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How Frequency Measurements can Impact Security of Frequency Elements in Digital Relays

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1. Introduction.

Frequency is one of most important parameters in power system as it indicates the balance between power generation and consumption. Power system will deteriorate fast if there is an excess of load over available generation. The prime movers and their associated generators begin to slow down as they attempt to carry the excessive load. While hydro-electric plants are relatively unaffected by the frequency decrease by even ten percent, a thermal generation plants are very sensitive to even five percent reduction. As system frequency decreases, the power output to auxiliaries begins to fall off rapidly which in turn further reduces the energy input to the turbine-generator. This situation therefore has a cascading effect leading to a loss of power, which can cause further frequency decrease, system islanding or even collapse.

After 2003 blackout regulatory bodies such as NERC, NPCC, IMOs are paying lot of attention to performance of system protection during off frequency system conditions in order to achieve harmonization among utilities practices and to increase robustness of the system as one whole entity. Frequency relays play a vital role in this regard but it's assumed that relays will measure frequency correctly without any other specific details.

Underfrequency protection is scrutinized in this paper. Although traditional, it is still considered the main protection for the power system stability, and the primary protection against imbalance between generated and consumed power in the power system. While underfrequency protection historically belonged to the substation level protection functions, with the introduction of digital technology, this role has changed, and underfrequency protection got distributed to the lower levels. Consequently, a variety of schemes exists in the utilities, depending whether the applied underfrequency relay is electromechanical, solid sate, or digital. Particular concern, a loss of security (undesired tripping) is analyzed and supported with the real life examples in this paper.

Frequency element should operate fast to help the power system to survive major system disturbances; on the other hand error in frequency measurement can have disastrous consequences. For example, frequency relay used in underfrequency load shedding schemes are expected to operate from few power cycles to minutes depending on the severity of the situation with measured frequency. This delay should be typically enough to overcome system transients or otherwise enough not to issue trip signal due to error in frequency estimation.

Frequency measurement is used in protective relays for critical elements, such as underfrequency for load shedding, overfrequency, frequency rate-of-change, volts/herz, phasor measurement unit, generator protection, etc. It is also used to track to the system frequency to ensure precise phasors measurements.

Some system conditions such as faults, switch-off transients, equipment energization etc can be mistakenly interpreted by frequency relays as valid under- or overfrequency conditions. This paper gives an overview of frequency measurement techniques used in digital protective relays and how frequency measurements can be validated to prevent erroneous measurement to take place. It also presents some field cases, where frequency relays couldn't distinguish between real system frequency change condition and transients associated with a fault clearing. This resulted in incorrect operation of frequency relays and disruption of customers power supply.

2. Overview of frequency measurement of protective relays

2.1. Methods used to measure system frequency

Varieties of methods, comprehensively described in [1] are used for frequency measurements in protective relays. The most commonly used method in protective relays to measure frequency is zero crossing. It could be based either on the single-phase signal obtained directly from single-phase system voltage or from 3-phase system voltage after for example Clarke transform. It's possible to use currents as well, but voltages are preferred because are always higher in magnitude and not affected by harmonics and decaying DC as much as currents. Zero-crossing method accuracy is affected by noise, harmonics, distortions caused by power system transients and sampling rate of the digital relay. Also zero-crossing measurement is available at most 2 times a cycle only, using single-phase either direct or after Clarke transform input as shown below in Equation 1 for voltages.

$$S_{freq} = \frac{1}{3} \cdot \left(2 \cdot v_A - v_B - v_C\right) \qquad \text{Eq. 1}$$

To improve accuracy of the zero-crossing method, pre-filtering such as low pass filter is used to reduce the harmonics and noise in the signal and post-filtering such as averaging is used. This, however, affects the speed of the frequency measurement.

Other common methods are Digital Fourier Transform, orthogonal sine and cosine functions composition, signal demodulation and others. Reference [1] gives comparative performance evaluation for different frequency measurement methods, which is outside the scope of this paper. However, depending on the method used in particular relay, frequency measurement may be more or less vulnerable to error in frequency measurement during power system disturbances and transients associated with these events.

Performance of frequency measurement method can be quantified by three factors:

1. Accuracy. Frequency measurement of the particular method can be very accurate under stable conditions but can exhibit significant errors when signal is fast changing.
2. Measurement delay. Minimum delay for underfrequency relay required by appropriate standards is 6 cycles. This dictates the averaging window length of the of frequency relay during frequency change.
3. Robustness. Frequency measurement should not be affected by the adverse system conditions. System disturbances and transients, instrument transformers transients, coupled with presence of harmonics and noise should not affect stated accuracy of the frequency measurement of the given relay.

Usually clauses 1 and 2 above are considered during evaluation testing of the frequency relay but clause 3 is out the scope of the testing.

2.2. Elements using frequency measurements, UF, OF, df/dt, tracking frequency, phasor measurement.

Measured frequency is used by under- and overfrequency elements, volts-per-hertz, load shedding, synchrocheck and automatic synchronizing functions and frequency tracking as well. There are some applications that should respond to the frequency change very fast, such as generator protection applied to machines with a low inertia, protection of variable speed motors or fast load shedding schemes.

2.3. Impact of erroneous frequency measurement for these elements

Error in frequency measurement can have dramatic impact on the system stability and ability to survive. Both overestimation and underestimation of the system frequency are dangerous especially for applications where fast response is required such as underfrequency load shedding.

2.4. UFLS requirements.

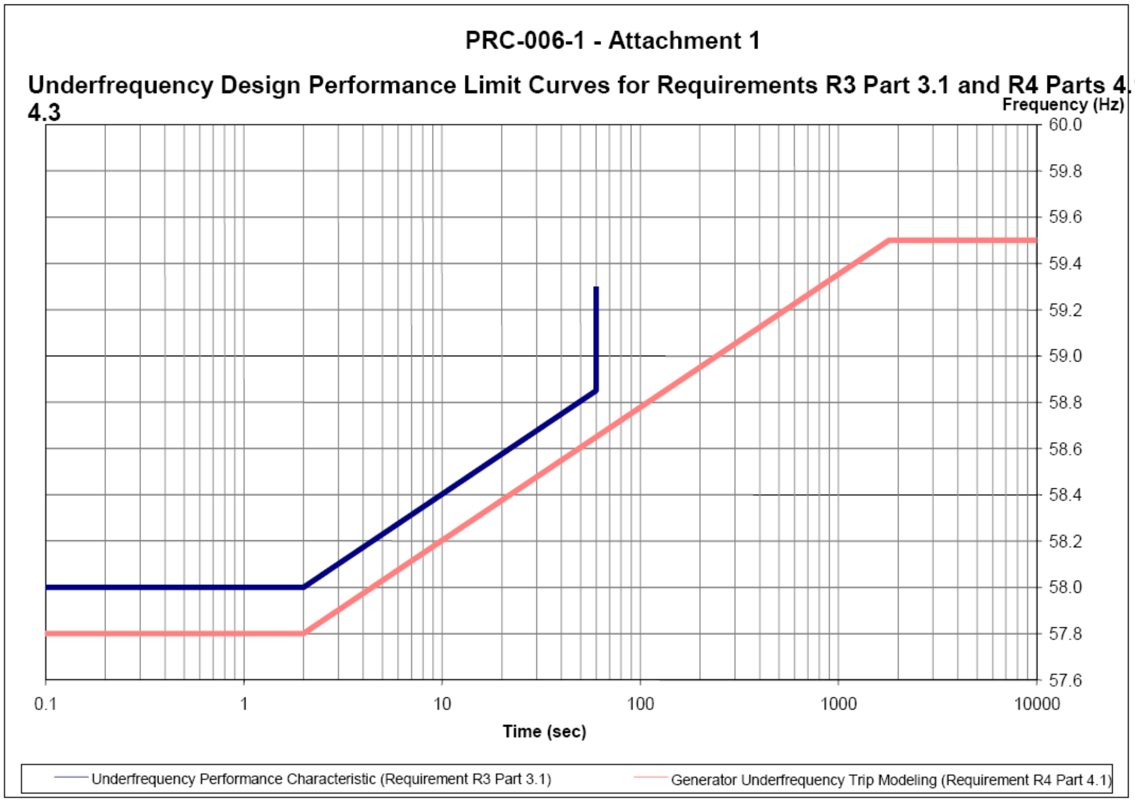

Figure 1. NERC PRC-006-1 Automatic Underfrequency Load Shedding standard frequency curves

NERC (North American Electric Reliability Corporation) released a standard PRC-006-01 "Automatic Underfrequency Load Shedding" which has to be followed by each regional council. Specifically, R3 clause is giving guidance to set points of frequency relays used for UFLS program

R3. Each Planning Coordinator shall develop a UFLS program, including a schedule for implementation by UFLS entities within its area that meets the following performance characteristics in simulations of underfrequency conditions resulting from an imbalance
scenario, where an imbalance = [(load — actual generation output) / (load)], of up to 25 percent within the identified island(s).

