A Novel Principle for Measuring Overfrequency and Frequency Rate of Change

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Abstract— **This paper presents a novel principle for frequency and frequency rate of change measurement. As opposed to the vast majority of other techniques proposed in the literature that use digital techniques and micro processor-based signal processing, our principle relies on a direct measurement of a positive-sequence AC voltage. Due to improved zero-crossing detection the proposed technique is highly immune to noise, DC offset, and higher-order harmonics present in the measured signal. Other advantages of the proposed principle are high speed, higher reliability due to less hardware needed, and much lower power-consumption, so no auxiliary supply is needed.**

Index Terms— **Frequency estimation, underfrequency relay, frequency gradient, underfrequency load shedding.**

I. INTRODUCTION

In recent years, power systems around the world have undergone dramatic changes due to deregulation and the introduction of electricity markets. This has had an enormous impact on the philosophy of the planning and the operation of power systems. In the past, the vertically integrated utilities were responsible for the whole electricity-supply process, from generation to distribution. The current organizational scheme gives the Independent System Operators (ISOs) the responsibility for the secure operation of the power system, while the producers and the consumers are free to choose their market strategy. One of today's most important issues in the operation of power systems is the increase in the amount of power in individual exchanges due to new transactions. This results in congestions of the transmission grids, with the consequence being reduced stability margins. It is widely felt that the uncertainties of power system restructuring efforts as well as utility economics have led many companies to operate their systems close to the maximum loadability limits, thereby unwittingly pushing their systems toward the brink of collapse. The main motivation for the study presented in this paper was the numerous blackouts that occurred in 2003. After the Italian blackout [1], [2], it became clear that some automatic procedures, with underfrequency load-shedding being one of the most important ones [3], need to be thoroughly revised. The analysis that followed the Italian blackout showed that the root-cause was frequency instability. The performance of the underfrequency load-shedding scheme was not successful in stopping the cascading tripping, which led to a total system blackout. Bearing all this in mind, the need for simple, yet effective, underfrequency protection schemes is obvious.

In the available literature, numerous methods for frequency measurement have been proposed. Historically, the estimation of power system frequency was based on the direct measurement of an AC signal (usually voltage). The main drawback of this approach was the zero-crossing detection. Namely, in the presence of noise in the signal, there exists more than one zero-crossing per cycle.

With the increased use of microprocessors for power system protection and monitoring, signal-processing based methods have gained increased interest. The main problem of these methods are complex computations, which can introduce a significant delay in frequency estimation. On the other hand, the hardware required is more complex, which reduces reliability and increases power consumption; the need for auxiliary supply, in turn, reduces reliability even further. One of the most widely used methods for frequency estimation is zero-crossing technique [4], [5]. When using zero crossing methods, one determines the time between zero crossings of the signal to determine the frequency. This can be carried out with a sliding window of samples and curve fitting using a least squares technique [6]. Such methods are not capable of fast frequency estimation from polluted signals [7] and their performances are sensitive to switching-type transients [6]. Another approach is to use discrete Fourier transform (DFT) [6], [8], [9]. These methods suffer from sensitivity to distortions and require a long measurement time window for small frequency deviations. Various authors have approached the problem of determining the frequency deviation using estimation techniques, such as non-linear least squares estimation, Kalman filters [10], and Newton-type algorithm [11]. The concept of three-phase phase-locked loop (PLL) is also widely used for phase and frequency estimation [12], [13]. A three-phase PLL provides a fast and robust frequency estimation for balanced three-phase systems. However, its performance is prone to error due to unbalanced conditions. An improved PLL approach is proposed in [4].

Rate of change of frequency also has application in power systems [9], [14]. Numeric differentiation of the frequency estimate, used in conventional methods, results in noisy estimate of the rate of change of frequency and requires further filtering stages.

The paper is organized as follows: A novel frequency measuring principle is explained in Section II. Section III evaluates the performance of the proposed principle under various conditions. In Section IV, the conclusions are given.

