whereas negative ramping will take place when there is more load than generated power.

Fig. 23 represents the frequency measurement with a signal ramping frequency of –0.5 Hz/s. The same plot represents the reference frequency and the sampling frequency. We can see that the delay in the frequency measurement never exceeds three cycles. Also noticeable is the delay between the establishment of the sampling frequency and the measured frequency.

In Section II, we presented an example of a mho element misoperation resulting from a frequency excursion consisting of a ramp of –0.5 Hz/s. If for the same waveforms, the sampling frequency of Fig. 23 is applied, we obtain for the angle between the operating and the polarizing vectors shown in Fig. 24. One can see now that the angle never gets below 90 degrees and the mho element remains stable. Fig. 25 shows the impact of the frequency tracking on the mho element and one can see that the scalar product, as expected, never crosses the line zero. Finally, in Fig. 26, we can see the impact of the frequency tracking on the A-phase voltage. The slight mismatch between the signal and the sampling frequencies is such that the error in the phasor calculation never exceeds 0.5 percent.

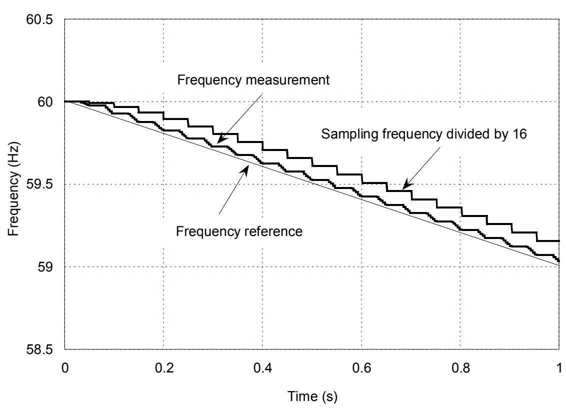

Fig. 23. Frequency measurement and sampling frequency with a ramp of slope equal to –0.5 Hz/s

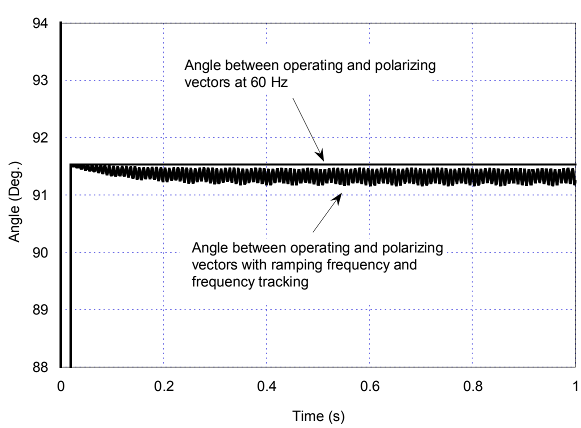

Fig. 24. Angle between operating and polarizing vectors at 60 Hz and with ramping accompanied by frequency tracking

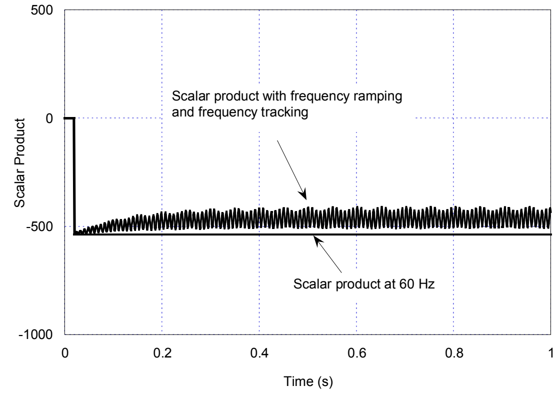

Fig. 25. Scalar product of mho AB element with ramping frequency and frequency tracking

