ISSUES ON SYNCHRONIZING POWER CONVERTERS CONNECTED TO A WEAK GRID

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Abstract **– In renewable and distributed generation systems the grid voltage quality can be poor. So, the connection of power converters to the grid requires accurate control of synchronism between the two sources. The paper discusses issues on synchronization of power converters connected to the mains and related control methods. In this paper a new zero crossing synchronizer is proposed having zero error in steady state, moderate speed response to grid frequency changes and amplitude voltage variations, and immunity to phase unbalance, harmonics and noise. The speed response, and harmonics and noise immunity are a trade-off. Simulation results and experiments based on synthesized voltage grids with strong disturbances in the grid voltage show the robustness of the proposed method.**

Keywords **– grid synchronizer, power quality, renewable energy, weak grid, power converter.**

I. INTRODUCTION

The interconnection of power converters to the grid requires accurate control of synchronism between converter and grid. This requirement becomes a critical one for systems in that voltage quality of grid is not good. This is the case for renewal generation if the location of the plant is either a remote one or an island. This has caused some research on developing synchronization methods that minimally are affected by this poor power quality. The paper discusses issues on synchronization of power converters connected to Mains and related control methods. The design and experimentation of a prototype of a 200 kW power converter that connects a wind generator to the grid help to validate the adopted approach. The main goal is to compute in real time an accurate estimate of the phase-angle (θ) of the grid voltages.

The environment of design may be summarized as: wind generator located in an island with a grid presenting bad characteristics - voltage sags and swells are frequent and heavy, the harmonic components are considerably high, and the frequency presents some oscillation around the 50 Hz. Some grid synchronizers reported in literature are done with a Phase Locked Loop [2]-[3] having the inherent slower response particularly if they use zero cross detection, others are based on the d-q transformation theory [4] having instant updates but are more sensitive to grid disturbances if the filtering is low to achieve fast response.

The authors have presented [6] a zero crossing synchronizer having zero error in steady state, moderate speed response to grid frequency changes and amplitude voltage variations, and harmonics and noise immunity. However this synchronizer is not robust in the presence of unbalanced voltages and DC offset.

In this paper a zero crossing synchronizer based on [6] is proposed having zero error in steady state, moderate speed response to grid frequency changes and amplitude voltage variations, and immunity to phase unbalance, DC offset, harmonics and noise.

The speed response, and harmonics and noise immunity are a tradeoff.

II. SYNCRONYSER BASIS

Synchronization is an operation based on detection of phase. Disturbances on voltage waveforms cause phase changes and difficulties on designing a simple method for synchronizing different waveforms. This synchronizer is based on the zero crossing detection of the grid voltages. The three phases provide six zero crossings, so the phase-angle and frequency are verified six times per period. If the lower order harmonics are not in phase, the zero crossings are changed, and if they have a high amplitude cause extra zero crossings detections. The lower order harmonics effects in zero crossings detection can be highly reduced through inclusion of a low pass digital filter.

The high frequency harmonics can also produce an error in zero crossings detection but this problem can be eliminated or highly reduced through appropriate anti-aliasing analog filters. The effect of the voltages spikes and notches are highly reduced using a digital filter as well as specific sampling techniques in which each voltage sample is an average of the voltage during samplings. This can be done by an analog integrator reseted after the analog to digital conversion or by an over sampling. This technique also reduces the noise in the measurements.

To obtain the phase angle of the three phase voltages grid, this method uses the synchronizer in single phase mode described in [6] to the three phases, thus obtaining the individual phase angle on each phase. The three phase angles are then averaged (taking into account the delays on the phases S and T) to achieve the three phase grid phase-angle.

The following sections describe the details on how to detect the zero crossings, obtain the individual period and phase angle to the three phases, and finally how to average the three values to achieve the grid phase-angle and frequency.

III. ZERO CROSSING DETECTION

The zero cross detection is based on the measured line voltages (V_R, V_S, V_T) required by the control algorithm. As stated in section 2 the harmonics, noise, voltages spikes and notches are highly reduced by the anti-aliasing analog filters, by using the average voltage between samples instead of the instant voltage value, and by a low pass digital filter. Using a FIR (Finite Impulse Response) filter the time delay is constant, so the phase angle delay is linear and easily computed in order to compensate the delay. To make the synchronizer immune to the DC offset, the output of the FIR filter is derived. The filter order must be a compromise between the delay and the harmonics attenuation. The phase delays introduced by the filter (θ_f [rad]), by the use of the average samples (θ_a [rad]) and by the derive (θ_d [rad]) are given by (1), where f_s [Hz] is the sampling frequency, f [Hz] the grid frequency, and N_f the FIR filter order [1].

$$\begin{aligned} \theta_f &= \pi\left(N_f - 1\right) f / f_s \\ \theta_a &= \pi f / f_s \\ \theta_d &= -\pi/2 \end{aligned} \tag{1}$$

At every sample instant (j), whenever a change in sign of two consecutive filtered measures (Sj) in the same voltage is detected, a zero cross of the respective voltage is obtained.

