Real Time Hardware-In-The-Loop Comparison of Frequency Estimation Techniques in Application to ROCOF Based Islanding Detection

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***Abstract*—Rate of change of frequency (ROCOF) is one of the most common islanding detection techniques because of its simplicity and economical benefits. However, it does need thorough considerations to avoid mis-operations of ROCOF relays during islanding. These relays operates based on frequency estimation, which is performed either from the phase voltages or by obtaining the speed measurement from generator. With the penetration of distributed generation (DG), there is high probability for unavailability of frequency measurement from a synchronous generator. This calls for frequency estimation based on network voltages and this has a significant influence on ROCOF operation performance. This paper discusses the most commonly used frequency estimation methods and summarizes the usability of these methods through real-time hardware-in-the-loop (RT-HIL) simulations for ROCOF relay.**

***Keywords*—ROCOF, islanding, frequency estimation, real time hardware-in-the-loop.**

I. INTRODUCTION

Increasing demand for electric power combined with governmental pressures on reduction of greenhouse gases emission favors renewable energy based power generation. Distributed generation (DG) can be a huge step forward in terms of future, more reliable power systems, as soon as the challenges related to their introduction are addressed and solved. With the increased penetration of DGs due to their smaller power generation capability, compared to traditional power plants, it is important for modern grids to adapt to the changes and challenges introduced by DGs. These challenges include modification of protection schemes to identify bi-directional power flow, variable short circuit level, sympathetic tripping, effect of measurements estimation and other vulnerable mis-operations.

One of the most important problem related to integration of DG's into distribution networks is a phenomenon known as islanding. It is a situation where DG's are disconnected from the main grid and continues to energize part of the local grid asynchronously from the rest of the system. Islanding may be intentional or unintentional. Intentional islanding is an effect of planned switching operation, leading to reliability improvement. While unintentional islanding may be caused by breaker operation being result of some power system disturbance. Regardless of the type of islanding, it is important to detect the disturbance immediately to protect the grid and avoid cascading blackouts, effects on protective device settings, controller actions and any other abnormal operations [1], [2].

Islanding detection methods can be divided into local and remote, where local methods can be further split into passive and active [3], [4]. Each group has its pros and cons, but it can be concluded that remote methods based on communication are the best when it comes to reliability and lack of non-detection zone, but the cost of an infrastructure can be high, thus not always feasible [5], [6], [7]. Local active methods can be implemented in converters, so they are cheap and significantly reduce non-detection zone, but tend to jeopardize power quality, especially where a big number of converters working with such methods are installed [3], [4], [8]. Finally, passive local detection methods are cheap to introduce and do not interfere with power quality even with large penetration of distributed generation, but have relatively big non-detection zone and are vulnerable for maloperations caused by power system events like external faults, or power swings.

Although, the future of islanding detection seems to be in communication based methods with, for instance Direct Transfer Trip, there will be always need for some backup scheme based on information available locally, like rate of change of frequency (ROCOF) or voltage vector shift (VVS) [9]. Due to simplicity and low costs the most popular detection methods are passive local methods - rate of change of frequency and voltage vector shift) [4].

ROCOF is a relay operating using frequency estimation. Frequency is a quantity which cannot be measured directly, so it has to be estimated from voltage waveform or speed of a rotor of a machine. A chosen estimation method can have an impact on ROCOF performance, since it operates based on frequency derivative it is sensitive to transient states occurring when, for instance islanding happens [12]. According to [10], different frequency estimation methods can have different transient responses, thus potentially altering ROCOF performance and even cause maloperations.

Section II presents rate of change of frequency relay fundamentals. Section III discusses popular methods used for frequency estimation for power system protection purposes, which will be further used for studying ROCOF performance. Section IV provides an overview of lab setup for testing the estimation algorithms. This is followed by section V with results of simulated cases. The paper ends with section VI containing conclusions.

II. RATE OF CHANGE OF FREQUENCY RELAY

For local detection methods of islanding phenomenon, the most important quantity to monitor, is system frequency which is directly related to active power balance. Over/under frequency relays which are normally installed for generators protection can provide islanding detection function. According to equation (1) frequency drift after islanding depends on active power mismatch, inertia within the island and time instance. Thus, in cases of close match of power locally consumed by loads and generated by DGs it may take too much time for the frequency to drift out of boundary values set in the relay. These values are specified in the Standard [13] and the lower is 47.5 Hz, while upper is 52 Hz. The way to speed up islanding detection, is to calculate a derivative of frequency. This method is called rate of change of frequency (ROCOF). ROCOF relay compares calculated value of the frequency drift slope with pickup value setting and commands trip right after the calculated values exceeded threshold. Filter window for calculations is typically between 2 and 40 cycles [14].

