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Voltage-Based Frequency Synchronization for Phasor Measurements in Microgrid Protection

Jorge I. Cisneros-Saldana
Department of Electrical Engineering
Texas A&M University
College Station, TX, USA
jicisneros@tamu.edu

Miroslav M. Begovic
Department of Electrical Engineering
Texas A&M University
College Station, TX, USA
begovic@tamu.edu

***Abstract*—The accurate measurement of current phasors is crucial for the reliable and effective protection of microgrids. However, the presence of harmonics and variations in the fundamental frequency due to the integration of inverter-based resources (IBRs), can lead to errors in current phasor measurements in islanded microgrids. In this work, we propose a novel approach to current phasor measurement in microgrid protection that utilizes voltage-based fundamental frequency stabilization. The proposed method is based on the use of voltage measurements to synchronize a set of variable frequencies, and three-phase signals to track changes in the fundamental frequency and adjust the current phasor measurements accordingly. Simulation results demonstrate that the proposed method is effective in reducing errors in current phasor measurements caused by variations in the fundamental frequency, at the same time it can segregate between a fault and a tap load. The proposed method has the potential to enhance the performance of microgrid protection systems and ensure the reliable operation of microgrids.**

***Index Terms*—Distributed generation (DGs), fault-ride through, inverter interfaced distributed energy resource (IIDER), Microgrid, Protection schemes, Phasor measurement units (PMUs).**

I. Introduction

In recent years, microgrids have emerged as a promising solution to meet the increasing demand for a reliable and sustainable energy supply. Microgrids are self-contained systems that can operate independently or are connected to the main grid and are typically composed of distributed energy resources such as solar panels, wind turbines, and battery storage. One of the key challenges in the design and operation of microgrids is to ensure their reliable and safe operation, particularly in islanded mode when they are disconnected from the main grid. Protection systems are crucial in preventing faults and ensuring the stable operation of microgrids..

Current phasor measurement is an essential part of microgrid protection systems. However, the integration of inverter-based resources (IBRs) into microgrids can introduce harmonics and variations in the fundamental frequency, which can cause errors in current phasor measurements. Existing methods to mitigate these errors involve complex filtering and processing algorithms that may be impractical for real-time operation. In this work, we propose a novel approach to current phasor measurement in microgrid protection that utilizes voltage-based fundamental frequency stabilization.

The proposed method utilizes voltage measurements to synchronize on a set of variable frequencies and three-phase signals to track changes in the fundamental frequency and adjust the current phasor measurements accordingly. Simulation results demonstrate that the proposed method effectively reduces errors in current phasor measurements caused by variations in the fundamental frequency. The results also demonstrate the ability of the proposed scheme to distinguish between a short circuit fault and a typical tap load within the protection zone. The proposed method can potentially enhance the performance of microgrid protection systems and ensure the reliable operation of microgrids. This paper provides a relay technique case study for correcting current measurements in islanded microgrids under non-nominal frequency operation, a microgrid benchmark is also proposed. The paper is organized as follows; Section II Identifies the problem, Section III Proposes a microgrid model, Section IV Proposes a new protection scheme, Section V presents thorough simulation results, and Section VI paper conclusion.

II. Original Problem

A. Periodicity in Phasor Measurements

While conventional Discrete Fourier Transform (DFT) offers simplicity and precision in steady-state conditions, when the signal frequency is temporarily or permanently off-nominal, the phasor estimation accuracy is affected when the sampling frequency is fixed and keyed to the nominal frequency. This can happen in practice since the frequency constantly varies around the nominal value in a very narrow range of $\pm 0.5Hz$. The situation is more pronounced in islanded systems, particularly in inverter-only microgrids where frequency excursions may reach $\pm 10Hz$ or the system frequency can settle to a frequency different from the nominal one. In practice, however, the frequency deviation is controlled and brought back to a value close to the nominal [1], [2], [3], [4].

Nsengiyaremye et all. [5] present that the exactitude of the protection scheme developed directly depends on the nominal frequency, due to DFT (Discrete Fourier Transform) dependence. After thoroughly testing a wide range of off-nominal frequencies $(45Hz, 49Hz, 51Hz, 55Hz)$ it was further verified and identified that the system phasor calculations only operate accurately with a nominal frequency of $50Hz$ [6].

Having a permanent frequency deviation of 0.0001 Hz causes a change in phase angle from 0 to 2π radians in just under three hours. In such conditions, the current phase angle becomes a periodic signal with a frequency equaling Δf. This means that accurately measuring the current/voltage phase angle using conventional recursive DFT is very challenging in practice even under slight frequency deviation [7].