II. A NOVEL FREQUENCY MEASURING PRINCIPLE

The frequency measurement comprises the following stages: the filtering stage, measurement of signal's period and the measurement of underfrequency and frequency gradient. The first two stages are common for both measurements; for underfrequency measurements and for frequency gradient measurement.

A. Filtering and the measurement of the signal's input period

Figure 1 shows the input circuit, which is made up of 4 crucial parts in cascade to obtain an optimal noise immunity. The input circuit should fulfill the following requirements:

- Input transformer is a mini-c-type, offering minimal possible parasitic coupling capacitance between the primary and secondary coils. This minimizes the crosstalk of high frequency noise. The analogue signal output voltage is much higher compared to the supply voltage.
- Fast limiter provides very fast slew rate in the threshold crossing area. This is an effective way to avoid noise that can disturb the period measurement. The limiter response time is in the range of 10 ns.
- The low-pass filter is usually dual; however, for better performance, it could be active, resonant. The filter's group delay is important only in the case of three phase frequency-voltage relays. These relays are using a positive sequence filter output as a measuring signal.
- Signal's period is measured using a high-threshold analogue comparator called a Schmitt trigger, using a high threshold gap to ignore the HF noise, if it is not sufficiently filtered in the previous unit.

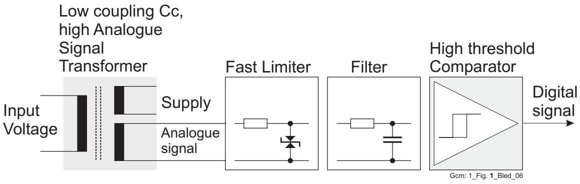

Fig. 1. Input filtering circuit.

Noise reduction using Schmitt trigger is shown in Figs. 2, 3, and 5. One should bear in mind that the input voltage must rise above the top of the band +H, and then below the bottom of the band -H, for the output to switch on and then back off. Noise of a sufficiently high amplitude can introduce an error in frequency measurement, as shown in Fig. 3. However, since the frequency cannot change instantaneously due to inertia present in the system, such erroneous information can be easily filtered out, as it presents a large deviation from the expected value. There are two ways to reduce the error as a result of noise. The first one is illustrated in Fig. 4, where a low-pass integrator is used. The second option is to take advantage of higher slew rate of a signal with higher amplitude, as shown in Figs. 2 and 5. Two signals are shown: signal “Analogue in-a” presents a signal of a relatively low amplitude. With no noise present, the period is measured correctly. The other one, “Analogue in-b”, presents a signal of a relatively high amplitude. Although shifted, the period is again measured correctly. Observe a higher slew rate of signal “Analogue in-b”. As a result, a high-voltage input signal is used for further processing, which introduces lower error due to noise in the input signal, as shown in Fig. 5. In practice, the amplitude is more than 50V. The fast recovery limitation is clamping a bit under the analogue saturation zone.

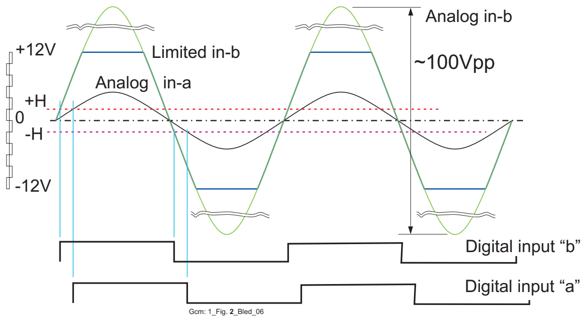

Fig. 2. Period measurement.

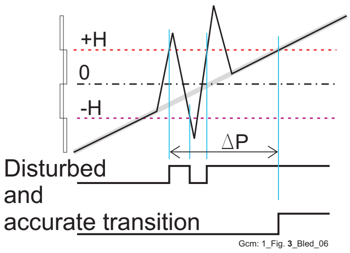

Fig. 3. Noise reduction using Schmitt trigger.

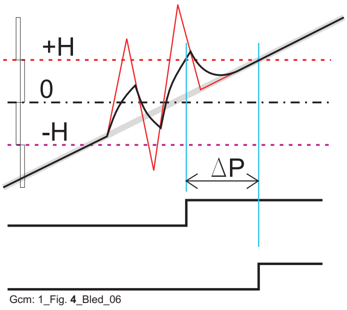

Fig. 4. Noise reduction using a low-pass filter.