$$\Delta f = \frac{\Delta P f_0}{2H} \cdot t \tag{1}$$

And further, rate of change of frequency can be expressed as:

$$\frac{df}{dt} = \frac{1}{2\pi}\frac{d\omega}{dt} = \frac{f_0}{2H} \cdot \Delta P \tag{2}$$

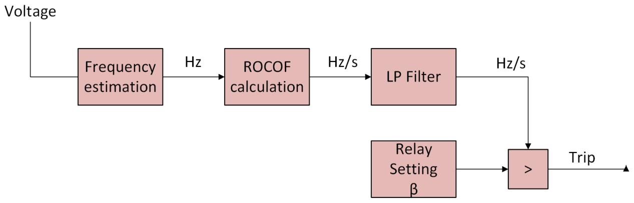


Fig. 1. ROCOF relay block diagram

III. FREQUENCY ESTIMATION METHODS

There are numerous algorithms used to extract frequency from voltage signal. First three subsections present the most popular methods introduced and initially characterized by transient response in [10], [12]. The last method presented was introduced by [15], [11]

A. *Adjustment of points to pure sine wave equation (APSW)*

The method utilizes measurements of three consecutive samples of voltage waveform spaced by fixed sampling period Δt. The fundamental frequency is calculated based on assumption that obtained points belong to pure sine wave, as described by an equation:

$$cos(2\pi f \Delta t) = \frac{V_{n-2} + V_n}{2V_{n-1}} \tag{3}$$

After extracting frequency from equation 4, final expression used to estimate frequency comes with a following form:

$$f = \frac{1}{2\pi\Delta t} \cdot cos^{-1}(\frac{V_{n-2} + V_n}{2V_{n-1}}) \tag{4}$$

One can observe that estimating frequency using this method is related to division by value of voltage sample $n-1$, thus in order to avoid dividing by a small number, what could introduce significant errors, frequency estimation is performed once per half period, when sample $n-1$ is around cosine peak.

B. *Zero Crossing (ZC)*

The method based on estimation of time between zero crossings of voltage waveform. Precise crossing time is calculated by linearizing function between samples with different signs. Formula for precise zero crossing extraction is:

$$t_{zc} = \frac{t_{n-1} \cdot V_n - t_n \cdot V_{n-1}}{V_n - V_{n-1}} \tag{5}$$

Calculated time is stored in the memory and after the next zero crossing frequency is computed using:

$$f = \frac{1}{2(t_{zc} - t_{zclast})} \tag{6}$$

C. *Discrete Fourier Transform (DFT)*

Frequency estimation using DFT can be performed in two ways - calculating stationary phasor (e.g. PMU, Recursive DFT) and tracking its angular speed relative to nominal frequency, or calculating rotational phasor (e.g. FCDFT) and calculation of its angular velocity [11].

First method assumes that the result of phasor estimation is a stationary phasor obtained by, for instance recursive FCDFT algorithm. In such situation, if signal frequency has a nominal value, phasor is not rotating. When frequency drifts off nominal stationary phasor starts rotating with speed relative to frequency deviation. So, for instance when $\Delta f = 1Hz$ phasor starts to rotate with the speed of $1Hz/s$ in counter-clockwise direction. The formula to calculate frequency is:

$$f = f_b + f_r \tag{7}$$

,where f_b is a nominal power system frequency in steady state and f_r is a deviation in frequency during some transient state. Relative frequency can be expressed with:

$$f_r = \frac{\alpha_n - \alpha_{n-1}}{\Delta t} \tag{8}$$

,where α_n and α_{n-1} are phase angles of phasor calculated in $n-th$ and $(n-1)-th$ sample and Δt is sampling time.

The second method assumes that the result of phasor estimation is a rotating vector obtained by, for instance FCDFT algorithm. Then frequency estimation is performed by differentiating angular position of a rotating phasor and scaling calculated angular velocity with sampling frequency:

$$f = \frac{\alpha_n - \alpha_{n-1}}{\Delta t} \cdot \frac{N}{2\pi} \cdot f_b \tag{9}$$

,where N is a number of samples per period of fundamental frequency sine and f_b is a nominal frequency.

In this paper frequency estimation is performed using the second approach.

