

Zero-Crossing Detection of Distorted Line Voltages Using 1-b Measurements

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Abstract—In thyristor power converters, zero crossings of the line voltage signal are used for the synchronization of thyristor gating pulses. In weak ac systems, however, the line voltage can be distorted, and faulty zero crossings occur. In addition, in isolated power transmission networks, the line frequency can alter. For the detection of true zero crossings in such cases, we describe a neural network (NN), which utilizes the measurements of the three line voltage components in a three-phase power delivery system. The line voltages are measured with comparators, thus enabling low-cost implementation. The NN structure is extended by using a logic circuit, which produces the time elapsed from the previously detected zero-crossing instant as a feedback signal for the network. Thus, the knowledge that the true zero crossings occur at regular intervals in practical power delivery systems is utilized. The simulation results show that the proposed NN provides competitive performance.

Index Terms—Level-crossing problems, neural networks.

I. INTRODUCTION

RECTIFYING thyristor power converters are often used in industrial installations. The control of these converters is realized by terms of line synchronization, phase-angle delay, and distribution of gating pulses, as illustrated in Fig. 1. In weak ac distribution systems, the electromagnetic pollution of the power line, introduced by various power electronic systems, includes harmonic distortion, interharmonics, interference, flicker, and commutation notches. As a result, the zero crossings of the corrupted line voltage cannot be used for the synchronization as such.

A phase-locked loop (PLL) is often applied to the zero-crossing detection of line voltages [1]. Due to its adaptive nature, the PLL approach enables a wide range of operating frequencies. However, the dynamical response of a PLL is typically slow. Thus, for instance, fast periodic load changes cannot be compensated for satisfactorily. A comparative summary of different solutions to line voltage noise reduction was presented in [2]. These methods include the choice of voltage sensing location, analog and digital low-pass and bandpass filtering, predictive linearization, and open-loop voltage drop compensation. All of these approaches have one or more of the following limitations.

- Zero-crossing signal is load-current and firing-angle dependent.

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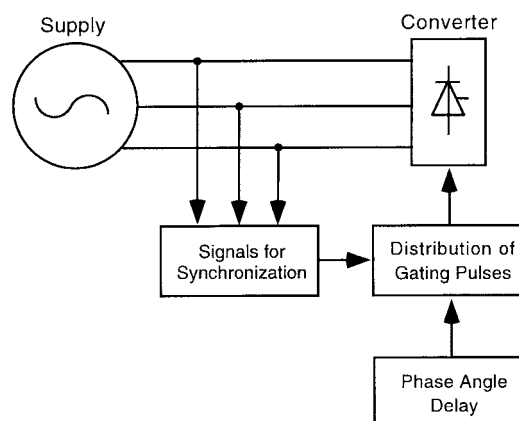


Fig. 1. Control diagram of the rectifying thyristor converter.

- Zero-crossing signal is sensitive to load transformer impedance and frequency variations.
- Detection method is only valid for a specific range of commutation overlap angles.
- Specialized instrumentation is required.

The adaptive approach proposed in [2] produces reliable zero-crossing instants. Its implementation, however, requires additional hardware, which is not preferred due to increased cost. Since the additional implementation hardware is undesirable, digital signal processing (DSP)-based methods for zero-crossing detection have been developed. Unfortunately, additional delay or lag, which is a drawback of conventional filtering methods, cannot be tolerated because the filtered signal is used for time-critical synchronization purposes. It is possible to design a digital low-pass or bandpass filter with substantial noise attenuation, without phase shifting the fundamental frequency. The problem of this approach is the restricted operating frequency range, however, because the filter is sensitive to frequency variations. Therefore, three predictive filtering systems for the zero-crossing detection task were developed in [3]–[5]. These multistage filters suppress notch-type disturbances and attenuate wide-band noise efficiently, while maintaining delay-constraint filtering properties.