If the sampling frequency is high enough, the phase-angle in sampling the period j can be determined by assuming that the signal $S(t)$ is a straight line between the sampling points (fig. 1). In this case the values a_j, b_j and θ_j are obtained through (2) where θ_{CP} is a value that depends on the zero crossing slope (0 if rising and π if falling)

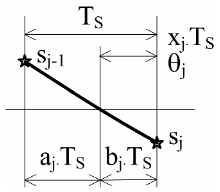

Fig. 1. Zero crossing detection.

$$\begin{aligned} a_j &= \frac{S_{j-1}}{S_{j-1} - S_j}; \\ b_j &= 1 - a_j; \\ \omega t_j &= 2\pi b_j \frac{T_s}{T} + \theta_{CP} \end{aligned} \tag{2}$$

If the sampling frequency is not high enough, a better approach is to assume that the signal $S(t)$ is a polynomial defined by four consecutive samples (two less than zero and two greater than zero) and apply the method described in [6] at the expense of more compute time.

A more complex filtering can be done using predictive filtering as described in [5].

IV. SINGLE PHASE FREQUENCY AND PHASE ANGLE ESTIMATION

The grid period is obtained by taking the time between two consecutive zero crossings. This is done with a counter to obtain the number of $_j$ samples between two consecutives zero crossings and by the values a_i and b_{i-1}, where i indicates the zero crossing detection order as is shown in fig. 2.

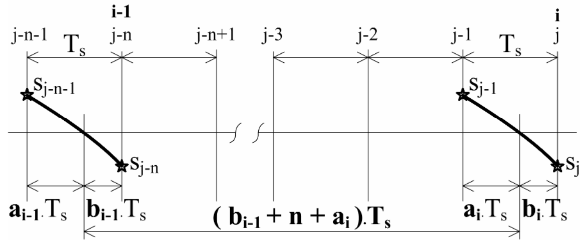

Fig. 2. Single phase grid period calculation from two consecutive zero crossings.

This way, the single phase grid period T_i is taken from (3) two times per period where a_i and b_{i-1} are obtained as explained in section III, n_i the number of j samples counted, and T_a the sampling period. The grid frequency (f_i) is the inverse of T_i.

$$\begin{aligned} T_i &= 2(b_{i-1} + n_i + a_i)T_a; \\ f_i &= 1/T_i \end{aligned} \tag{3}$$

The phase angle estimation in the sample instant j ($\hat{\theta}_j$) is obtained by increment every sample instant its value by the value Δ_i as indicated in (4). Thus, Δ_i needs to be computed in order to maintain the phase angle error (θ_j^{err}) null every instant j. θ_j is only known in the zero crossings instants i and its value is given by (2) as indicated in section III. Note that i represents the instants when a zero crossing is detected.

$$\begin{aligned} \hat{\theta}_j &= \hat{\theta}_{j-1} + \Delta_i; \\ \theta_j^{err} &= \theta_j - \hat{\theta}_j \end{aligned} \tag{4}$$

Assuming that the measured grid period in i (T_i) is maintained during the time interval between i and $i+1$, $T_{i+1}^* = T_i$ the number of instant samples j between i and $i+1$ will be the same: $n_{i+1}^* = n_i$. Thus the expected value of θ_{i+1} in the next zero crossing is given by (5) (the superscript * denotes assumption values).

$$\theta_{i+1}^* = \theta_i + n_i 2\pi \frac{T_s}{T_i} \tag{5}$$

With the same assumption, the phase angle estimation in the next zero crossing instant is given (6).

$$\hat{\theta}_{i+1}^* = \hat{\theta}_i + n_i \Delta_{i+1} \tag{6}$$

Now the goal is to make $\hat{\theta}_{i+1}^* = \hat{\theta}_{i+1}$, that is, in the next zero crossing the phase angle estimation is expected to be the same as the grid phase angle. Due to the phase angle circular nature ($\theta \in [-\pi ... \pi]$), Δ_i is calculated to speed up or slow down the phase angle in order to $\hat{\theta}$ converge to θ by the shortest path as shown (7).