D. Least Error Squares (LES)

Background behind frequency estimation by LSE method is presented in details in [15] and here only essentials are introduced. Measured voltage signal can be expressed by equation:

$$v(t) = V_m sin(2\pi ft + \Theta) \tag{10}$$

,then phase offset can be extracted from sine function and the expression will be:

$$v(t) = V_m cos\Theta sin(2\pi ft) + V_m sin\Theta cos(2\pi ft) \tag{11}$$

Sine and cosine function from equation (11) can be further expanded with Taylor series and rearranged so the final equation is:

$$v(t) = V_m cos\Theta \cdot \alpha + V_m sin\Theta \cdot \beta \tag{12}$$

,where

$$\alpha = sin(2\pi f_0 t) + 2\pi t(f - f_0)cos(2\pi f_0 t) \\ - (f - f_0)^2 sin(2\pi f_0 t)$$

and

$$\beta = cos(2\pi f_0 t) + 2\pi t(f - f_0)sin(2\pi f_0 t) \\ - \frac{(2\pi t)^2}{2}(f - f_0)^2 cos(2\pi f_0 t)$$

Now equation (12) is grouped into knowns and unknowns having following form:

$$v(t) = a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5 + a_6x_6 \tag{13}$$

,where unknowns are related to signal magnitude V_m, phase offset Θ, and frequency deviation $(f - f_0)$

$$x_1 = V_m cos\Theta,\ x_2 = (f - f_0)V_m cos\Theta, \\ x_3 = V_m sin\Theta,\ x_4 = (f - f_0)V_m sin\Theta \\ x_5 = (f - f_0)^2 V_m cos\Theta,\ x_6 = (f - f_0)^2 V_m sin\Theta$$

and knowns are terms related to sampling time and nominal frequency components:

$$a_{n1} = sin(2\pi f_0 t_n) \\ a_{n2} = 2\pi t_n cos(2\pi f_0 t_n), \\ a_{n3} = cos(2\pi f_0 t_n) \\ a_{n4} = 2\pi t_n sin(2\pi f_0 t_n) \\ a_{n5} = -sin(2\pi f_0 t_n) \\ a_{n6} = -2\pi^2 t^2 cos(2\pi f_0 t_n)$$

,where $t_n = (n - 1)\Delta t$.

When sampling voltage signal with deterministic sampling time Δt, samples buffer can be filled with n voltage samples and over-determined set of equation can be formulated in order to solve coefficients $x_1, x_2, x_3, x_4, x_5, x_6$.

$$\begin{bmatrix} v(0) \\ v(1) \\ \cdot \\ \cdot \\ v(n) \end{bmatrix} = \begin{bmatrix} a_{01} & a_{02} & a_{03} & a_{04} & a_{05} & a_{06} \\ a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ a_{n1} & a_{n2} & a_{n3} & a_{n4} & a_{n5} & a_{n6} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix}$$

In order to solve this equation one needs to calculate pseudo-inverse matrix of a - coefficients and multiply both sides of the equation from the left. Frequency deviation is obtained from division:

$$(f - f_0) = \Delta f = \frac{x_2}{x_1} = \frac{(f - f_0)V_m cos\Theta}{V_m cos\Theta} \tag{14}$$

, so exact frequency would be then:

$$f = f_0 + \Delta f \tag{15}$$

One can observe that elements of the coefficients matrix are not time dependent, so it is possible to precalculate elements of the pseudo-inverse matrix. Since for frequency calculation only x_1 and x_2 are necessary it is further possible to take only first two rows of the pseudo-inverse matrix and implement them in form of two FIR filters.

IV. LAB SETUP

Algorithms discussed in section III were tested in the lab. The model of an islanded grid is a part of a 22 kV distribution network, It consists of a synchronous distributed generator connected to through a step up transformer and a load modeled as a constant impedance. The power system was modeled as ideal voltage source behind impedance. Islanding is executed by opening the circuit breaker. Model schematic is presented in the Figure 2.

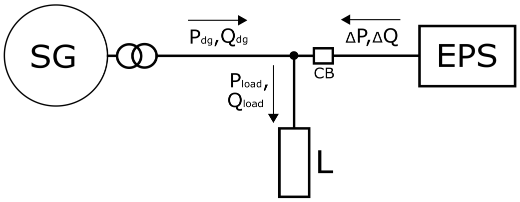


Fig. 2. One line schematic of the used model (SG - synchronous generator, L - load, EPS - electric power system, CB - circuit breaker)

The islanded power system was modeled in Matlab/Simulink using SimPowerSystems library and prepared for real-time simulation using Opal-RT[16]. In order to reproduce the real world circumstances in which physical relay operates as closest as possible to the network changes, i.e.., delays, noises on communication channel, etc. - frequency estimation part and ROCOF computation were implemented on the STM32F7 Discovery board [17]. The heart of the board is a ARM Cortex-M7 processor which is able to run at frequency up to 216 MHz and can work with numerous peripherals e.g. responsible for communication with external devices. Communication between the board and Opal RT is realized with Ethernet via UDP/IP protocol, since it provides better bandwidth than serial communication based on UART, thus allowing for fast data transfer to and from the board.