B. Underfrequency measurement

After the input signal is properly filtered and the information about the period is obtained, the underfrequency and the frequency gradient is estimated. The

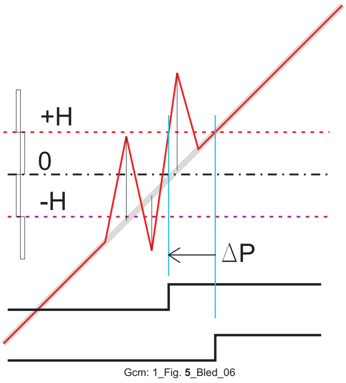

Fig. 5. Noise reduction using high-voltage input signal.

underfrequency measurement is a crucial part of any underfrequency load shedding scheme. The frequency gradient, although not commonly used nowadays, is becoming increasingly popular. An underfrequency relay using the proposed measuring principle can be realized with an arbitrary number of steps, although up to four steps are commonly used.

Figure 6 shows the measuring circuit schematically. Observe that the period measuring counter Px is common for underfrequency measurement and for frequency gradient measurement, so both relays can be realized within a single circuit board unit.

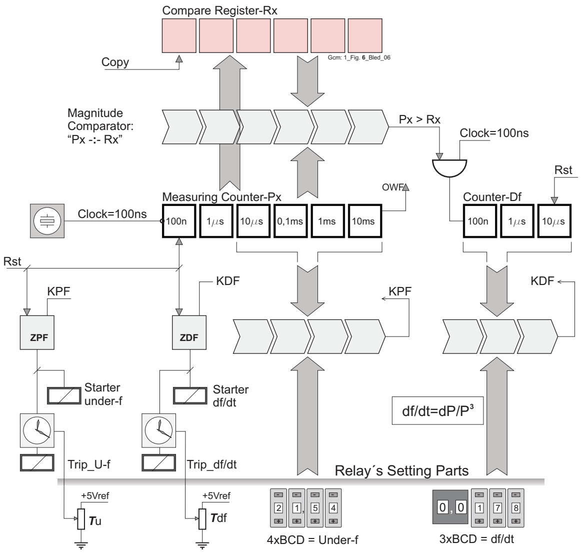

Fig. 6. Measuring principle.

Underfrequency relay operation is illustrated in Fig. 7. The signal flow diagram shows the input signal in relation to the Rst pulses, created by the falling edge of the input signal. Advancing of the state of the measuring counter Px is shown with a linear rising line, forming a sawtooth function. A continuous linear rising function is reset to zero with the appearance of the Rst pulse. The reset pulse delay and duration sequence has to be shorter than the clock period. The height of the saw reflects the information of the measured period. The straight line above the sawtooth function presents the limit value for the under frequency relay, set by the thumb wheel switch array, denoted “4xBCD= Under-f” in Fig. 7.

The width of the pulse that appears at the output of the underfrequency magnitude comparator KPF is proportional to the excess of the measured period in relation to the underfrequency period reference “Under-f”, set by the BCD array. If the period was constant in the under frequency state, the pulses at the output of the underfrequency magnitude comparator KPF would form a sequence of pulses. In Fig. 7, there is a sequence of 3 such pulses. These pulses are integrated in the ZPF integrator, the output of which triggers the underfrequency starter and initiates the Tu countdown timer. The ZPF integrator, as well as the ZDF integrator mentioned later, are of a special quantum type, which means that they can change the sequence of pulses, regardless of the pulse duration, to a perfect continuous signal with the integer value of processed input periods.

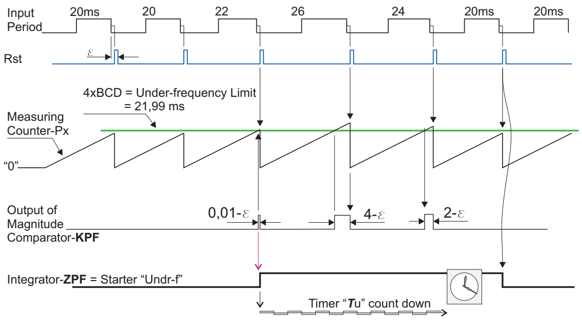

Fig. 7. Underfrequency measurement.