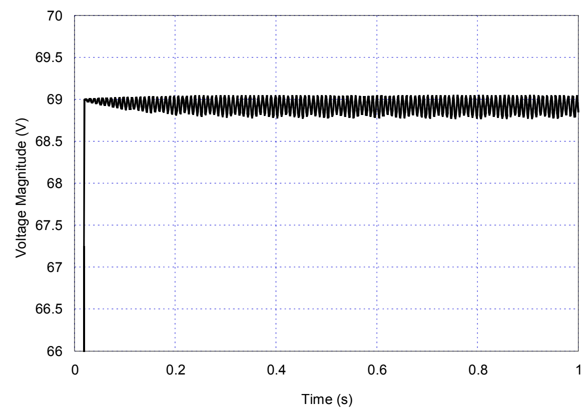

Fig. 26. Magnitude of VA voltage phasor with frequency tracking

Power swings will develop on a network following a major disturbance like a short-circuit, the loss of a major load center, or a generator rejection. We can simulate power-swing-like waveforms by modulating the phase angle of a power source as shown in Annex I. As described in the Annex, we will use a sinewave to modulate the phase angle of one of the two sources of an elementary network. With the parameters selected as V = 100 V, k = 2 and $\omega = 2\pi$ rad/s (corresponding to 1 Hz), we obtain an A-phase waveform the phasor of which has the following time-varying magnitude at the swing-center voltage:

$$\left|\overline{V_{SCV}}\right| = 50 \bullet \sqrt{2[1+\cos(2\bullet\cos(2\pi t))]} \tag{27}$$

The phase A voltage phasor at the SCV has a time-varying phase angle equal to the following:

$$\angle\overline{V_{SCV}} = \cos(2\pi\, t) \tag{28}$$

The signal frequency in Hertz of the SCV waveform is equal to the derivative of the instantaneous phase:

$$\text{frequency (Hertz)} = 60 - \sin(2\pi\, t) \tag{29}$$

When we apply the three-phase voltages to the relay with the frequency tracking operational, we obtain the frequency measurement shown in Fig. 27. The reference frequency corresponds simply to (29). Fig. 28 represents the trajectory of the sampling frequency divided by 16 together with the measured frequency. Finally, Fig. 29 represents the A-phase time-voltage waveform together with the magnitude the Cosine filtering system acquired for this waveform.