Since the line voltage, corrupted by various kinds of noise, can be regarded as a nonlinear signal, it is natural to apply a nonlinear computational network [6]. The objective of this paper is to describe a neural network (NN) which detects the true zero-crossing instants of the line voltage signal. The main advantage of the proposed NN is that the line voltages are measured by simple comparators (“1-b A/D converters”), thus

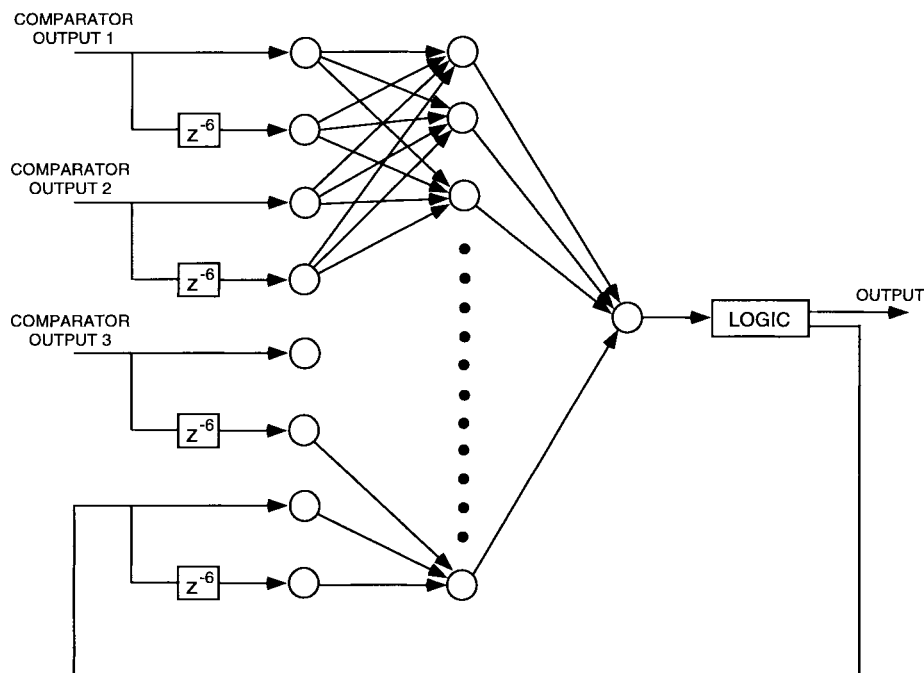


Fig. 2. Structure of the proposed NN.

enabling low-cost implementation without need for multibit A/D conversion and complex circuitry to provide galvanic isolation. Accurate operation is achieved by utilizing the redundant information obtained from all three phases for the zero-crossing detection of one line voltage component.

This paper is organized as follows. In Section II, we describe the structure of the proposed NN and discuss the training procedure. Simulation results for operating with distorted test signals are provided in Section III. Besides the proposed NN, some other methods are simulated for comparison. The simulation results are evaluated, and the advantages and limitations of the NN are discussed. Section IV concludes this paper.

II. STRUCTURE OF THE NEURAL NN

There exist two synchronization strategies. In the first approach, each line voltage component synchronizes the gating pulses of one thyristor in the upper branch and another thyristor in the lower branch of the six-pulse thyristor bridge. Another strategy is to synchronize all gating pulses with one reference zero crossing per line period followed by six equally spaced gating pulses, i.e., the equidistant synchronization method. Here, we produce one reference zero crossing per half of the line period, followed by three equally spaced pulses.

Commutation notches and other disturbances can cause incorrect sign changes of the line voltage. Consequently, the comparator outputs cannot be used directly to synchronize the thyristor gating pulses. Therefore, the NN, which is illustrated in Fig. 2, is trained to distinguish between the true and false zero crossings. In the following, the network structure is described in detail.

The output of the NN is calculated at the rate of 10 kHz, which provides sufficient time resolution for the firing

TABLE I
COMPUTATIONAL COMPLEXITY OF THE PROPOSED NN

	hidden layer	output layer	total
multiplications	20	10	30
additions	80	10	90
$\pm 1 \times$	60	-	60
hyperbolic tangent functions	10	-	10
logistic sigmoid functions	-	1	1

angle control; in 50-Hz power delivery systems, the difference between two consecutive samples of the fundamental sinusoid becomes $1.8^\circ (= (50 \text{ Hz}/10 \text{ kHz}) \cdot 360)$. The comparator outputs of the three phases are inputs for the NN. Two samples of each line voltage are used: one of the two samples is the latest sample, and the other is delayed by six samples because $600 \mu\text{s} [= 6 \cdot (1/10 \text{ kHz})]$ has been reported to be the worst case duration of commutation disturbances in thyristor power converters [7]. The aim is to provide at least one uncorrupted sample of each comparator output to the network. However, IEEE recommended practices and requirements [8] allow even more severe notching. Thus, the selected delay line depends on the length of the commutation notches encountered in the particular system.