$$\Delta_{i+1} = \begin{cases} \left(\theta_{i+1}^* - \hat{\theta}_i\right)/n_i & if \quad \hat{\theta}_i < \theta_{i+1}^* + \pi \\ \left(\theta_{i+1}^* + \pi - \hat{\theta}_i\right)/n_i & if \quad \hat{\theta}_i \geq \theta_{i+1}^* + \pi \end{cases} \tag{7}$$

V. GRID FREQUENCY AND PHASE ANGLE ESTIMATION

The three phase angles $\hat{\theta}_R$, $\hat{\theta}_S$, $\hat{\theta}_T$ and periods $\hat{T}_R$, $\hat{T}_S$, $\hat{T}_T$ are obtained applying the technique described in III and IV to the three phase voltages V_R, V_S and V_T.

The grid period is estimated by averaging the individual phases period (note that in steady state they are equal) as shown in (8):

$$\hat{T} = (\hat{T}_R + \hat{T}_S + \hat{T}_T)/3 \tag{8}$$

The first step to estimated the grid phase angle is referencing the phases S and T to the phase R as shown in (9) where *norm1()* is a function that normalizes its angle argument to an angle between 0 and 2π.

$$\begin{aligned} \breve{\theta}_R &= \mathrm{norm1}(\hat{\theta}_R) \\ \breve{\theta}_S &= \mathrm{norm1}(\hat{\theta}_S + \tfrac{2}{3}\pi) \\ \breve{\theta}_T &= \mathrm{norm1}(\hat{\theta}_T + \tfrac{4}{3}\pi) \end{aligned} \tag{9}$$

Second, by using the phase angle circular property, the phases S and T phase angles are chosen to be located nearest the phase R phase angle as in (10), where *X* stands for S and T:

$$\bar{\theta}_X = \begin{cases} \breve{\theta}_X - 2\pi & \mathit{if}\ (\breve{\theta}_X - \breve{\theta}_R) > \pi \\ \breve{\theta}_X + 2\pi & \mathit{if}\ (\breve{\theta}_X - \breve{\theta}_R) < -\pi \\ \breve{\theta}_X & \mathit{if}\ -\pi < (\breve{\theta}_X - \breve{\theta}_R) < \pi \end{cases} \tag{10}$$

Finally, the grid phase angle estimate is calculated from (11):

$$\hat{\theta} = \mathrm{norm1}((\bar{\theta}_R + \bar{\theta}_S + \bar{\theta}_T)/3) \tag{11}$$

VI. PERFORMANCE OF SYNCHRONISM METHOD

This approach for a synchronizer operating in a hard environment is validated through analysis of simulation results carried out within Saber Designer tool and its applicability in real systems is testify by using the controller platform used by the authors in a 200kW power converter. The controller platform is based on a Texas TMS320C6713 DSP starter kit with a Signalware AED106 daughterboard having an xilinx Virtex FPGA and Analog to Digital Converters (ADC). The FPGA controls the ADCs and performs the over sampling summing. The DSP implements the remaining algorithm. The result (phase angle estimation) is outputted by means of PWM carried out in the FPGA.

The three grid voltages are synthesized using a siemens C167 microcontroller platform developed and used in previous works. In all experiments, the sampling frequency is 3.2 kHz, each sample is obtained by averaging 128 over-samplings and the filter is a 29th order Low Pass Equiripple FIR.

Figures 3 to 8 show the results of the proposed synchronizer operating in different conditions of grid voltages based on simulations.

V_R, V_S and V_T represents the grid line voltages, f the grid frequency, $\hat{f}$ the estimated grid frequency, θ the grid phase-angle, $\hat{\theta}$ the estimated grid phase-angle and $\theta - \hat{\theta}$ the estimated grid phase angle error magnified 10 times.