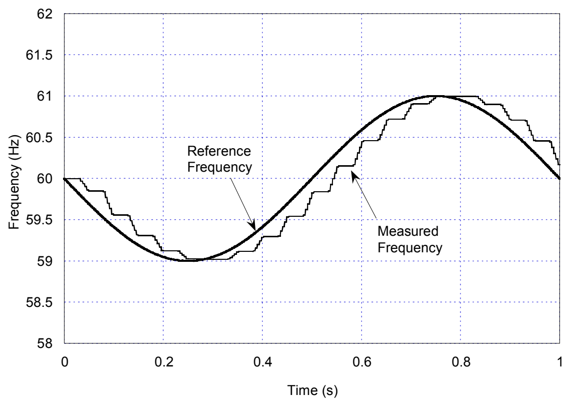

Fig. 27. Power swing frequency measurement

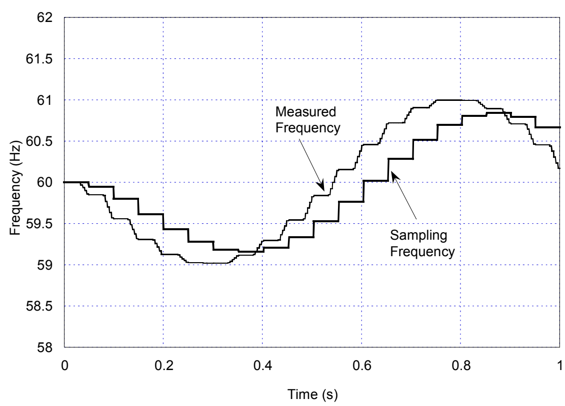

Fig. 28. Power swing frequency and sampling frequency

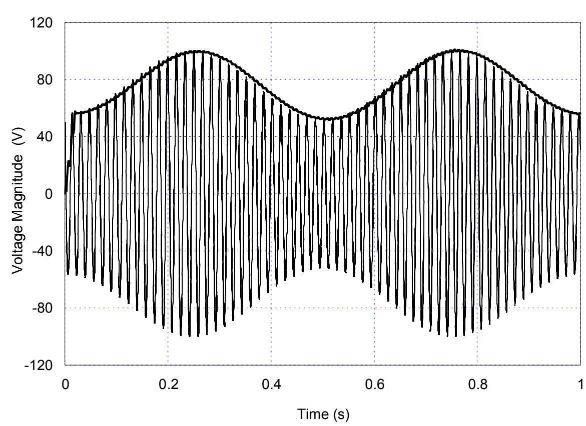

Fig. 29. A-phase voltage during power swing test

VII. Practical Implementation of 81 Elements in a Digital Relay

Once the filtered measurement of the frequency MESFREQ is available, and provided the frequency measurement complies with the basic requirements this paper already expressed, the implementation of 81 frequency elements is relatively simple. We review this implementation here for the sake of completeness.

An overfrequency (81O) or underfrequency (81U) element is simply implemented by comparing the filtered frequency measurement to a threshold and then following the resulting Boolean variable with an adjustable definite time delay.

Fig. 30 shows the logic of a frequency element that can serve either as an 81O or an 81U function. We have the following nomenclature:

FNOM = rated frequency (60 or 50 Hz)

MESFREQ = filtered frequency measurement

81XnTP = frequency pickup value

FREQTROK = frequency tracking okay signal (Boolean)

81XnTD = timer pickup value delay

81XnT = 81 element status (Boolean)

The logic represents an overfrequency element if the pickup threshold is greater than the rated frequency FNOM. Alternatively, it represents an underfrequency element if the pickup threshold is smaller than the rated frequency FNOM. If set as an overfrequency function, the element will assert if the measured frequency is greater than the threshold 81XnTP and after the delay 81XnTD has elapsed. If set as an underfrequency function, the element will assert if the measured frequency is smaller than the threshold 81XnTP and after the delay 81XnTD has elapsed.

Typically, a relay will have at least six elements of this type.

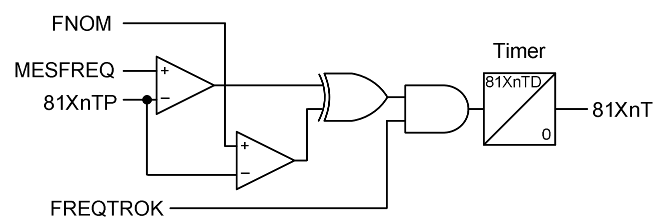

Fig. 30. 81 element logic

VIII. Conclusion

1. Many relays accomplish frequency measurement directly on the voltage input waveforms before waveforms are sampled. For these relays, frequency measurement and frequency tracking are intrinsically independent.
2. For relays that use an adaptive principle to accomplish frequency measurement after sampling voltage and current waveforms, it is necessary to apply at least two basic rules in order to make the frequency measurement independent from the sampling frequency.
   a. No frequency measurement should be made following a change to the sampling frequency during an interval of time equal or greater than the response time of the filtering system using for the computation of the phasors.
   b. No sampling frequency change should be performed before the complete filtering interval required by the frequency measurement filtering is terminated.

3. The time-response trajectory to a frequency-step is a powerful test to determine the dynamics of the frequency measurement.
4. For the purpose of implementing 81 elements in a relay, we want a time response of two to five cycles with a minimum (ideally zero) overshoot.
5. The use of 81 elements requires a steady-state minimum absolute accuracy of 0.01 Hz. Some digital relays achieve accuracy better than 0.005 Hz.
6. Step-response and steady-state accuracy tests should be supplemented with response to frequency ramping functions and power-swing waveforms as defined in the paper.