3.1. Frequency shall remain above the Underfrequency Performance Characteristic curve in PRC-006-1 - Attachment 1, either for 60 seconds or until a steady-state condition between 59.3 Hz and 60.7 Hz is reached, and

3.2. Frequency shall remain below the Overfrequency Performance Characteristic curve in PRC-006-1 - Attachment 2, either for 60 seconds or until a steady-state condition between 59.3 Hz and 60.7 Hz is reached, and

3.3. Volts per Hz (V/Hz) shall not exceed 1.18 per unit for longer than two seconds cumulatively per simulated event, and shall not exceed 1.10 per unit for longer than 45 seconds cumulatively per simulated event at each generator bus and generator step-up transformer high-side bus.

For example NPCC (Northeast Power Coordinating Council is specifying requirements of UFLS as:

"The intent of the Automatic Underfrequency Load Shedding program is to stabilize the system frequency in a Balancing Authority area during an event leading to declining frequency while recognizing the generation characteristics in each area. The goal of the program is to arrest the system frequency decline and to return the frequency to at least 58.5 Hertz in ten seconds or less and to at least 59.5 Hertz in thirty seconds or less, for a generation deficiency of up to 25% of the load".

Typically, utilities include about 37% of their load in underfrequency load shedding schemes. Table 1 shows typical utility program for underfrequency load shedding scheme with first five steps primarily allocated for fast load tripping, to reach as soon as possible the equilibrium between load and generation. The remaining steps are used only if the system stalls and does not recover to nominal frequency, and their tripping is in seconds, or minutes. The main conclusion from Table 1 in this paper is that when frequency is decreasing and reaches certain underfrequency setpoint, excessive load has to be curtailed as soon as possible, in order to conserve the rest of the load in stable power system. The decision to remove excessive load has to happen as fast as 6 cycles (about 100 milliseconds) for the first five steps of UFLS setpoints.

UF and OV relays settings	Load block assignment (%)	Trip frequency (Hz)	Trip delay (cycles)	Reset frequency (Hz)	Reset delay (min)	Reclosing
1st step	5.3% of load	59.1	6 cycles	59.95	30+	Manual/automatic
2nd step	5.9% of load	58.9	6 cycles	59.95	30+	Manual/automatic
3rd step	6.5% of load	58.7	6 cycles	59.95	30+	Manual/automatic
4th step	6.7% of load	58.5	6 cycles	59.95	30+	Manual/automatic
5th step	6.7% of load	58.3	6 cycles	59.95	30+	Manual/automatic
6th step	2.3% of load	59.3	15 sec.	59.3	30+	Manual/automatic
7th step	1.7% of load	59.5	30 sec.	59.5	30+	Manual/automatic
8th step	2.0% of load	59.5	1 min.	59.5	30+	Manual/automatic
Generation assist (1st & 2nd)	5%	-	-	60.5	5 sec.	Automatic

Table 1. Example of utility UFLS program relay setting and assignments

Traditionally, utilities have been utilizing UFLS schemes centralized on a substation level [3], with just one underfrequency relay, which would shed the load/feeders per utility load shedding program for that particular substation. This means that typically, distribution substation would have two, or three distribution transformers 230kV or 115kV on the HV side and 12 kV or 21 kV on the LV side, where each of them would feed one 12 kV or 21kV distribution bus section. Substation level underfrequency relay would get voltage signals from one of two LV bus sections through the selector switch or potentials switch logic. Figure 2 shows such typical distribution substation with two distribution transformers and one underfrequency relay on the substation level, tripping selected feeders, as per utility's UFLS Program. Due to the fact that UFLS for the whole substation is done with one relay only, the additional security is introduced by blocking UF trips in case voltage is decreasing bellow the certain threshold. Typically UFLS trips are blocked, if the voltage decreases bellow 50-70% of the nominal in accordance with [3].

All generators require tripping for underfrequency condition and trip conditions are based on the turbine-generator design. This is to protect generators from underfrequency conditions, but removing generators from the system is reducing system chance to survive. Automatic load shedding on the transmission and distribution system is first to protect generators from underfrequency conditions and secondly quickly restore system frequency to normal to prevent system islanding or even system collapse. Each regional council has a strict guidance for underfrequency set points to limit the amount of generation that is allowed to trip prior to the operation of the underfrequency load shedding schemes.

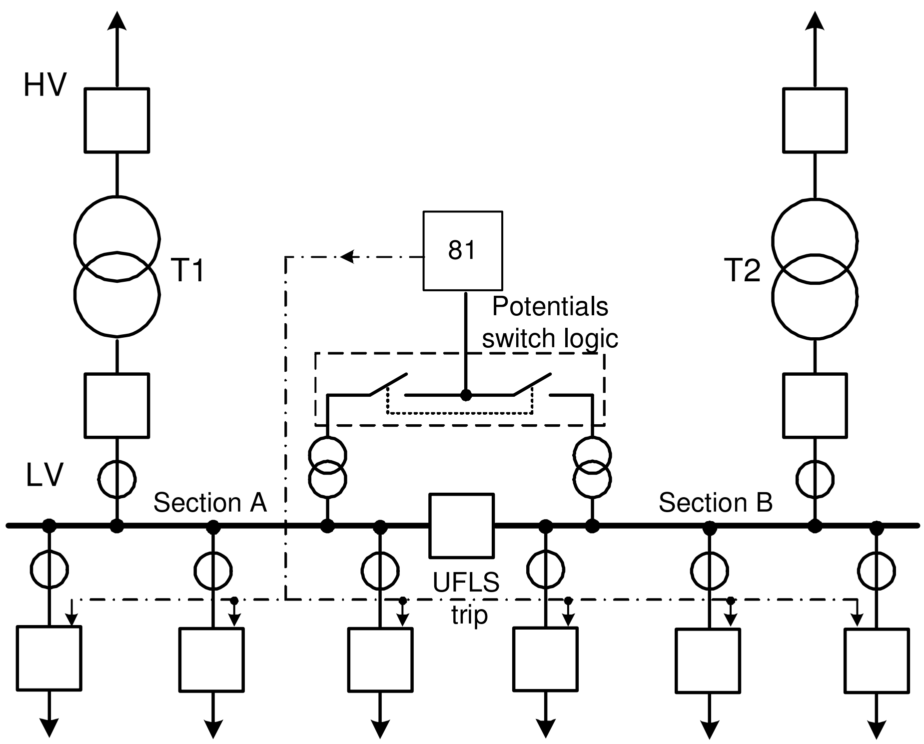

Figure 2. Typical UFLS arrangement at distribution substation with one UF relay

Typical power system events, which can cause frequency measurement error, are following:

- <u>Faults.</u> Especially in the distribution system, faults can last longer than on the transmission system. Time of faults clearing can easily be longer that UFLS time delay. During fault in the distribution system can happen transient processes such as sub -synchronous oscillation due to interaction of the active elements of the distribution system.

