c)

Fig. 4 Detection time under different sag magnitudes for the 1st and the 2nd Detection Technique: (a) 1ph sags, (b) 2ph sags, (c) 3ph sags

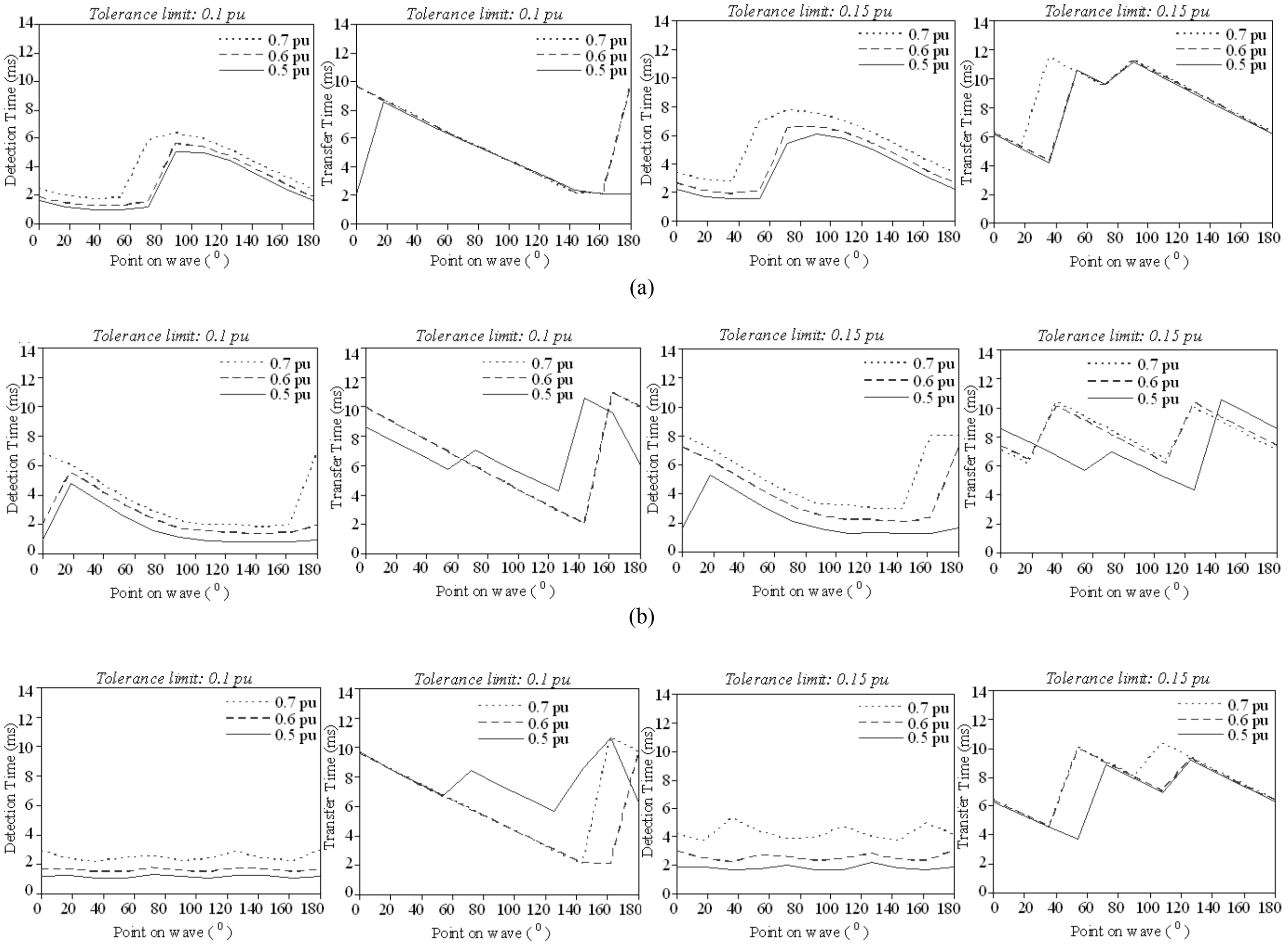
The control logic of the transfer procedure for an STS model is analytically described in [8], [9]. Full details are given for the developed STS model and the conditions for a fast and safe transfer to the alternate source. This model is designed to operate for all sag types and point-on-wave, for a load power factor in the range 0.85-1 and phase displacement between the two power sources of $\pm 40^0$.