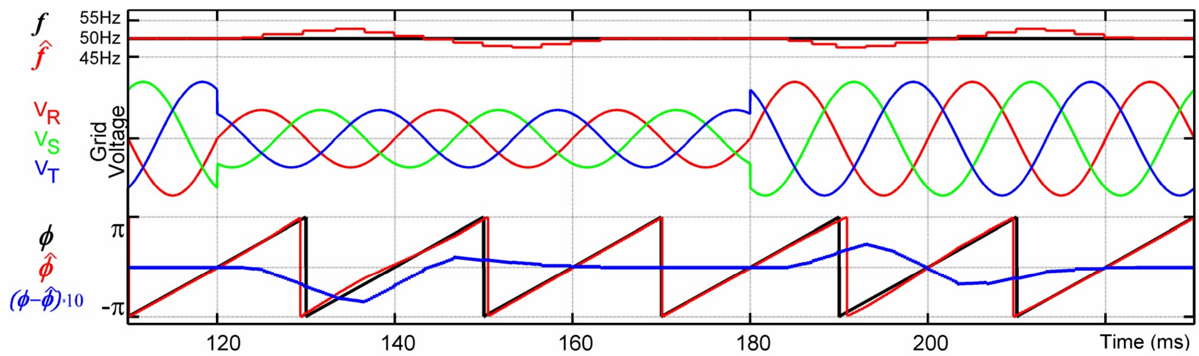

Fig. 3. Synchronizer performance in a symmetrical voltage sag (50 %).

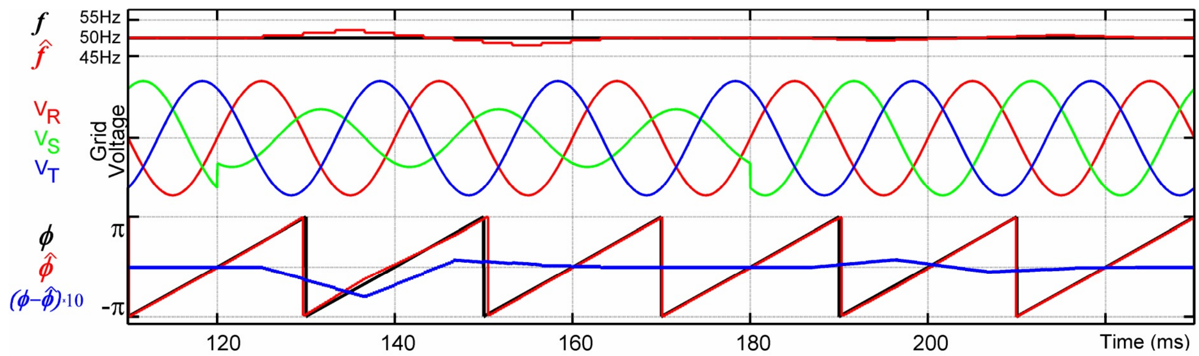

Fig. 4. Synchronizer performance in an unbalanced voltage sag (50 % phase S).

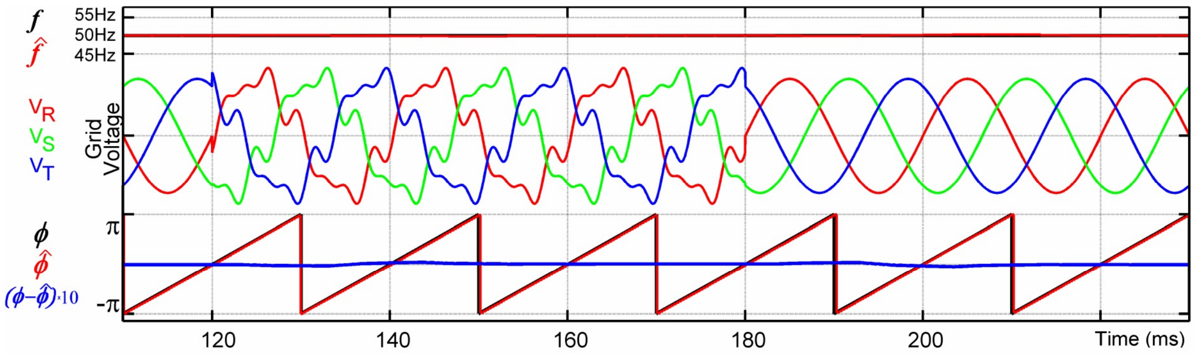

Fig. 5. Synchronizer performance when the grid gets polluted with harmonics (20% 5th, 15% 7th).