Recognizing that an islanded microgrid can operate at off-nominal frequency [8], a change in frequency values may not accurately reflect a disturbance as it would if the system was operating at a nominal frequency. Then such disturbance cannot be detected based on the phase angle slope value.

To correct this, it is proposed to calculate the Frequency and Fundamental Component of a three-phase signal and recalculate the phase angle based on this frequency. Ideally, the frequencies of voltage and current will be the same but are not necessarily in phase. When the phase angle difference between the voltage and the current does not equal zero, the maximum of the current does not occur when the driving voltage is at its maximum. In practice, This is because in the case of distribution lines, due to receiving end load and line inductance, the current lags the voltage in the time phase but remains in almost constant frequency. The allowable range for frequency variation is $49.9 - 50.1Hz$. Also, there will be harmonic voltages and currents at harmonic frequencies.

But power transmission or power loss can occur only with a voltage and current of the same frequency. For that reason, the voltage waveform can usually be approximated by the fundamental frequency of voltage. If this approximation is used, current harmonics produce no effect on the real power transferred to the load.

B. *Voltage and Current Off Frequency Operation*

In a three-phase circuit with an inverter as a voltage source converter (VSC), the frequency of the voltage and the current may be different due to several factors. The frequency of the voltage produced by the inverter is determined by the switching frequency of the power electronics, which is typically much higher than the system frequency. This means that the inverter can generate a voltage with a frequency that is different from the frequency of the AC power system. The frequency of the current flowing through the circuit is determined by the load impedance and the voltage frequency. Since the load impedance is not constant and may vary with the operating conditions, the current frequency may also vary. The VSC can control the amplitude and phase of the voltage it generates, but it cannot directly control the frequency of the current flowing through the circuit. This means that even if the VSC generates a voltage with a specific frequency, the current frequency may be different due to the load impedance.

For Inverter operation, the output voltage Total Harmonic Distortion (THD) factor, under worst operating conditions, is given to be $\leq 5\%$. Nevertheless, when there is a non-linear component in the grid, typically it will end up with harmonics of the driving frequency. It is generally the case that voltage harmonics are indeed small compared to current harmonics. Hence, Non-linear loads can further complicate the relationship between voltage and current frequency in a three-phase circuit with inverters operating as grid forming such as VSC. These types of loads are characterized by their nonlinear current-voltage relationship, which means that the current flowing through them is not proportional to the voltage applied. These Non-linear loads can produce harmonic currents, which are currents with frequencies that are multiples of the fundamental frequency.

III. Proposed Microgrid Model

We created a modified microgrid version of the IEEE 4-bus system and propose this benchmark microgrid for testing protection schemes in grid-connected mode of operation. This modified microgrid includes distributed energy resources such as Photovoltaic (PV) systems in a grid-forming mode of operation to closely resemble a real-life implementation. The microgrid was tested for various types of short circuit faults, including single-phase, phase-to-phase, phase-to-phase with ground, three-phase, and three-phase with ground. The fault was represented by red lightning in the middle of Line 1, as shown in Fig.1.

We used Matlab/Simulink to model the 4 Bus microgrid system, shown in Fig.1. It has 4 DGs (Distributive Generation) with different types of loads. The distribution lines are modeled as short type in Medium Voltage (MV) and the Distributive Energy Resources (DERs) and Loads in Low Voltage (LV), representing a real-life topology seen in a residential area. The DER consists of solar PV with IBr in grid forming mode of operation or VSC based on [9] with droop control, voltage restoration, and frequency restoration based on [11], voltage and current instantaneous limiters for protection of the semiconductors against faults. The microgrid was tested for all types of short faults in an islanded mode of operation, and the most important values for microgrid parameters are listed in Tab.I.

TABLE I: 4 Bus Microgrid Parameters

Main Components	Parameter Specification
Distribution Line (MV) & Load (LV)	$4.1kV/240V$, $50Hz$
Distributive Generation (DG) in LV	$240V/120V$, $50Hz$
DC Link **Distributive Energy Resource (DER)** **Grid Forming in LV**	$750V$ $30kW, 240V/120V$ VSC, $50Hz$
IBr Switching Frequency	$5000Hz$
IBr LCL Filter	$L = 0.0073H$ $C = 0.00027631F$ $L = 0.000485H$
Transformers(TR) (Y-Y) (MV/LV)	$30kVA$, $4.1kV/240V$, $50Hz$
Distribution Line (L) **Short Type Line**	$4.1kV$, $500m$ $R = 0.0805Ohm/km$ $X = 0.0950Ohm/km$
Protection Relay Sampling Rate **Protection Type**	$1000Hz$ $Differential$