A. Transfer versus Detection Time

Transfer time is the time from the detection of voltage sag (or other disturbances) to the completion of transfer for all three phases of the preferred source. It becomes obvious by the previous analysis that fast sag detection will probably lead to a fast completion of the transfer procedure. This is mainly due to the fact that if the detection time is short, the remaining phase voltages of the preferred source will be smaller than the corresponding phase voltages of the alternate source. Thus, the thyristors can be turned off faster applying a reverse biased strategy instead of a zero-crossing detection [7]-[9].

In general, transfer time is not constant and depends on several factors. Some of them include the detection and transfer strategy, the sag type, magnitude, rate-of-change and point-on-wave, the phase-angle jump for fault-induced sags, the instant voltage magnitude of the alternate source at the transfer initiation, and the load's power factor.

In Fig. 5, the transfer time is compared with the detection time received with the 3rd technique, that is, the minimum rms phase voltage calculation. Similarly with the previous comparisons presented in Fig. 4, transfer and detection time is calculated through simulations in PSCAD with relation to the sag's point-on-wave for 1ph, 2ph and 3ph fault-induced sags. Again, three sag magnitudes and two tolerance limits are considered. Load power factor is assumed to be 0.9, and alternate source's rms voltage equals to 1 pu. Moreover, each transfer time shown in Fig. 5 is the maximum among the values taken for all the phase displacements between the two power sources in the range of $\pm 40^0$ with 10^0 steps.



(a)

(b)

(c)

Fig. 5 Detection and Transfer time for the 3rd Detection Technique: (a) 1ph sags, (b) 2ph sags, (c) 3ph sags

Transfer time shown in Fig. 5 is the time after the sag detection. It can be observed in Fig. 5 that transfer time does not follow a similar pattern as the detection time. Specifically, higher values can be taken for sags with lower magnitude (larger depth) in some cases.

However, the performance of STS models is normally characterized by the total transfer time for the transfer completion, that is, the summation of the detection and the transfer time. In Table I, the minimum, maximum and average values of the total transfer time is presented for each tolerance limit (0.1 and 0.15 pu) and sag magnitude (0.5, 0.6 and 0.7 pu) as calculated by simulations. It can be seen that the total transfer time is less than 20 ms even for a 0.15 pu tolerance limit, that is, the transfer procedure is completed within a cycle at 50 Hz power systems.

TABLE I
TOTAL TRANSFER TIME STATISTICAL VALUES

	Tolerance 0.1 pu (ms)	Tolerance 0.15 pu (ms)
Minimum	3.43	5.5
Average	8.84	11.49
Maximum	16.77	18.86

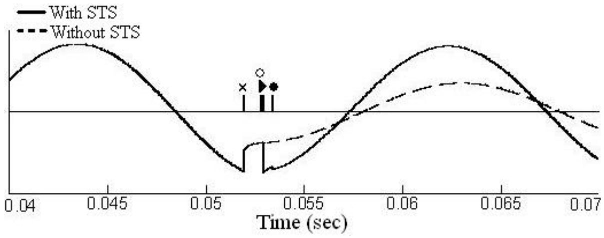
B. STS Performance

In Fig. 6, the STS performance is presented in case of a 1ph sag on phase A. Fig. 6 (a) depicts the sag experienced by the load with and without STS for the most sagged phase. It can be observed that the voltage drops to the same value regardless of STS presence but it lasts much shorter with the presence of STS. In case of R-L load, the sag duration is also the time until the transfer initiation to the alternate source, which is activated by the triggering of the alternate source's thyristors. Moreover, the transfer procedure for each phase is shown in Fig. 6 (b). The transfer procedure for phases B and C starts later than phase A and at the moment that current flowing through them becomes zero for the first time after the sag is detected.

Furthermore, the STS performance in case of a 3ph sag is shown in Fig. 7. Fig. 7 (a) shows the sag experienced by the load with and without STS. Similarly with the previous case, the voltage drops at the same value regardless of the STS presence but lasts much less when STS is present. In Fig. 7 (b), the transfer procedure is depicted for each phase. It should be noted that sag detection does not always coincides with transfer initiation because some conditions should be fulfilled before transfer initiation is activated, as shown in Figs. 6 and 7.