C. *Frequency gradient measurement*

The frequency gradient relay operation is explained in Fig. 8. As mentioned earlier, the period measuring counter Px is the same as for the underfrequency measurement.

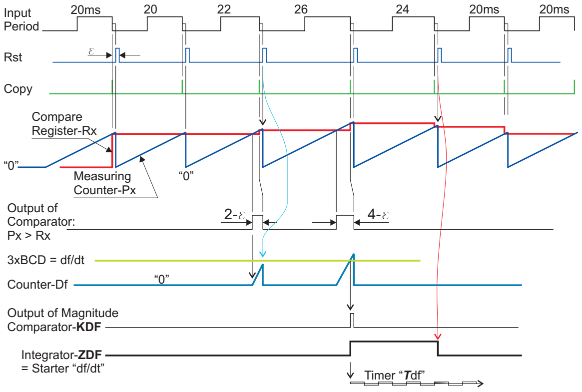

Fig. 8. Frequency rate of change measurement.

The frequency gradient measurement is based on the use of the compare register Rx and the exceed counter Df. The signal flow diagram in Fig. 8 relates to the input signal in relation to the Rst and Copy pulses. Both pulses are created by the falling edge of the input signal. The Rst and the Copy pulse are supposed not to overlap. The duration ϵ of the Rst-Copy sequence has to be negligible otherwise the accuracy suffers.

The reset pulse Rst forces all counters to state “0” and starts counting-up from zero again. The compare register Rx exchanges the previous period value with a new one at the moment of each Copy pulse. During the count-up sequence of the period measuring counter Px, the magnitude comparator Px>Rx changes the state, if the digital input Rx is greater than the digital input Px. The output of the comparator Px>Rx is in the state logical “1” only when the present period is greater than the previous one, stored in the compare register Rx; in such case, the counter DF starts counting up.

Observe in Fig. 8 the “gaped” sawtooth function of the Df counter, where the height of the tooth corresponds to the difference between the two consecutive periods, and the second period is greater than the first one. The flat line above the Df counter function symbolizes the limit value of the gradient setting set by “3xBCD = df/dt” switch array. The width of the pulse that appears at the output of the gradient magnitude comparator KDF is proportional to the measured excess of the “Gradient-df/dt reference, set by “3xBCD = df/dt” switch array. These KDF pulses are then integrated in the ZDF integrator, the output of which triggers the df/dt starter and initiates the Tdf timer. Both time delay units have the delay, determined by the reference voltage potential Tdf and Tu, set by potentiometer slider’s angle. All BCD switches and both potentiometers are connected by flat cables, so they can be easily replaced.

The presented df/dt relay uses two magnitude comparators; the first one compares over 6 decades, while the second one compares just the increase of the measured period dP by observing 3 decades of the Df counter. If one adds additional 4 decades for the comparison of the output of the period measuring counter Px, the gradient relay can be, seemingly free, upgraded with an underfrequency function.

D. *Sensitivity of the frequency gradient relay*

Operating range of a frequency relay is defined by an interval $[P_{\max}, P_{\min}]$, which translates into $[f_{\min}, f_{\max}]$. For our relay, these values are [29.99 ms, 20.00 ms], and [33.34 Hz, 50.00 Hz]. The lowest permissible frequency is around 44 Hz for hydro turbines, and around 47.5 Hz for steam turbines (in a 50 Hz system). So, for practical load shedding applications, the relay’s operating range is more than sufficient.