- o <u>Fault switch-off transients</u>, including ring-down effect. When breaker opens, it could be long lasting ring-down effect with fast decaying frequency.
- o <u>Autoreclosure dead-time.</u> During autoreclosure dead time of the line feeding the distribution system, there is no any coordination of UFLS relays and line relays.
- o <u>Motor load</u> off the bus being de-energized.
- o <u>Harmonics and noise</u>. It affects reliable-zero-crossing detection.
- o <u>Transformer energization inrush or capacitor bank switching.</u> When transformer or capacitor are switched, there may be sustained distortions on the voltages and currents on this bus.
- o <u>Local generation swings</u>. This can happen after system disturbance clearance when local generators swing back and forth to synchronize with a system.
- o <u>Failures in the VT secondaries</u>. When fuse is blowing in one phase, this can cause distortion of the voltage signal effecting frequency measurement.

3. Field examples of erroneous UFLS and other elements operations

This section will present some real-life examples of erroneous operation of underfrequency and rate of frequency change elements.

3.1. Field case #1

Distribution transformer T1 115/12 kV in Figure 2 of distribution network was tripped by transformer differential protection. This kind of system event would normally cause temporary interrupt of supply to all feeders connected to the 12 kV bus section "A" only, which transformer T1 was connected to. However, due to undesired underfrequency relay operation which was fed from the same 12 kV bus section "A" all feeders from both sections of this particular substation were tripped by UFLS. This caused unnecessary outage of half of the feeders and delayed return of all feeders included into UFLS scheme back into service.

Further analysis of this unexpected operation revealed the following:

- Solid-state UF relay with a 59.1 Hz pickup (1^{st} step), 0.67pu undervoltage supervision and 6 cycles delay initiated an UFLS trip.
- 12 kV bus section did not lose voltage signal instantly, but unexpectedly voltage of 12 kV distribution bus section "A" decayed linearly during 0.24 seconds after breaker opens. At the time of the UF relay operation voltage still was still above the UV setting, allowing UFLS trip.
- There were two digital relays from two different manufacturers connected to the same bus VT both having UF function enabled and capable to operate. First of all these two relays helped to capture oscillography record for this event. Interestingly, these two relay showed quite different frequency measurement prompting reasonable question: "why measurement is different and how secure are these digital relays for UFLS purposes".
- Figure **3** below demonstrates waveforms from this event, graph 3 of this figure presents instantaneous frequency measured from 3-phase voltages (dark blue trace), averaged over 3 cycles (light blue trace) and frequency measurements from both digital relays.
- In 1 ¾ cycles after transformer breaker opened relay 2 (red trace) measured frequency at 58.56Hz which is below 1^{st}, 2^{nd} and 3^{rd} steps of UFLS per Table 1 above. Frequency measured by this relay continued to decay dramatically and in 6 cycles it was below 57Hz with a positive sequence voltage at 0.62pu. In 1 ¼ cycles after breaker opened measured frequency dropped

from 60.02 Hz to 56.97 Hz yielding 150 Hz/sec frequency rate of change. Obviously, this relay, if used for UFLS purposes, could repeat solid-state relay erroneous operation.

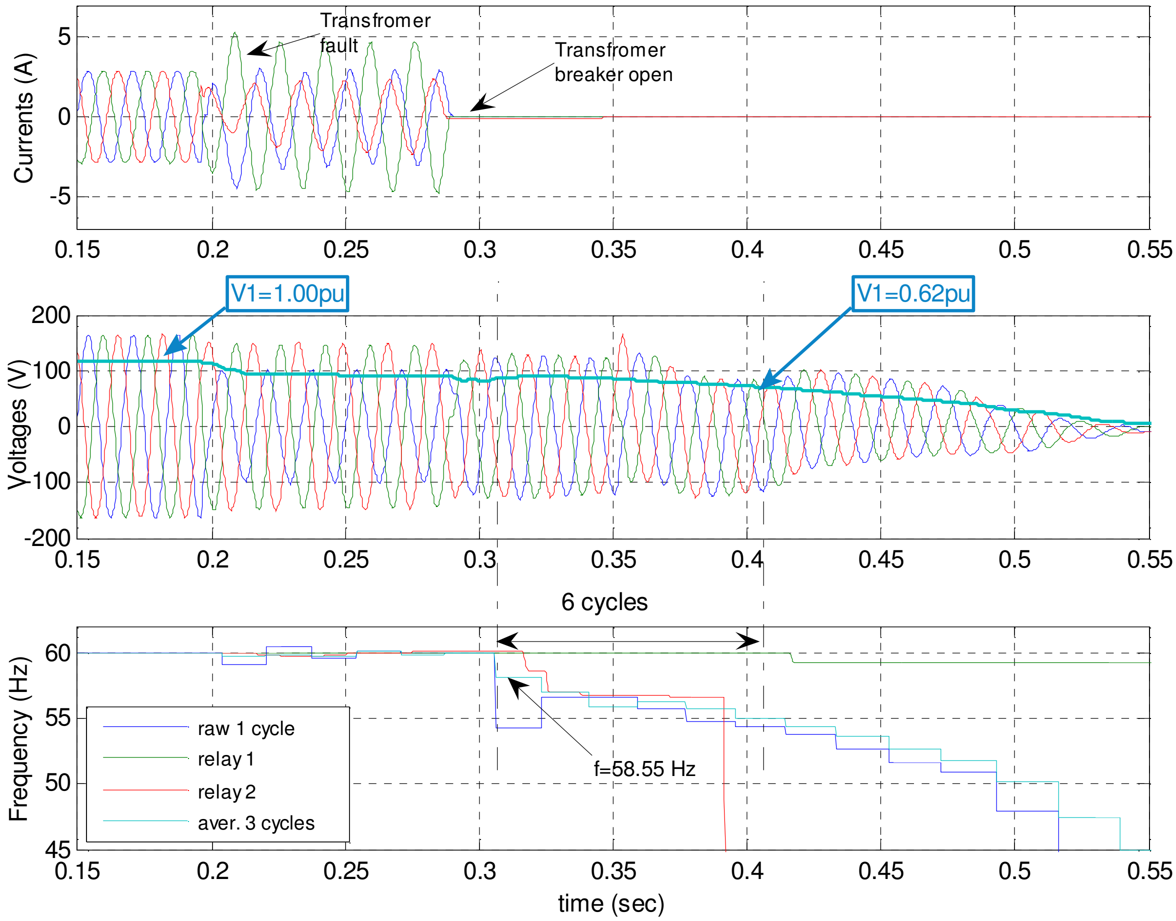

Figure 3. UFLS erroneous operation at distribution substation case 1

- On the contrary, relay 1 (green trace) would not respond to such frequency change and would rather maintain previous frequency measurement and after 7 3/4 cycles only would drop the frequency to 59.92Hz.
- Reasonable question to be asked is "Which relay frequency measurement is correct and which relay is secure for UFLS application?"
- Updated analysis on the load of distribution transformer T1 showed the typical mixture of industrial and residential customers. The customers did have compressor motors, pump motors, crane motors, but they were always there; however event like this has never happen before. The only noticeable change in transformer T1 load in the recent years was introduction of numerous small DGs (distribution generation). There were many small generators recently interconnected, primarily with PV (photo-voltaic, i.e. solar) technology. Please note that each of this distributed generation connection was analyzed, and IEEE standard 1547 was strictly followed, as well as state local rules.

- After this UFLS erroneous operation, it was verified that during small CO-GEN interconnection process, primarily two things were checked only.
    - Is the aggregate small generating facility capacity on the line section less than 15% of the line section peak load? (Significance is to secure low penetration to ensure minimum impact to the power system).
    - Is the Short Circuit Current Contribution Ratio less than 0.1? (Significance is to secure that system's short circuit duty, fault detection sensitivity and relay coordination are not impacted by small Co-Gens).
- IEEE standard and local state rules allow small co-gens as much as 2 seconds after the fault, or any type of outage to get off line
- Although it is not a scope of this paper and it is not proven, but there is strong evidence that existing rotating machines interacted with recently added small Co-Gens. This ultimately resulted in much slower than before voltage and frequency decay.