Besides the comparator outputs, the time elapsed from the latest detected zero crossing is used as a feedback signal. Although frequency variations can occur in power transmission

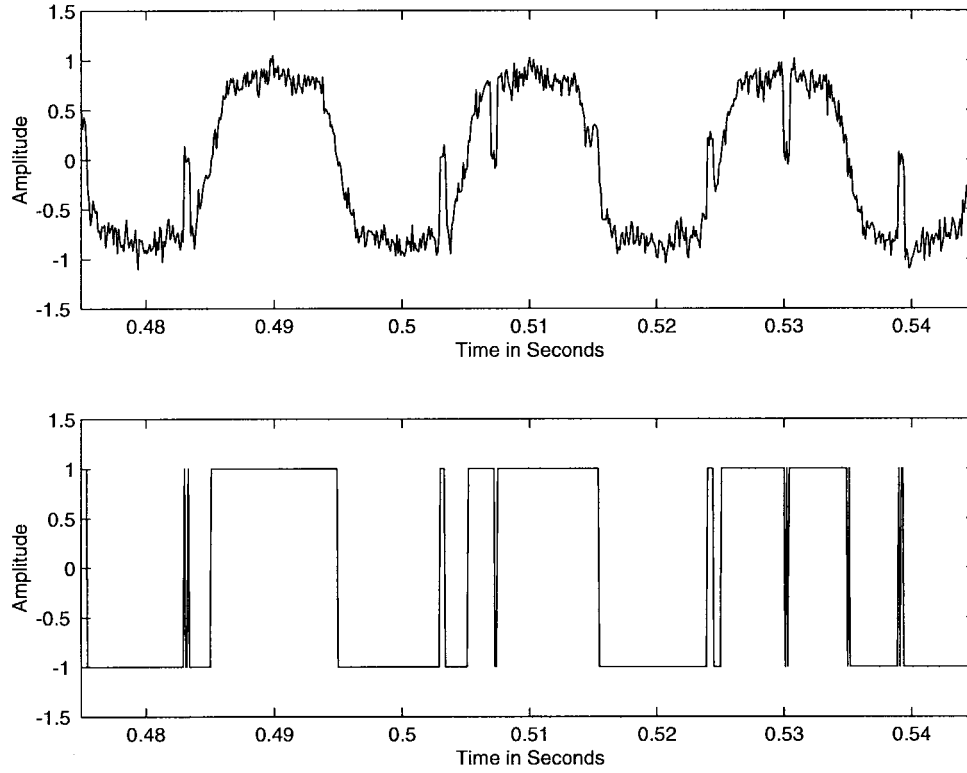


Fig. 3. A sample of the simulated line voltage signal and the corresponding comparator output.

networks, it is reasonable to assume certain specifications for the frequency range, e.g., $\pm 2\%$ of the nominal line frequency. In an ideal 50-Hz power delivery system, a zero crossing of each line voltage would be available every 10 ms. By considering the frequency variation of $\pm 2\%$, the zero crossings occur every $9.8 \cdots 10.2$ ms. Note that the time signal is also fed into the network through a delay line of six samples. In simulation experiments, this improved the performance of the NN considerably.

The box labeled *LOGIC* in Fig. 2 is used to determine whether the NN has detected a zero crossing or not. The output of the NN (before the logic) has a value which is between zero and one due to the use of sigmoidal activation function [9] in the output neuron. This value is compared with a threshold value λ . If the output of the NN is greater than λ , the zero crossing can be confirmed. The choice of λ is essential for the performance of the NN, because the logic is inside the network structure. If λ is set too low, the logic can detect false zero crossings. If λ is too great, some true zero crossings cannot be detected.

The time window in the logic is used to ensure that if a zero crossing has not been detected during a predefined time t_2 after the latest detection instant, a zero-crossing pulse is produced by the logic. Obviously, t_2 is a little longer than one-half of the signal period of the fundamental sinusoid, e.g., $t_2 = 10.5$ ms. If the output of the NN has a value greater than λ before another predefined time t_1 after the latest detection instant, the logic ignores it. Clearly, t_1 should be a little smaller than the nominal half-period, e.g., $t_1 = 9.5$ ms. In this way, we can take advantage of the fact that the time period between two successive true zero crossings is approximately constant.