If P_1 and P_2 are two subsequent periods differing by only one less significant bit, the sensitivity of the frequency gradient relay can be estimated using the following expression.

$$\Delta f = f_1 - f_2 = 1/P_1 - 1/P_2 \qquad (1)$$

Since the arithmetic average of P_1 and P_2 equals P, and because P_1 and P_2 are very close values, one can assume that $1/P_1 \approx 1/P_2 \approx 1/P = \Delta T$, so one can write

$$\frac{\Delta f}{\Delta T} = \frac{1/P_1 - 1/P_2}{P} \quad \approx \Delta P/P^3 \qquad (2)$$

Since the clock pulse is 100 ns, the relay can only detect the difference between two consecutive periods if it exceeds this value. Frequency gradient setting range, limited by min df/dt and max df/dt, and minimal frequency that can be detected depend on the frequency as shown in Table I.

TABLE I

FREQUENCY GRADIENT SETTING RANGE AS A FUNCTION OF THE INPUT SIGNAL’S PERIOD

P [ms]	f [Hz]	min df [mHz]	min df/dt [mHz/s]	max df/dt [mHz/s]
20.00	50.000	0.250	0.0125	12.500
21.00	47.619	0.227	0.0108	10.798
22.00	45.455	0.207	0.0094	9.391
23.00	43.478	0.189	0.0082	8.219
...	...	...	...	...
29.99	33.344	0.111	0.0037	3.700

III. PERFORMANCE EVALUATION

The measurement accuracy depends on how “polluted” the measured signal is; in other words, this means how much random noise, DC offset, and higher-order harmonics exist in the signal. Another issue that needs to be proporly addressed is how robust is the measurement with respect to amplitude and phase jumps of the input signal.

Note that the signals used in Figs. 9-13 are exaggerated for illustrative purposes and do not properly resemble the ones observed in reality. What was also ignored is the use of high-voltage signals (100 V peak-to-peak), which reduces the error considerably.

A. *Random Noise*

Figure 9 shows a signal polluted with zero-mean Gaussian noise with the standard deviation of 1 V. Since the input voltage must rise above the top of the band, and then below the bottom of the band, for the output to switch on and then back off, white noise of a relatively low amplitude does not produce oscillations in period measurement, as is usually the case when conventional zero-crossing detection is used. However, there is an error in the period measurement, which can be effectively reduced using the output signal of a relatively high amplitude, as explained in Section II-A, which also applies to other cases described below.

Again, like in the rest of the cases presented below, note that the values shown in Fig. 9 are exaggerated. In real operation, they are much lower due to many features of the measuring principle not taken into account here for illustrative purposes.

B. *DC Offset*

A DC component can exist in power system voltages and currents during transients. It is therefore desirable that these components are filtered out. Figure 10 shows a hypothetical case where an exponential DC component is added to the input signal at 20 ms. Such DC component can appear after a short circuit. Observe how an exponentially diminishing DC component affects the measurement. In practice, the DC component is, to a large extent, filtered-out by the measuring transformer.

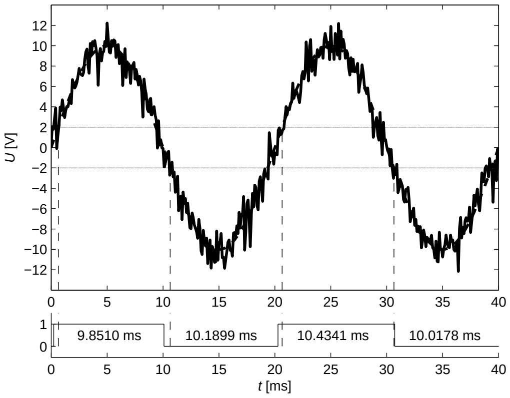

Fig. 9. White noise.

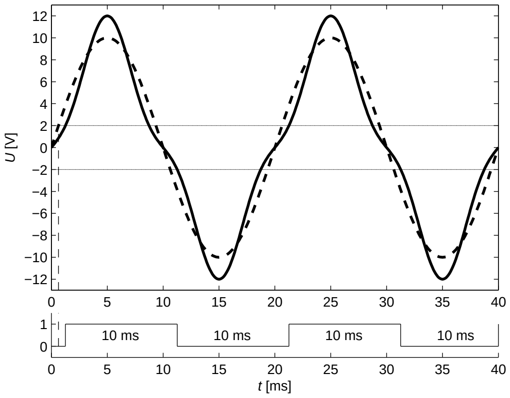

Fig. 11. Higher-order harmonics.