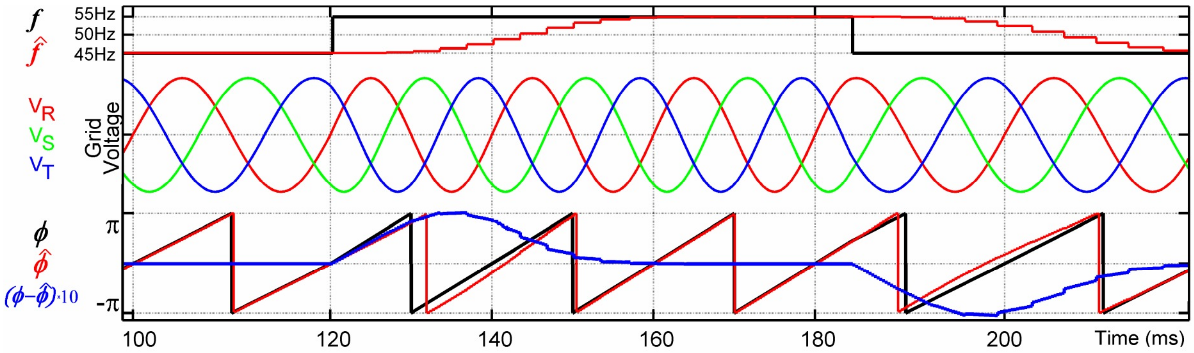

Fig. 6. Synchronizer performance when the grid frequency is subjected to a step change (45Hz, 55Hz).

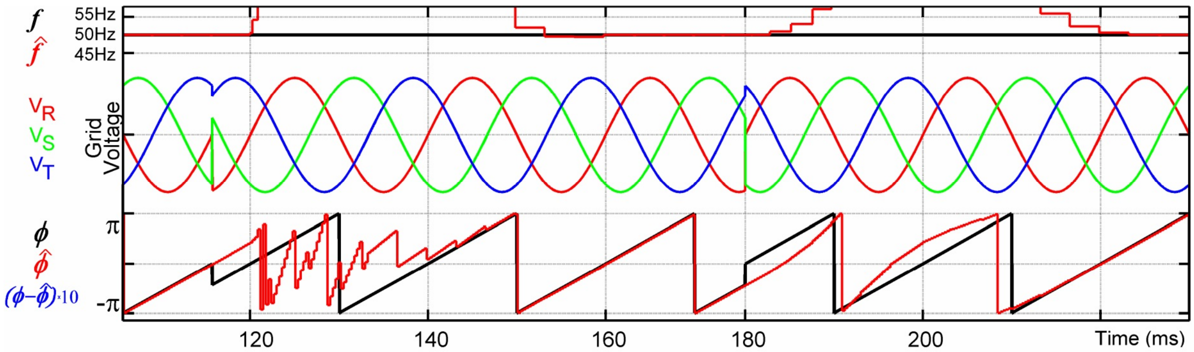

Fig. 7. Synchronizer performance when the grid is subjected phase change (+45º and -45º).

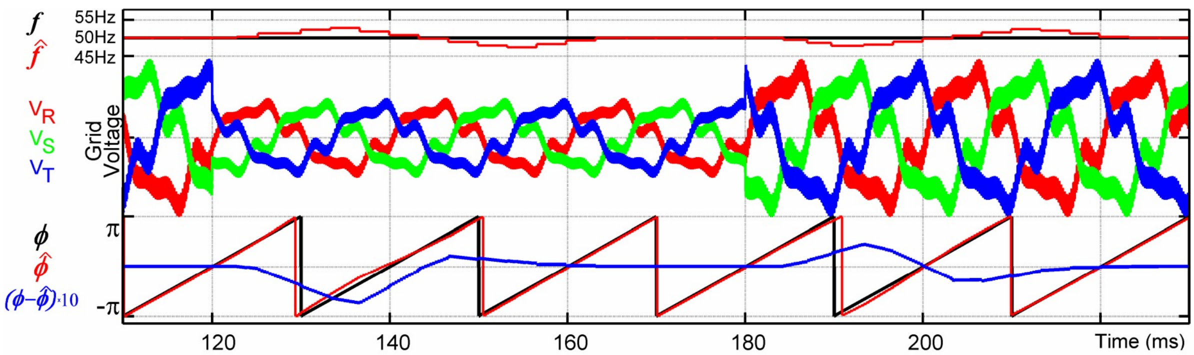

Fig. 8. Synchronizer performance in a symmetrical voltage sag (50 %), in a grid polluted with harmonics (20% 5th, 15% 7th) and high frequency noise.

Figures 9 to 13 show the results of the proposed synchronizer operating in different conditions of grid voltages implemented by the described test platform. Channel 1 represents phase R voltage, channel 2 the phase S voltage, channel 3 the synthesized (the real) phase angle and channel 4 the estimated phase angle.