3.2. Field case #2

Distribution transformer 230/60 kV of the Source substation for 60kV distribution network in the Figure 4 on the left was cleared for relay testing. Accidently during relay tests, the only remaining in service transformer 115/60 kV supplying the radial 60 kV network grid was tripped. This resulted in de-energizing of all 60 kV network, and momentary outage to all 60/12 kV substations. The error was corrected within few seconds, when source transformer 115/60 kV was returned back into service. All substations experienced momentary outage, except Substation #1, where underfrequency relay tripped all feeders included in UFLS program, and then locked out all feeders. It took some time to return back into service these loads. This case was recorded as "sustained outage" for customers. There were two substations only in this isolated 60 kV network under UFLS schemes, substation #1 and substation #2 shown in the figure. While substation #1 has centralized substation level UFLS scheme with solid state UF relay, which tripped, another substation #2 had distributed UFLS on the feeder level with digital relays, which did not trip for exactly same conditions and UFLS settings.

Further analysis of this unexpected operation revealed the following:

- Solid state UF relay with a 58.9 Hz pickup (2nd Block), a 0.67pu undervoltage supervision (80 V secondary) and 6 cycles delay issued a UFLS trip.
- 60 kV decayed linearly in 0.34 seconds after breaker opens and at the time of the UF relay operation still was above the supervising UV blocking setting.
- Detail analysis showed similar conclusions to case #1. It took 0.33 seconds for voltage and frequency to decay to zero.
- Figure 5 below demonstrates waveforms from this event, graph 3 of this figure presents instantaneous frequency measured from 3-phase voltages (dark blue trace), averaged over 3 cycles (red trace) and frequency measurements both digital relay (green trace) which correctly didn't not respond to this frequency change.

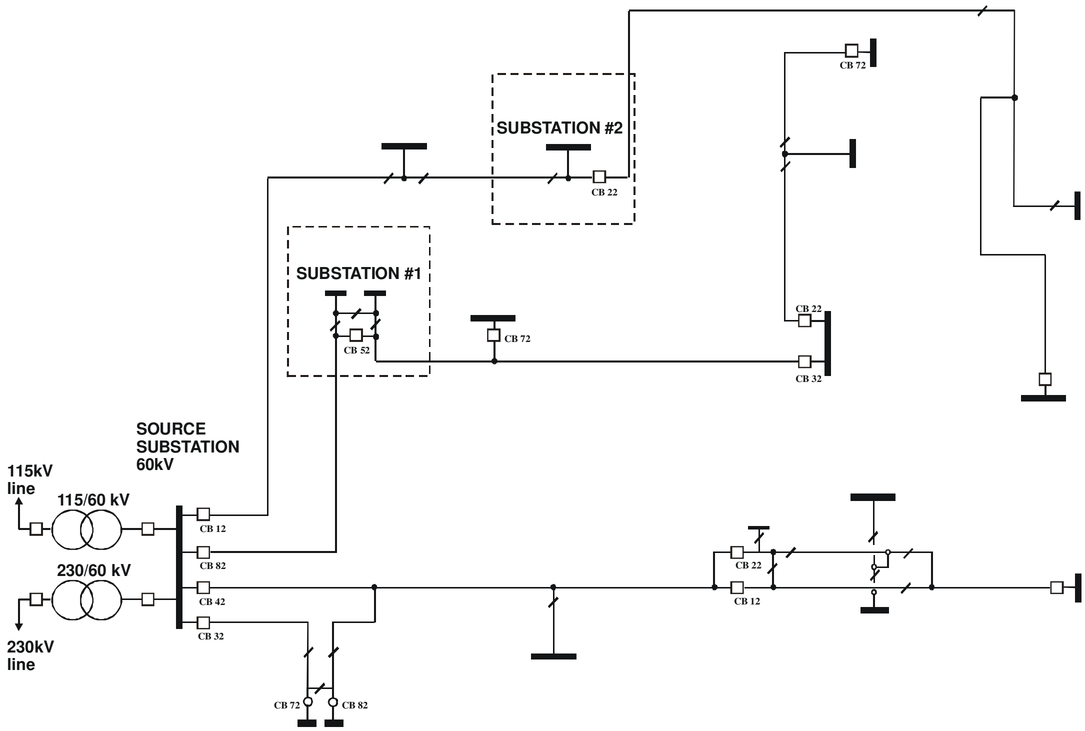

Figure 4. Distribution network topology case 2

- It can be seen again from the hypothetical 3-cycle average measurement that from the instance when frequency dropped to 58.05 Hz 1 ½ cycles after source substation breaker open up to the instance where 6 cycles delay would time out, the positive-sequence voltage remained at 0.6pu, which can be again sufficient for UFLS erroneous operation. Error in voltage measurement depends on the method used in a particular relay and accuracy, as well- it can easily can be as high as 5-7% during fast changing frequency event.
- Rate of change of frequency from hypothetical 3-cyles average frequency measurements during event was reaching 65 Hz/sec, which is unrealistic and should be rejected.