IX. Appendix: Derivation of Power Swing-Like Waveforms

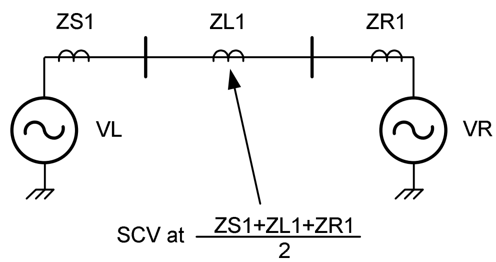

Fig. 31. Elementary network for power swing simulation

Consider the elementary network represented in Fig. 31 and assume that the right-side voltage sources are fixed and provided as follows:

$$\begin{aligned} VRA &= V \bullet \cos(\omega_0\, t) \\ VRB &= V \bullet \cos(\omega_0\, t - 120°) \\ VRC &= V \bullet \cos(\omega_0\, t + 120°) \end{aligned} \tag{30}$$

In (30), ω_0 is the rated frequency. A sinewave modulates the phase for the left-side voltage sources so that we have the following:

$$\begin{aligned} VLA &= V \bullet \cos[\omega_0 t + k \bullet \cos(\omega t)] \\ VLB &= V \bullet \cos[\omega_0\, t + k \bullet \cos(\omega t) - 120°] \\ VLC &= V \bullet \cos[\omega_0\, t + k \bullet \cos(\omega t)] + 120° \end{aligned} \tag{31}$$

In this last equation, ω is the phase angle modulation frequency. The following equation provides A-phase voltage at the swing center voltage (SCV):

$$V_{SCV} = \frac{VLA + VRA}{2} \tag{32}$$

We then have the following:

$$V_{SCV} = \frac{V}{2} \bullet \{\cos[\omega_0\, t + k \bullet \cos(\omega t)] + \cos(\omega_0\, t)\} \tag{33}$$

After a few manipulations, we express V_{SCV} as:

$$V_{SCV} = \frac{V}{2} \bullet \sqrt{2[1 + \cos(k \bullet \cos(\omega t))]} \bullet \left\{\cos(\omega_0\, t + \frac{k \bullet \cos(\omega t)}{2})\right\} \tag{34}$$

The V_{SCV} phasor has a time-varying magnitude equal to:

$$\left|\overline{V_{SCV}}\right| = \frac{V}{2} \bullet \sqrt{2[1 + \cos(k \bullet \cos(\omega t))]} \tag{35}$$

The V_{SCV} phasor has a time-varying phase angle equal to:

$$\angle\overline{V_{SCV}} = \frac{k \bullet \cos(\omega t)}{2} \tag{36}$$

The frequency of the SCV waveform is equal to the derivative of the instantaneous phase:

$$\begin{aligned} \text{frequency} = &\ \frac{d}{dt}\left(w_0 t + \frac{k \bullet \cos(\omega t)}{2}\right) \\ &= \omega_0 - \frac{k \bullet \omega \bullet \sin(\omega t)}{2} \end{aligned} \tag{37}$$

In units of Hertz, the frequency is given as:

$$\text{frequency (Hertz)} = \frac{2\omega_0 - k \bullet \omega \bullet \sin(\omega t)}{4\pi} \tag{38}$$

X. References

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XI. Biographies

Gabriel Benmouyal, P.E. received his B.A.Sc. in Electrical Engineering and his M.A.Sc. in Control Engineering from Ecole Polytechnique, Université de Montréal, Canada in 1968 and 1970, respectively. In 1969, he joined Hydro-Québec as an Instrumentation and Control Specialist. He worked on different projects in the field of substation control systems and dispatching centers. In 1978, he joined IREQ, where his main field of activity has been the application of microprocessors and digital techniques for substation and generating-station control and protection systems. In 1997, he joined Schweitzer Engineering Laboratories in the position of Principal Research Engineer. He is a registered professional engineer in the Province of Québec, is an IEEE Senior Member, and has served on the Power System Relaying Committee since May 1989. He holds over six patents and is the author or co-author of several papers in the field of signal processing and power networks protection and control.

Angelo D'Aversa received from Drexel University his BSEE degree in 1990 and an MSEE degree in 1994. After graduation he developed distribution relays for General Electric for 9 years. In 1999 he joined Schweitzer Engineering Laboratories as a test engineer and since joining SEL has spent many years developing firmware for a variety of protective relays. Presently, he is R&D Manager for the Industrial Systems group for SEL. Industrial Systems specializes in motor and generator relays for Industrials and Utilities.

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