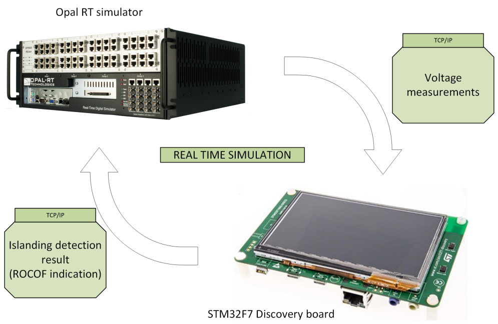
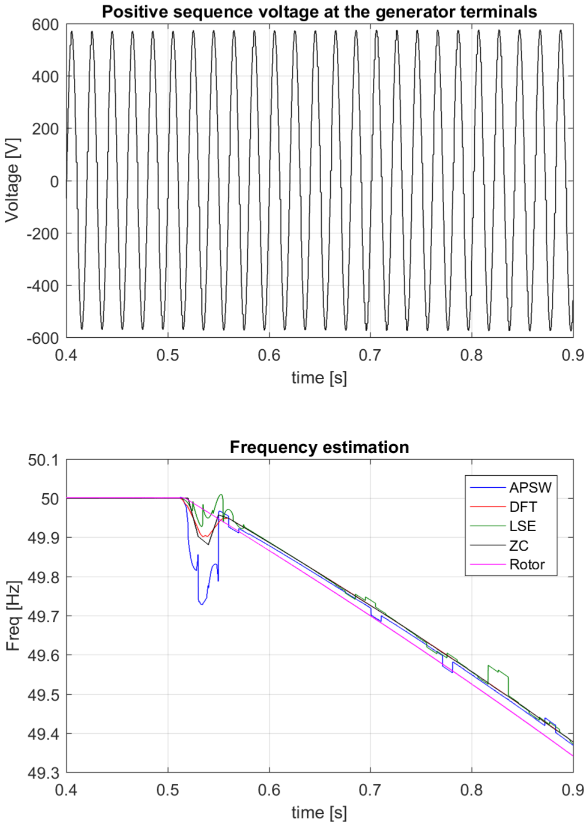


Fig. 3. Lab setup

V. SIMULATIONS

Results presenting performance of frequency estimation methods in real-time simulations are discussed in this section. Figure 4 presents the estimated frequency from various techniques implemented on the STM32F7 Discovery board. Positive sequence voltage derived from network voltages is used as input to the estimation algorithms. Islanding event occurs at $t = 0.5s$, it can be observed that each algorithm behaves identically at steady state prior to islanding indicating exactly $50Hz$. However, differences become clear during transient states and off nominal frequencies.


Positive sequence voltage at the generator terminals

Frequency estimation

Fig. 4. Frequency estimated by the algorithms implemented on the STM32F7 board

Figure 5 presents the ROCOF calculation based on frequency estimation from various techniques presented in section III. Basically ROCOF is calculated as a derivative of frequency that amplifies higher harmonics that start to appear in the frequency signal during disturbances. During the transient changes introduced by breaker opening, ROCOF does experience high harmonics and none of the presented frequency estimation methods is sufficiently accurate in this period, thus making resulting ROCOF estimation unacceptably high right after islanding event. In comparison with other 3 algorithms, APSW does not have the ability to eliminate the harmonics caused by transient changes, this is because it uses only three consecutive voltage values for frequency estimation. The rest of the algorithms resulted in lower values of the transient state estimation, but still unacceptably high. Another interesting observation is that Least Error Squares algorithm gives some inaccuracies for off-nominal frequencies.

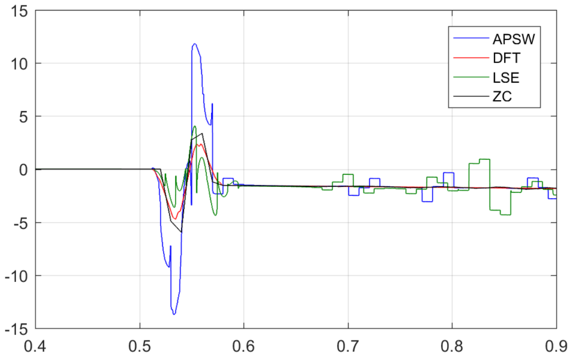


Fig. 5. Rate of change of frequency estimated by the algorithms implemented on the STM32F7 board

One possibility to mitigate transient state in ROCOF estimation is to use another source of frequency input. In some situations it is possible to extract frequency value from the speed of the rotor. Figures 4 and 6 present comparison in frequency estimation between estimation using DFT algorithm and taken directly from rotor speed. It is clearly visible that while DFT have some transient state at $t = 0.5s$, measurement based on rotor speed is very fluent due to machine inertia. As a result ROCOF performs in a much more secure manner settling directly on exact value of the frequency slope after islanding.