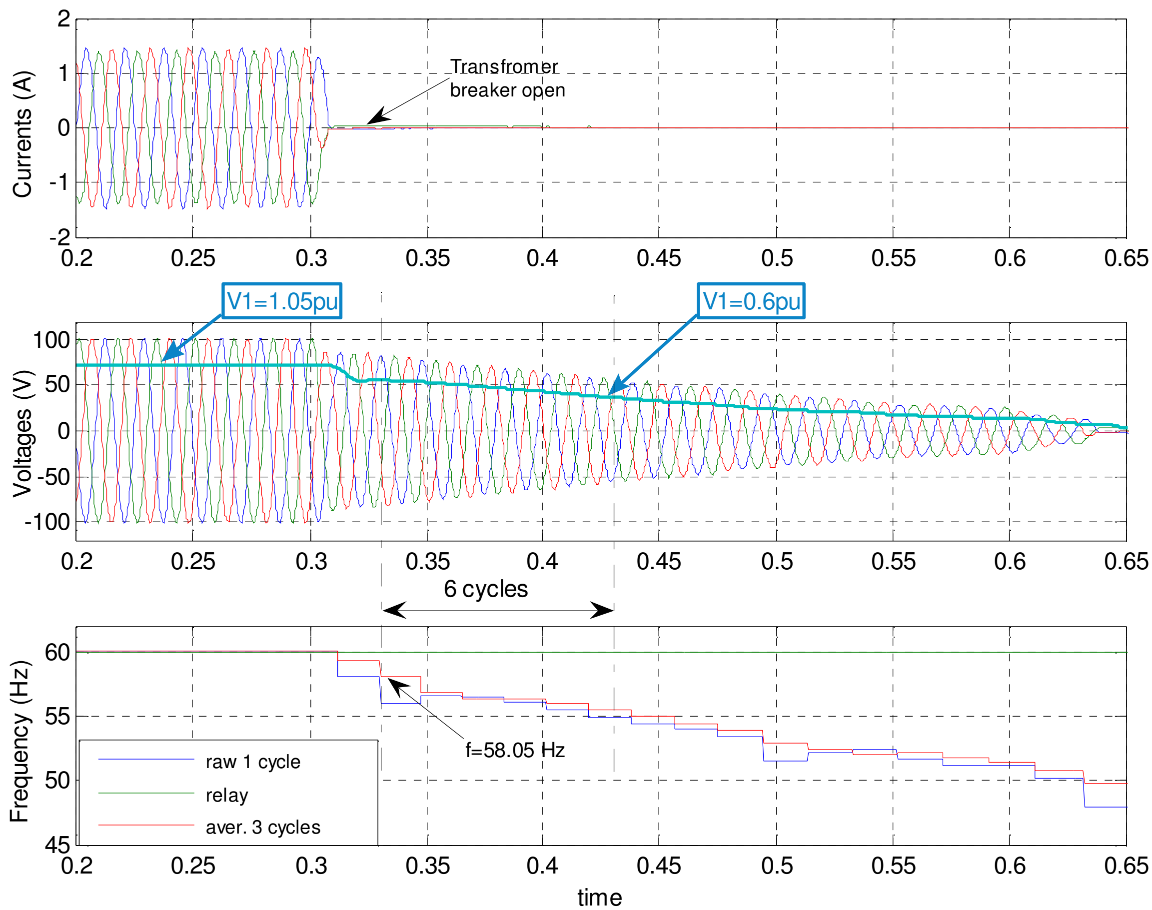

Figure 5. UFLS erroneous operation at distribution network case 2

3.3. Field case #3

Rate of change of frequency with a 1.2 Hz/sec pickup setting and 10 ms delay with decreasing frequency trend in a digital relay was used to produce controlled separation of the power system in case of fast frequency decay. For this particular application voltage AB was used to measure frequency. During line-to-ground AG fault, relay incorrectly measured frequency, which resulted in wrong rate of change of frequency measurement and operation of this element. In spite of rate of change of frequency element was secured by number of supervisory conditions, this element still operated what resulted in unnecessary separation of the power system.

Rate of change of frequency element in the relay may not have similar luxury in operating time as underfrequency element. Sometimes, which was the case in this application, the requirement for operating time are tough, 10ms only. Therefore, this element cannot have long filters or averaging and has to operate with nearly instantaneous frequency. A step change in frequency from 60.07 Hz to 59.364 Hz in 2 cycles was interpreted by the rate of change of frequency of the relay as valid in this case and resulted in operation.

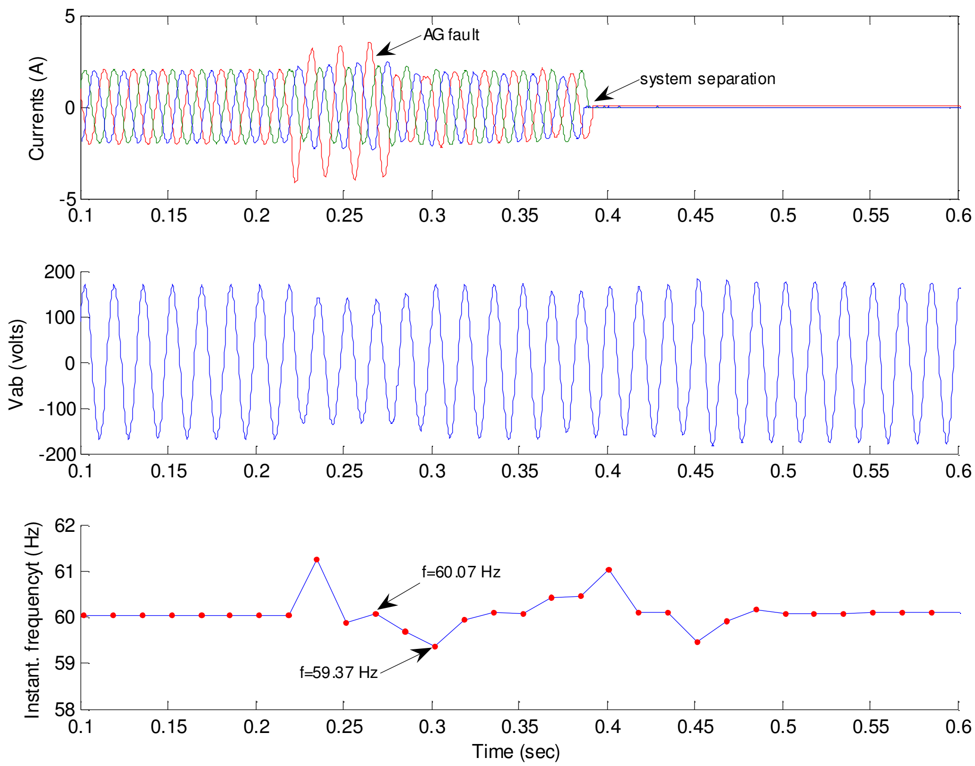

Figure 6. Rate of frequency change operation case 3.

4. Validation of the frequency measurement

As it's known and shown in the previous section, error in frequency measurement can be dramatic. While some security can be achieved at the application level through setting, supervision, voting schemes etc, but if relay fundamentally doesn't utilize rigorous validation algorithms, it may be impossible to achieve high level of security.

This section of the paper will present some techniques in a digital relay, which can prevent erroneous frequency measurement and misoperation of the frequency dependant elements.

4.1. Pre-filtering

Pre-filtering is required to remove high-frequency noise and harmonics from the signal used to measure frequency, regardless this is a single-phase signal or derived from 3-phase voltages or currents.

Figure 7 below demonstrates the effect of pre-filtering on the highly contaminated with harmonics voltage signal for frequency measurement purposes.

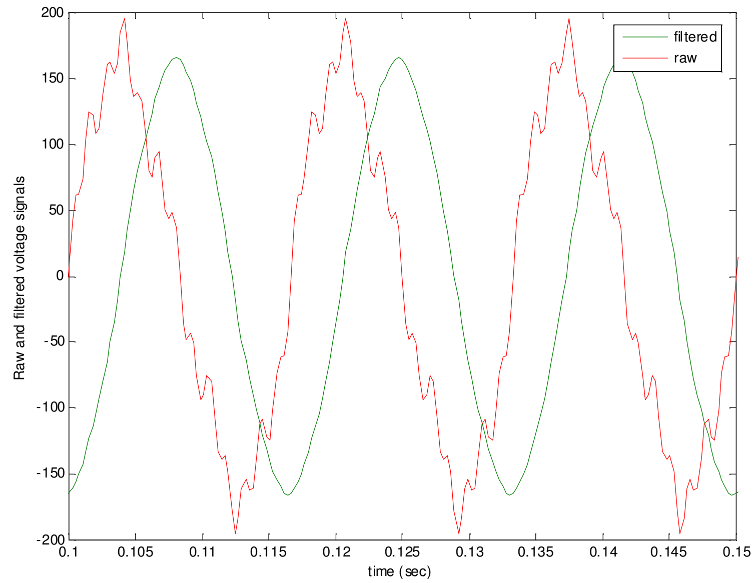

Figure 7. Effect of pre-filtering on the signal

4.2. Validating of frequency measurements and frequency change

During system transients such as faults, there may be an abrupt change in time between two zero-crossings of a given waveform. This is caused by phase anomalies, not change in frequency, and should not be mistaken for frequency changes. If relay is designed to reject such anomalies by applying extra security checks to the raw frequency and using certain amount of post-filtering when measuring the actual system frequency then algorithm is robust and secure.

4.2.1. Validating that frequency is within maximum and minimum range

We are dealing with power system frequency and we all know the possible range of the frequency.

$$F_{MAX(k)} = T_{RAW(k)} - \frac{1}{f_{MAX}} \geq 0 \qquad \text{Eq. 2}$$

$$F_{MIN(k)} = T_{RAW(k)} - \frac{1}{f_{MIN}} \leq 0$$

Where $T_{RAW(k)}$ is instantaneous frequency measurement period at the (k) index, f_{MAX} and f_{MIN} are limits for allowable frequency range, set for example at 70-90Hz and 2-5Hz respectively.