The NN structure that was experimentally found to be appropriate for this application is a feedforward multilayer perceptron (MLP) network with one hidden layer of ten neurons. The computations required at each sampling period are given in Table I. Since each comparator output has either value -1 or 1 , the multiplications related to the corresponding weights in the NN only require sign changes, which is beneficial from the implementation point of view. This applies to 60 multiplications in the hidden layer.

For the training of the NN, we generated line voltage signals with frequencies ranging from 49 to 51 Hz, with different levels of harmonic components and noise, and with commutation notches with different depths and widths. As a training algorithm, the backpropagation algorithm was applied [9]. In the training, the most important requirement was that the outputs for the true zero crossings should have as equal values as possible; if the network response for some zero crossings is considerably greater than for the others, it is difficult to find a suitable threshold value λ . During the training, we did not use the feedback loop to produce the time elapsed from the previously detected zero crossing, but the time elapsed from the previous true zero crossing was used instead, i.e., during the training, the logic was not considered.

III. SIMULATIONS

For evaluation of the NN, we constructed a test signal, as depicted in Fig. 3. The frequency of the primary sinusoid varies between 49–51 Hz at the sweeping rate of 1 Hz in 1 s. The test signal contains third and fifth harmonics, which are the main harmonic components encountered in practical power transmission networks. The amplitude of the third harmonic

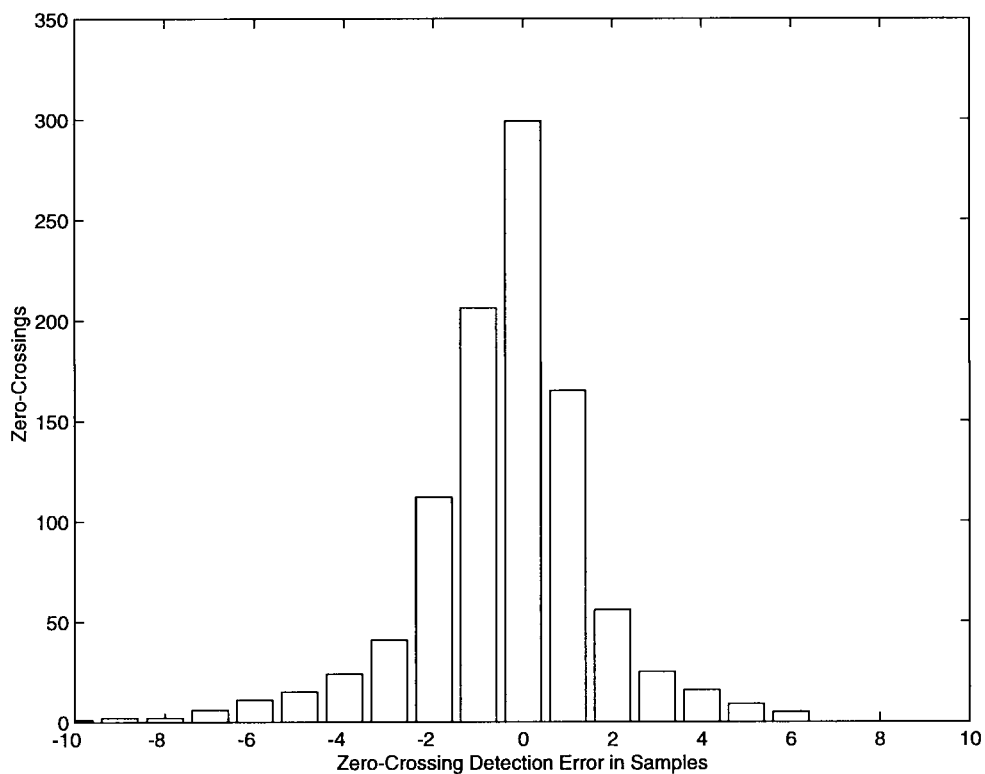


Fig. 4. Misplacements of detected zero crossings when the NN was applied to the zero-crossing detection of the test signal of Fig. 3 (1000 samples).