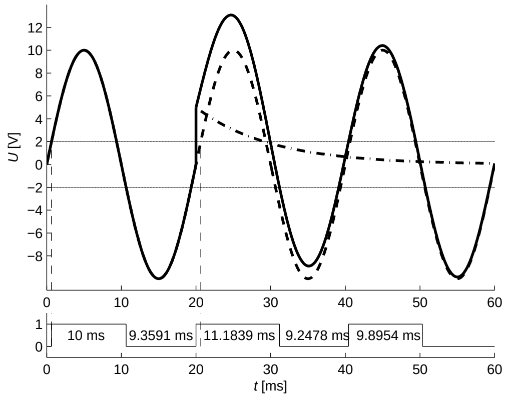

Fig. 10. DC offset.

C. Higher-order Harmonics

Due to the increased penetration of distributed generation that uses power electronics, the level of higher-order harmonics in power system is increasing. Harmonics introduce an error in the frequency measurement only when the harmonic content in the input signal changes with time. The error is due to the shift in the measurement when the change takes place, as observed in Fig. 11. Note that, as a result of a step change in harmonic content, only one period is not measured correctly.

D. Amplitude and Phase Jumps

Step changes in the amplitude and/or phase of the input signal can occur in power systems due to switchings or faults. The amplitude can also change when one or two phases of the input signal diminish to zero, which results in a lower amplitude of the input signal. A relay should therefore be immune to such changes, so that the measurement accuracy does not suffer too much.

In order to evaluate the performance of the relay with respect to amplitude jumps, a hypothetical signal, where the amplitude increases by 20% from one period to the next, is shown in Fig. 12. Observe that there is an error only in the half-phase when the change takes place, so only one period is not measured correctly. If this error is signifficant, the relay can ignore the measurement, which prolongs the evaluation.

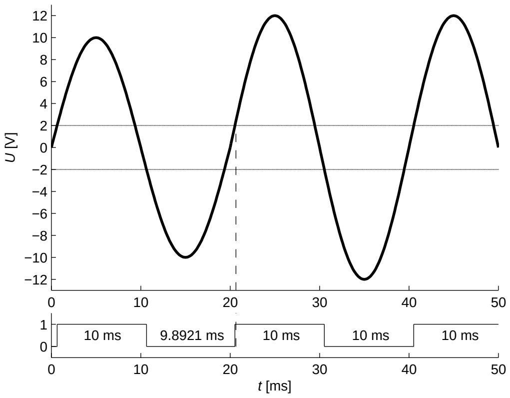

Fig. 12. Amplitude jump.

Similar phenomenon can be observed in Fig. 12, where the phase of the input signal is increased by 30 degrees. The error is much bigger then in the previous case. Again, in order to eliminate the error as the result of the phase jump, the relay has to ignore the erroneous measurement at the cost of a longer evaluation time.

IV. CONCLUSIONS

In the paper, a novel design of a frequency and frequency gradient relay is presented. The main features of the relay are: direct measurement without using any advanced microprocessor-based signal processing, low power consumption and high immunity to noise, harmonics, and DC offset in the input signal. It is shown that the measurement accuracy suffers only in the period when the input signal changes. If such changes are significant, the erroneous measurements can be ignored at the cost of slightly longer evaluation period.

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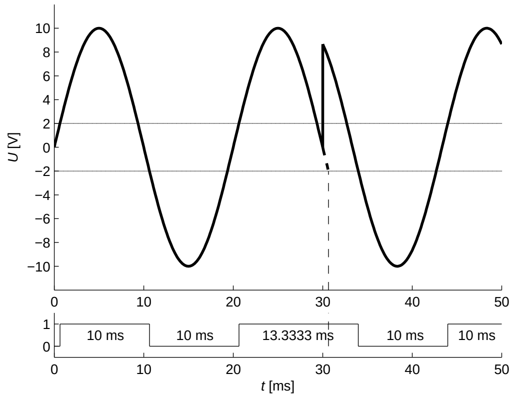

Fig. 13. Phase jump.

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