4.2.2. Validating that frequency change is within allowable range

Abrupt changes or step changes in frequency are not possible. System frequency is not an instantaneous electromagnetic value like currents and voltages, but is slower electromechanical value, reflecting mechanical inertia of the machines. "Final Report on the August 14, 2003 Blackout in the United States and Canada" prepared by "U.S.-Canada Power System Outage Task Force" indicates that Frequency declines or increases from a mismatch between generation and load on the order of about 3,200 MW per 0.1 Hertz in North America. The maximum reported frequency change during 2003 Blackout was not exceeding 10 Hz/sec.

$$\Delta f_{(k)} = f_{RAW(k-1)} - f_{RAW(k)}$$

$$F_{CHANGE(k)} = T_{RAW(k)} - \left|\Delta f_{(k)}\right| \frac{1}{f_{RATE\_MAX}} \geq 0 \qquad \text{Eq. 3}$$

where f_{RATE_MAX} is the maximum allowed rate of change of frequency, set for example at 15-20Hz/s;

This means that at 60Hz the allowable frequency change between two consecutive power cycles with 20Hz/sec threshold is limited to 20/60=333 mHz.

4.2.3. Validating that frequency change is linear

This check should ensure that frequency is decreasing or increasing linearly, without any abrupt changes (for example for three consecutive estimates) to accept the new frequency measurements.

$$F_{ACCEL(k)} = T_{RAW(k)} - \left|\Delta f_{(k)} - \Delta f_{(k-1)}\right| \frac{1}{f_{ACCEL\_MAX}} \geq 0 \qquad \text{Eq. 4}$$

where f_{ACCEL_MAX} is the maximum allowed acceleration rate, set for example at 5Hz/sec^2 .

This check ensures that the difference between two consecutive frequency changes is limited to 5/60 = 83.3 mHz at 60Hz. This and previous checks mean that under a near-linear frequency ramp, wider changes are allowed, 333 mHz but during abrupt changes it's limited to 83.3 mHz for 3 consecutive measurements:

4.2.4. Validating that frequency jitter is within frequency deadband

Random, small variations in frequency are normal, as loads come on and off and generators modify their output to follow the demand changes. Figure 8 from NERC report on the 2003 blackout below demonstrates normal frequency deviations in the power system. Therefore, if measured frequency is oscillating close to nominal or system frequency it should not invalidate frequency measurement. This can be accomplished, for example, by analyzed the raw frequency for magnitude-limited jitter by calculating the maximum and minimum value in a 5-sample window.

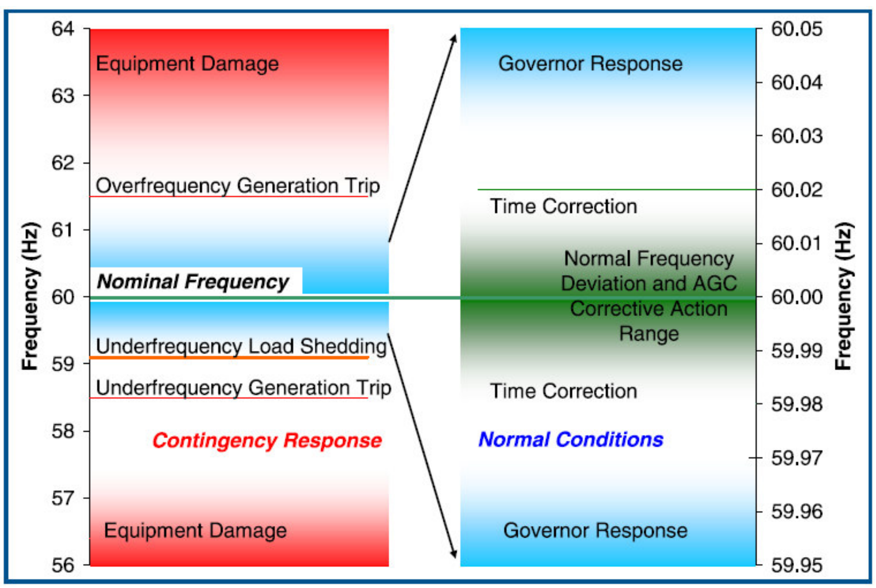

Figure 8. Normal and Abnormal Frequency Ranges

$$f_{RAW\_MIN(k)} = \min\left(f_{RAW(k)}, f_{RAW(k-1)}, \ldots, f_{RAW(k-4)}\right)$$
$$f_{RAW\_MAX(k)} = \max\left(f_{RAW(k)}, f_{RAW(k-1)}, \ldots, f_{RAW(k-4)}\right)$$
$$F_{JITTER(k)} = \left|f_{RAW\_MAX(k)} - f_{RAW\_MIN(k)}\right| \le F_{JITTER\_MAX} \quad \text{Eq. 5}$$

where F_{JITTER_MAX} can be set for example to 0.4-0.5 Hz what is in accordance with NERC report per Figure 8.

4.2.5. Security counts

The example of the frequency measurement and validation is given in the flowchart in Figure 9. Beyond security conditions described above, the magnitude of the signal is checked as well because low or fading signal is not a reliable source for frequency measurement. To enhance robustness of the algorithm, the security counts are usually applied as well. This ensures that only valid and consistent with previous measurements will be used for further processing, such as post-filtering. Because measured frequency will be used for frequency elements and also to calculate tracking frequency as well, high degree of security is required here. For example, three security counts for three consecutive frequency measurements can guarantee consistent and valid frequency measurement.

4.2.6. Post-filtering

Finally, when raw frequency measurements are validated, the post-filtering can be applied to smooth out raw frequency measurements. Filtering introduces some time delay but that delay is not so critical as the frequency is not an instantaneous value, but rather reflects a mechanical parameter of the rotating generators, which don't change abruptly. Simple averaging or IIR filter would provide good result. However, too long filter is not desirable when frequency is changing fast as this would delay frequency elements response for system conditions when they require operating quite fast as in case of UFLS schemes.

4.2.7. Frequency when measurements are invalidated

If signal is lost or faded or raw frequency measurement is invalidated, then previous valid and trusted measurement can be used. This however, cannot last forever, because first of all it's not reflecting current system frequency anymore and secondly it's providing wrong input to elements requiring frequency measurements. Therefore, if raw frequency continues to be invalid, then frequency can be reset to 0 after some time to give clear indication that frequency cannot be measured anymore or can be reset to nominal with an alarm or quality flag. Tracking frequency is reverted to the nominal in this case.