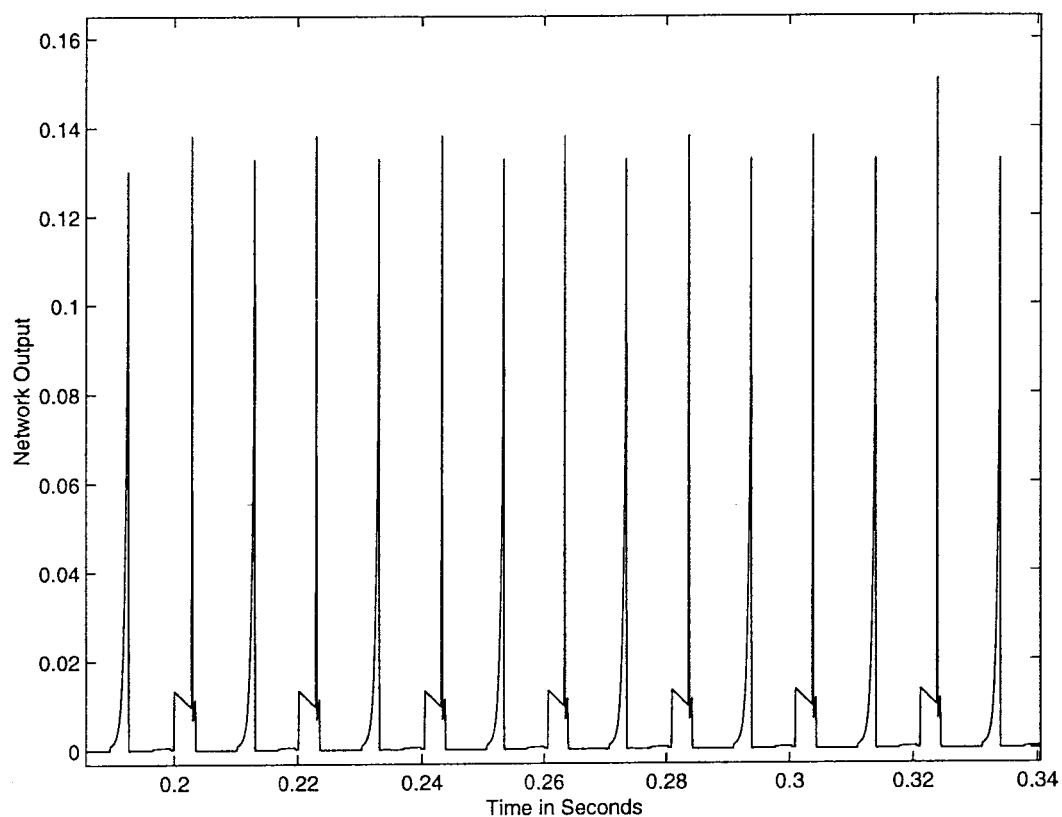


Fig. 5. Output waveform of the NN of Fig. 2 before the logic circuit.

TABLE II

SIMULATION RESULTS FOR APPLYING THE PROPOSED METHODS TO ZERO-CROSSING DETECTION OF SEVERELY DISTORTED TEST SIGNAL WITH FREQUENCY VARIATION

zero-crossing detection method	mean error in samples	standard deviation of the error in samples	maximum error in samples
proposed Neural Network (NN)	-0.39	2.0	10
digital bandpass filter	1.2	2.0	6
predictive FIR filter	-1.1	2.3	9
look-up table-based predictive FIR filter	-0.15	1.2	4
adaptive predictive FIR filter	0.13	1.8	5

TABLE III

SIMULATION RESULTS FOR APPLYING THE PROPOSED METHODS TO ZERO-CROSSING DETECTION OF A SINUSOIDAL TEST SIGNAL WITH FREQUENCY VARIATION

zero-crossing detection method	Mean error in samples	standard deviation of the error in samples	maximum error in samples
proposed Neural Network (NN)	0	0	0
digital bandpass filter	0.048	1.9	4
predictive FIR filter	0.029	0.62	1
look-up table-based predictive FIR filter	-0.25	0.75	3
adaptive predictive FIR filter	-0.013	1.4	3

and the fifth harmonic are 0.2 and 0.1, respectively, when the amplitude of the primary sine wave is normalized to unity. The test signal contains uniformly distributed white noise, which models the high-frequency noise brought by the edges of the waveforms of switching power converters. Finally, the test waveform contains deep commutation notches. The test signal, as well as the simulations, are realized in a Matlab environment [10].