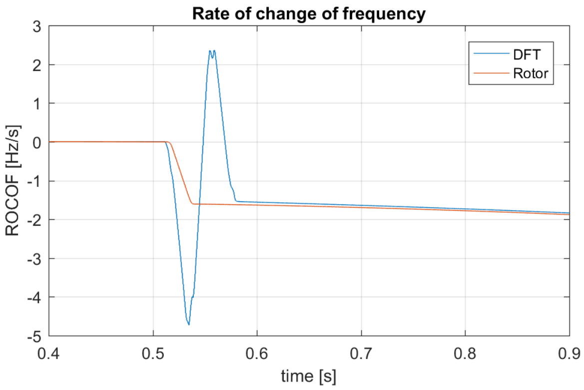

Rate of change of frequency

Fig. 6. Rate of change of frequency estimated from DFT vs rotor of the machine

Other way to deal with the ROCOF transient is to apply averaging filter, which smooths transient state. Averaging were performed over five fundamental frequency cycles. Effect of such a filter is presented in figure 7.

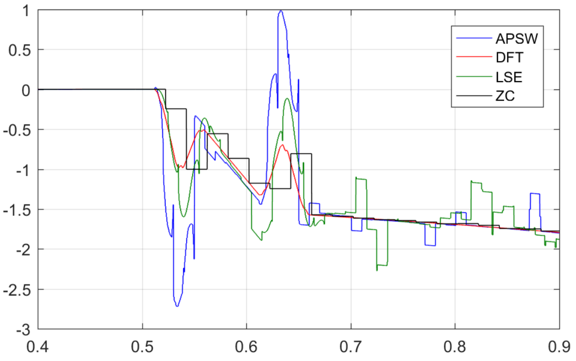


Fig. 7. Rate of change of frequency indication with 5 cycles averaging filter

Application of averaging filter is presented in figure 8. It can be observed that it significantly improves security, because there is no overshoot of ROCOF. However, it is takes significant time to converge to steady state value.

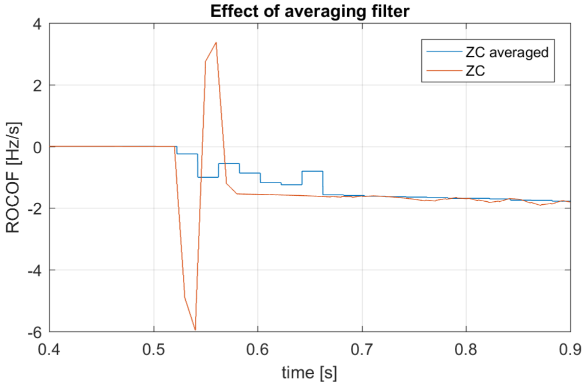


Fig. 8. Comparison of 'raw' ROCOF indication and indication averaged through five cycles

Observations regarding suitability of presented algorithms to being an input for ROCOF relay are as follows. The best algorithms are zero crossing and DFT, since they have both relatively small initial transient and stable calculation for off-nominal frequencies. LSE algorithm as a filter based method was expected to be also appropriate and although it has small transient, it reveals poor estimation for off-nominal frequencies. APSW, due to bad transient response is the worst algorithm of the presented ones, since to be applicable it requires the longest averaging window, which lengthens reliable detection time.

VI. CONCLUSION

The paper presents the RT-HIL comparison of most common frequency estimation techniques by using network voltages. Further it discusses possibilities of utilizing these methods as an input to ROCOF relay, this demonstrated through RT-HIL simulation using Opal-RT real time simulator with frequency estimation algorithms embedded on the STM32F7 Discovery board. Frequency estimation based on voltage signal is exposed to transient states caused by discontinuities in the measured signals. As presented, methods based on filtering are better in mitigating fast changes in input signal, thus are more suitable for ROCOF relays, but these are not completely free from transient spikes. Smoothing with averaging filter, or adding some delayed tripping logic is necessary to ensure relay secure operation without sympathetic tripping.

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