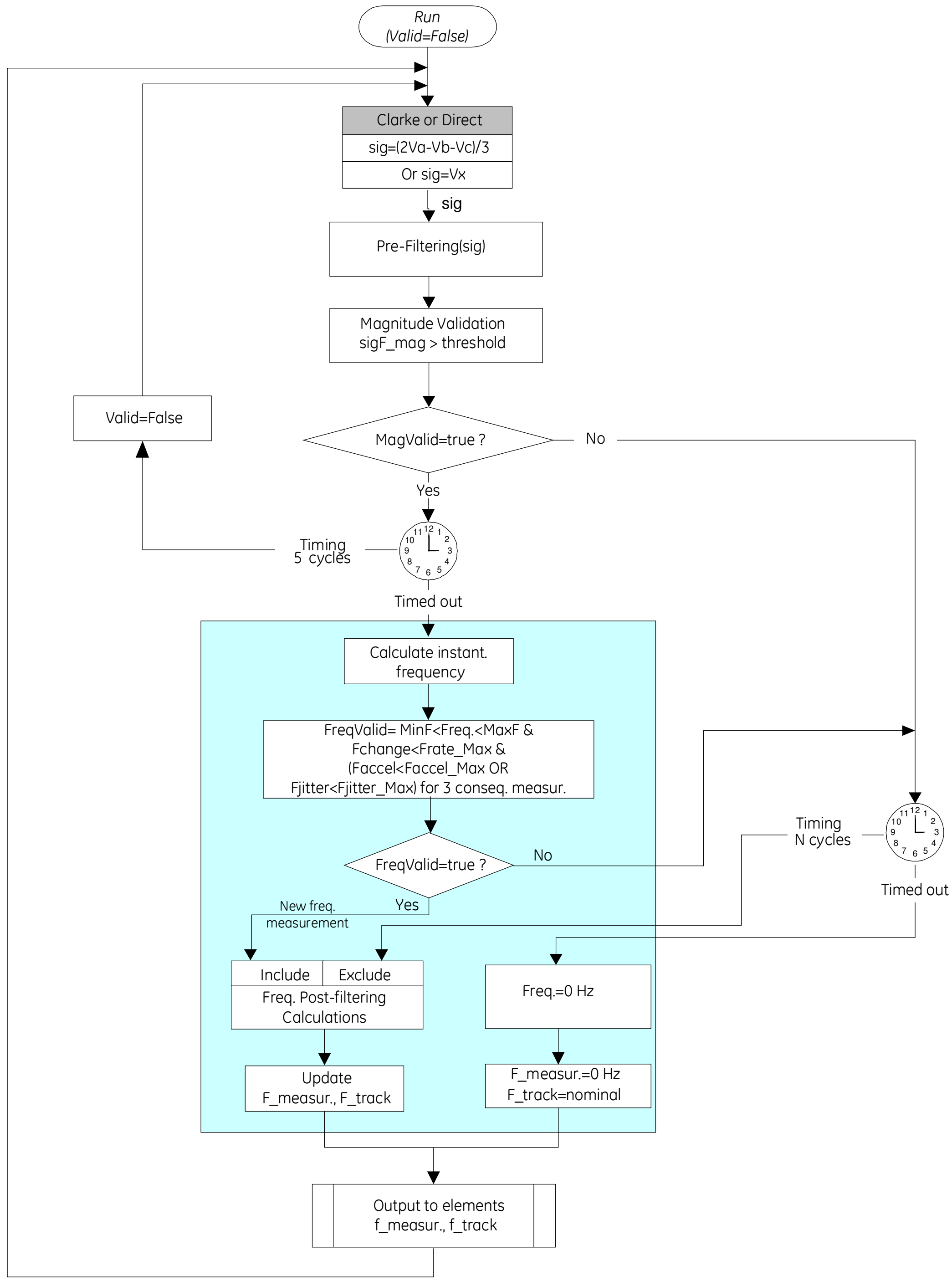

Figure 9. Example of the frequency validation and calculation process flow.

4.2.8. Example of frequency measurement and validation

Figure 10 below gives an example of validation checks described above for the case 1. It can be seen that even during fault rate of change and acceleration checks are not satisfied what results in maintaining previous frequency measurement. It also can be noticed that during voltage ring-down and fast frequency ramp, these checks were not satisfied as well and new frequency measurement were not accepted. Validation check for minimum and maximum frequency were not included in the graph as they were satisfied anyways.

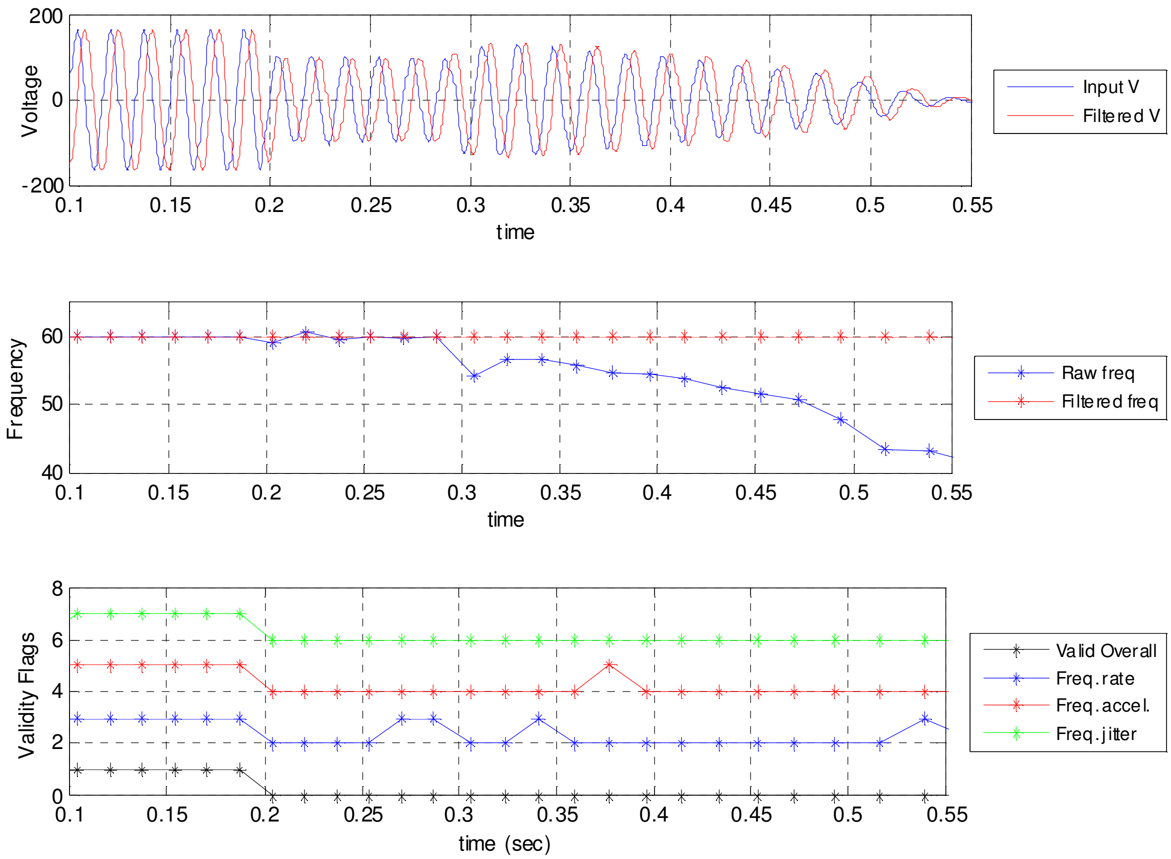

Figure 10. Example of the frequency validation and calculation for case 1.

Figure 10 below demonstrates frequency validation for the real system disturbance where part of the system was separated. One can notice that when raw frequency makes abrupt changes and is not validated therefore, the previous valid measurement is maintained. If however, raw frequency is again validated, post-filtering is then providing smooth frequency measurement. During switching events seen in the Figure as a sudden voltage change or faults, relay would not use erroneous frequency measurement and would not change measured frequency until raw frequency measurements is again validated.

Figure 11 gives another example of major North America system wide-area disturbance. It can be seen that frequency is always validated through this because such frequency change truly reflect system mechanical and electrical behavior.