The misplacements of the detected zero-crossings are shown in Fig. 4. It can be observed that the NN was able to detect the true zero crossings accurately, although the noise content of the test signal was severe. For comparison with other DSP-based zero-crossing detection methods, we compute the mean error \bar{x} and the standard deviation of the error σ_x . For the results of Fig. 4, the mean error is $\bar{x} = -0.39$ in samples, and the standard deviation of the error is $\sigma_x = 2.0$ in samples. In the logic circuit, we used the following constants: $t_1 = 9.5$ ms, $t_2 = 10.4$ ms, and $\lambda = 0.12$. Negative mean error corresponds to, on average, premature zero-crossing detection. The output waveform of the NN before the logic is illustrated in Fig. 5. It can be observed that the selected threshold value $\lambda = 0.12$ is suitable for tracking the zero-crossing instants.

When the NN was applied to detect the zero crossings of a pure sinusoid with altering frequency, all the zero-crossing instants were detected correctly. This is an important result, because an NN with a hidden layer of ten neurons should

definitely provide the same performance as a simple logic would provide.

To evaluate the above results, we constructed four DSP-based zero-crossing detection methods introduced in the technical literature. These methods employ a conventional digital bandpass filter and three multistage filtering systems based on predictive finite-impulse response (FIR) filter for line frequency signals [3], lookup-table-based predictive FIR filter [4], and adaptive predictive FIR filter [5]. As a configuration for the adaptive filtering system of [5], we used the version with a fixed infinite impulse-response (IIR) prefilter, and an adaptive FIR filter of length 22. The multistage filtering systems of [3] and [4] were used exactly as suggested by their authors. The mean errors and the standard deviations of the errors produced by these filters, or filtering systems, for the test signals are given in Tables II and III. The maximum error in each case is included.

The proposed NN was capable of detecting the true zero-crossing instants with approximately similar accuracy as the other evaluated methods. However, the main advantage of our NN is that only *1-b comparators are required* in the voltage measurement. This is a considerable benefit in terms of the implementation cost, because multibit A/D conversion with galvanic isolation is not needed here.

The main disadvantage of the NN is that, if it fails to detect a couple of consecutive true zero crossings before t_2 and the

zero crossings are generated by the logic at t_2 , the true zero crossings begin to occur before t_1 . As a consequence, the true zero crossings are not accepted, and the zero crossings are generated by the logic at t_2 as long as the true zero crossings again start to occur within the time-window. This phenomenon hinders the starting of the program as well, because the time window can be displaced and, as a consequence, the convergence of the NN lasts several signal periods before the true zero crossings can be detected. For instance, if $t_2 = 10.4$ ms, the time window is shifted 0.4 ms every half period until the true zero crossings start to occur within the time window. Thus, it can take 25 half periods (10 ms/0.4 ms), or 12–13 signal periods for the NN to converge.

IV. CONCLUSIONS

An NN for zero-crossing detection of line voltage signals was constructed. The proposed NN is capable of detecting the true zero-crossing instants, although the noise content of the line voltage is severe, and the line frequency varies over time. As an input of the NN, only comparator outputs are used, thus enabling low-cost implementation with "1-b A/D converters." The reliable performance of the NN was achieved by using the time elapsed from the previous detected zero crossing as a feedback signal. Therefore, we can utilize the knowledge that the true zero crossings occur at approximately regular intervals in practical power delivery systems.

The DSP implementation of the proposed NN is computationally moderate, and the NN can be easily programmed as a part of the control software. Comprehensive simulations were performed to confirm the applicability of the NN to the zero-crossing detection task. Infinite wordlength was assumed in the paper. In practice, the computations are discretized. The sensitivity to discretization is beyond the scope of this paper,

however. Further, we selected the values for t_1 , t_2 , and λ experimentally. However, a genetic algorithm could be applied to determine optimal values for them.

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Sami Väliiviita (S'97–M'99), for a photograph and biography, see this issue, p. 888.