V. CONCLUSION

In this paper, three detection techniques are developed and compared using simulations. The detection time is proved to be affected by the sag characteristics such as the type, the magnitude and the point-on-wave that sag initiates. The effect of fast sag detection on the transfer time is validated for a proposed STS model. The transfer procedure for two sag types and the reduced sag magnitude experienced by the load due to STS operation is presented and analyzed.



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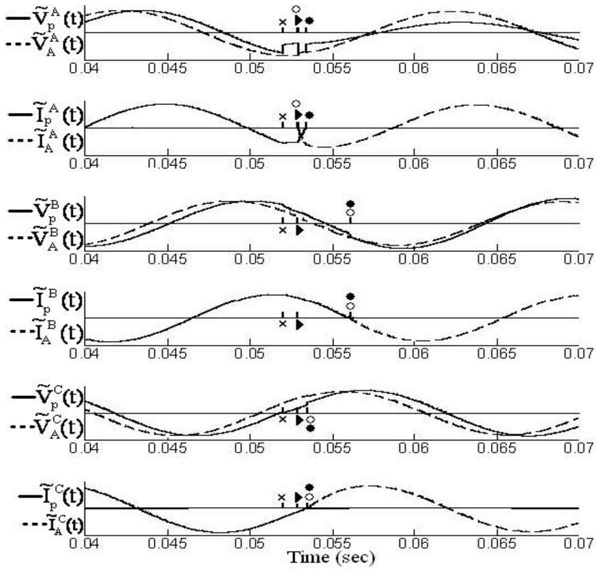
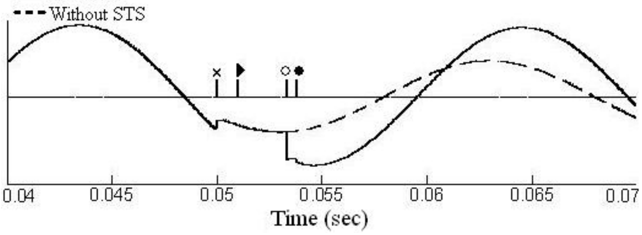


(b)

Fig. 6 STS performance for a 1ph sag (a) Sag experienced by the load with and without STS (b) Transfer procedure per phase

× Fault occurrence ► Sag detection
○ Transfer initiation ● Transfer completion



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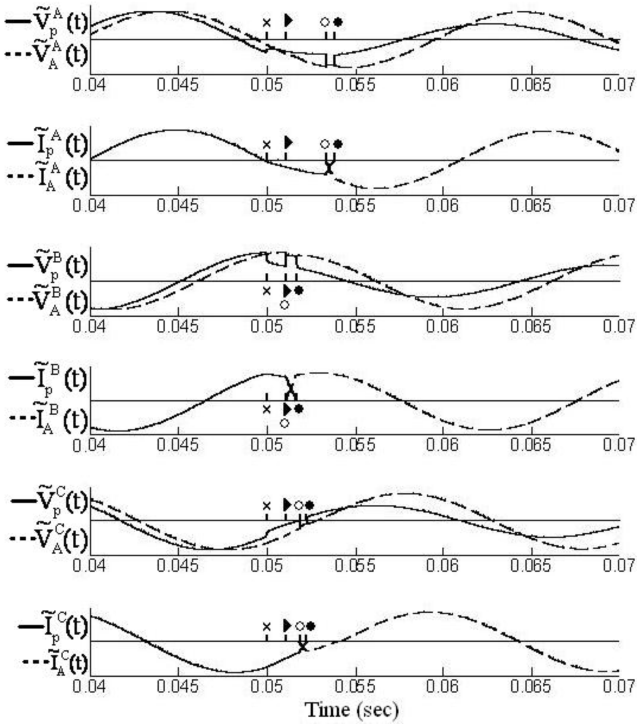

(b)

Fig. 7 STS performance for a 3ph sag (a) Sag experienced by the load with and without STS (b) Transfer procedure per phase

× Fault occurrence ► Sag detection
○ Transfer initiation ● Transfer completion

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