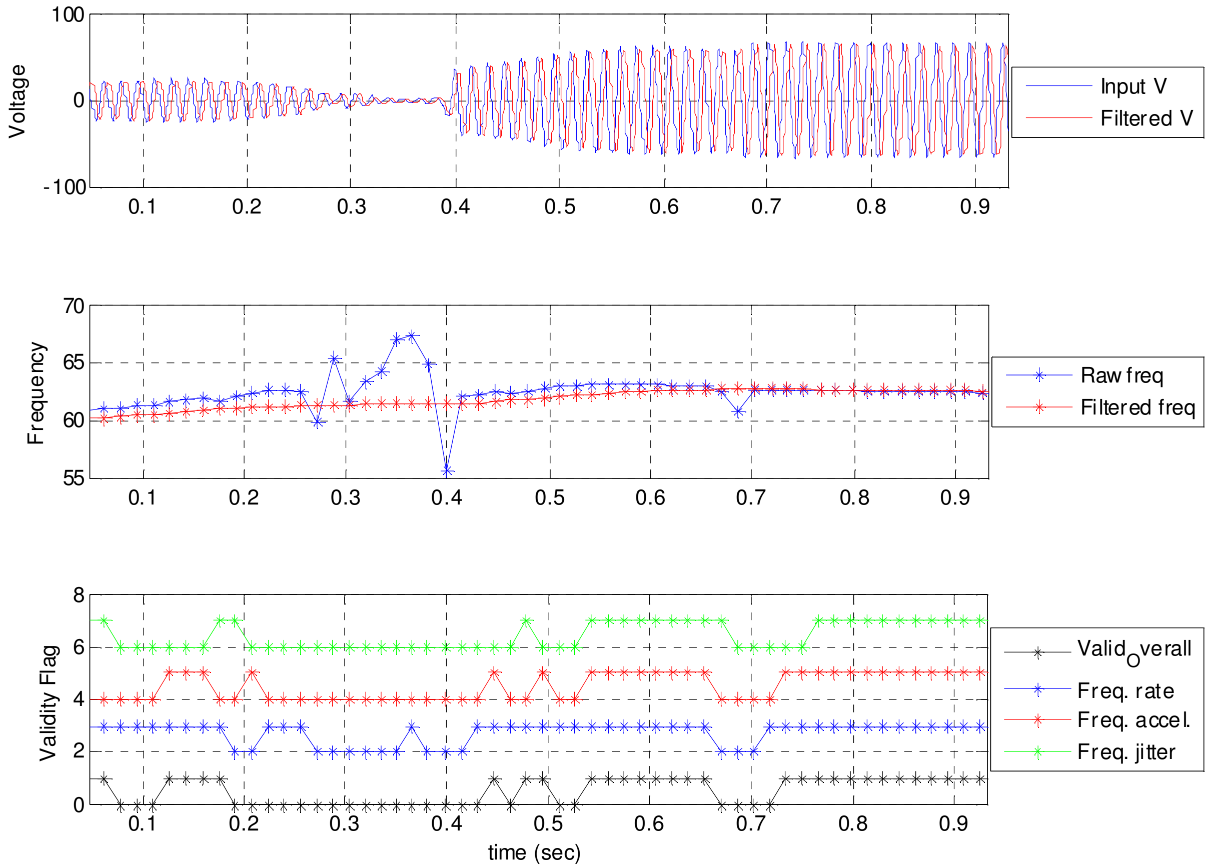

Figure 11. Example of the frequency validation for real-life system wide-area disturbance.

4.2.9. Securing the UF relay

Traditional methods of securing frequency relays are well known and described in [3].

These methods for secure and dependable UFLS scheme design are as follows:

1. Voltage supervision
2. Current supervision
3. Directional power supervision.
4. Redundant frequency relays fed from multiple voltage sources in a voting scheme.
5. Adding extra delay where motor loads are significant

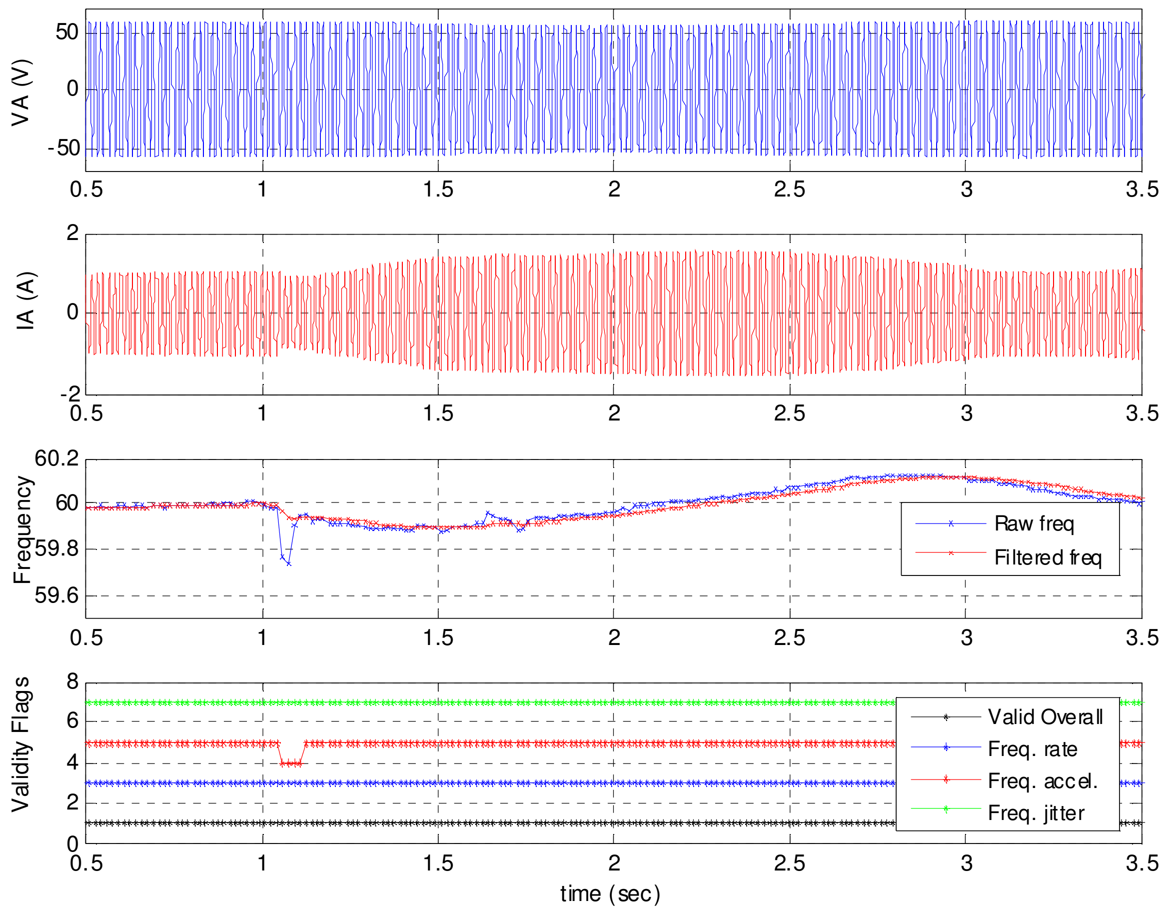

Figure 12. Example of the frequency validation during major North America system wide-area disturbance.

6. Using rate of change of frequency to supervise underfrequency element. If rate of change of frequency higher than 10Hz/sec is detected than extra delay can be added or simple supervision can be implemented.
7. Selecting frequency relays with different operating principle or from different manufacturers.
8. Using IEC 61850 or other channels to monitor position of remote breaker, feeding distribution area as shown in case 2 above. Also IEC 61850 can be used to share status and pickup of frequency relay at the adjacent buses.

5. Conclusions.

Fast penetration of distributed generation into distribution networks and smart grid initiatives are jeopardizing security of frequency relays and particularly involved in UFLS schemes. In spite of IEEE C37.117 is giving a guidance of securing UFLS schemes, slower voltage decays are more likely to happen now and in the future making undervoltage supervision is less reliable than before.

This paper presented field cases where UFLS relays operated incorrectly and gave some insights of frequency measurements in digital relays. It also presented some examples of how digital relays can secure frequency measurements for such critical elements as underfrequency, overfrequency or volts/hertz relay elements.

Frequency relays are usually tested in the lab using test sets providing smooth frequency ramp. In the real life, frequency relays are exposed to system conditions, which can force them to make a wrong measurement and/or decision Frequency relay could be evaluated before use with either real life system waveforms during system disturbances or simulated using appropriate software programs. It is quite often that utility is qualifying transformer or line relays using simulation software, but this is not common for frequency elements in relays.

6. Bibliography and references

Miroslav Ristic has been with System Protection of Pacific Gas and Electric Company for almost ten years. Prior to this, he was an Application Consultant with GE Multilin and an Application Engineer with GE Large Motors and Generators. He gained his practical experience on the Electric Power System of Yugoslavia working in protection. He has served on the Board of Electric Power Transmission Network of Yugoslavia, and the Board of Power Stations and Electricity Production of Yugoslavia. He has a B.Sc.E.E. degree, and more than 25 years of experience in relay protection. He holds a P.Eng license in Ontario/Canada, and a P.E. license in California/USA.

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