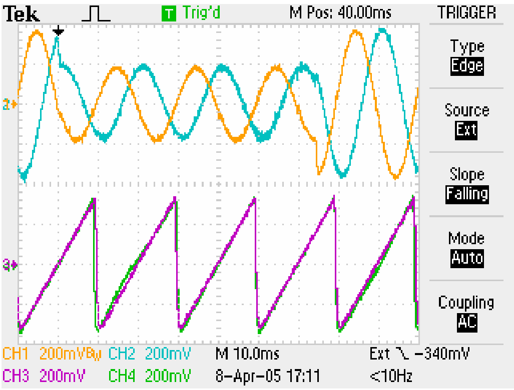

Fig. 9. Synchronizer performance in a symmetrical voltage sag (50 %)

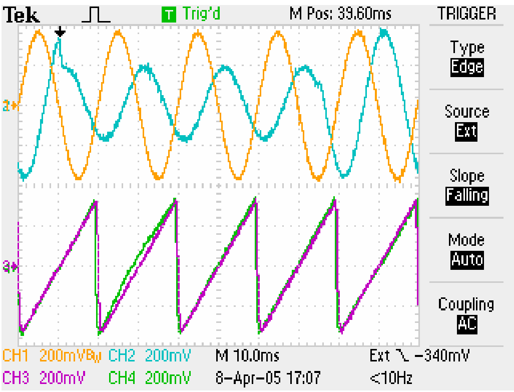

Fig. 10. performance in an unbalanced voltage sag (50 % phase S).

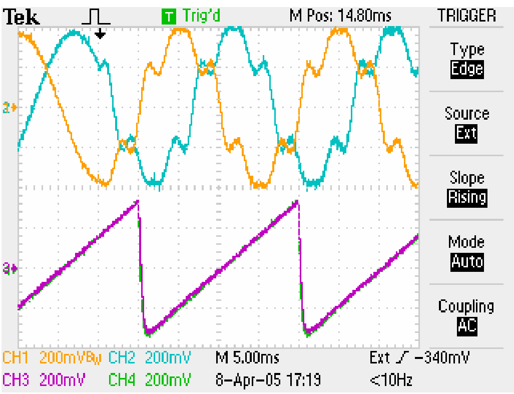

Fig. 11. Synchronizer performance when the grid gets polluted with harmonics

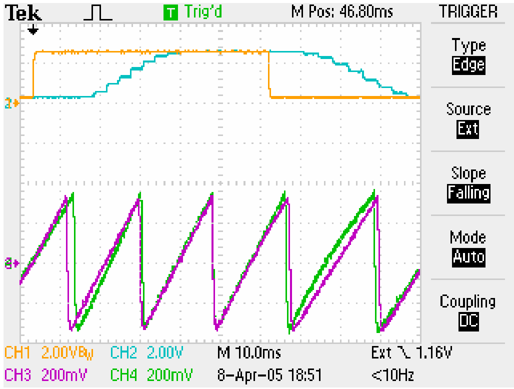

Fig. 12. Synchronizer performance when the grid frequency is subjected to a step change (45Hz, 55Hz).

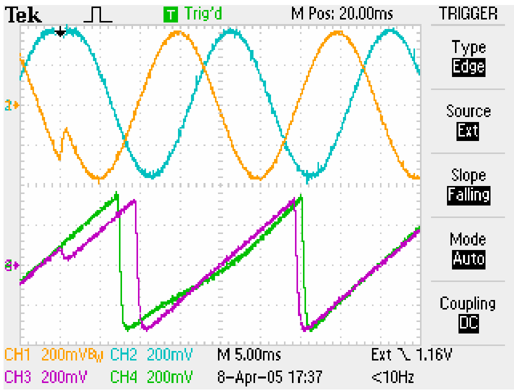

Fig. 13. Synchronizer performance when the grid is subjected phase change (-45º)

The proposed synchronism method was tested with extreme disturbances on the grid voltage. In all conditions the estimated grid phase angle converges to the real value in less than one and a half grid period, showing its robustness.

VII. CONCLUSIONS

The paper discusses the main disturbances occurring within a weak grid in what concerns phase detection in order to get an accurate synchronism between an electronic converter and the grid. It is an important issue in the domain of electrical generation as the control of power flow demands for an accurate control of phase angle between the both systems.

The authors proposed a method to handle the phase disturbances and presented a synchronizer with results carried out within Saber Designer environment that validate the adopted approach. Its applicability in real systems is testified by using a digital control platform.

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