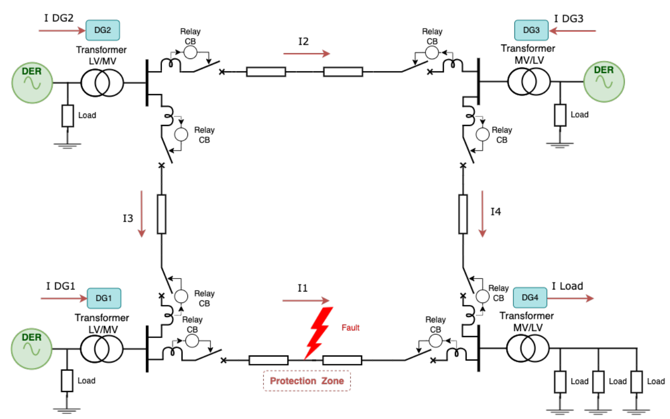


Fig. 1: Microgrid 4 Bus System - Islanded

IV. Proposed Protection Model

The proposed model for the measurement of current phasors in microgrid protection is based on the phase-locked loop (PLL), which uses voltage measurements to obtain the frequency and ωt of the system, to further calculate the positive sequence components of the three-phase current measurements, magnitudes and phase angles.

Where:
ω is the angular frequency in $radians/seconds$.
ω is equal to $2\pi f$, f is the frequency in $hertz(Hz)$.
t is the time in $seconds$.

To identify a shift in the direction of the current flow, an ingenious yet straightforward strategy was implemented, which involves maintaining the pre-fault angle as the reference point and evaluating the cosine of the angle. Consequently, any modification in direction is reflected by a change in the sign of the cosine value. These phase angles are used to compare the positive sequence cos of the angle sign at both ends-of-the-line to detect a change of current directions, as proposed by [5]. The principle is shown in Fig. 3. This is a differential relay type technique, The principle of differential protection is commonly used in microgrids as it satisfies the technical prerequisites for effective protection [12]. This approach remains immune to non-sensitive bidirectional power flow, varying current levels, the presence of numerous distributed energy resources (DERs) within the microgrid, different microgrid operation modes, and weak power inputs [10].

A. Phase-Locked Loop for Frequency and Phase Angle

In the proposed model, voltage measurements are used to obtain the frequency and phase angle of the system using a phase-locked loop (PLL). The PLL is used to track the variations in the frequency and phase angle of the system caused by the integration of inverter-based resources (IBRs), and non-linear loads. The PLL output is then used as a reference signal for the current phasor measurement and as a synchronization device. The three (3ph) PLL is designed to monitor and synchronize the frequency and phase of a sinusoidal three-phase voltage signal by an internal frequency oscillator. The control system continuously modifies the frequency of the internal oscillator to ensure that the phase difference remains at 0. The principle is shown in Fig. 2 based on [13]. The PLL operating principle deals with the input three-phase signal, which undergoes a dq0 rotating frame transformation, utilizing the angular velocity of an internal oscillator. The resulting quadrature axis from park transformation represents the phase difference between the Voltage abc signal and the rotating frame of the internal oscillator. This quadrature axis is then filtered through a Variable Frequency block. To maintain a phase difference of zero, a Proportional-Integral-Derivative (PID) controller equipped with automatic gain control (AGC), operates on a controlled oscillator. The output of the PID controller, which corresponds to the angular velocity, undergoes additional filtration and conversion into the frequency in hertz, for our case study the Grid nominal frequency is $50Hz$.

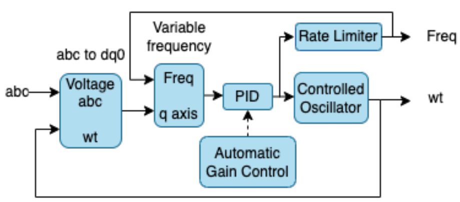


Fig. 2: Voltage Based PLL (Phase locked loop)

B. Positive-Sequence Recursive DFT Current Phasor Measurements

The proposed model also includes a positive sequence phasor current measurement. Whereas the equivalent scheme uses the synchronized frequency and phase angle obtained from the voltage measurements as a reference signal and applies it to the current measurements. The estimation of phasors relies on the utilization of a discrete Fourier transform (DFT) across the complete cycle, chosen for its deterministic nature and ability to eliminate harmonics. The phasor estimates are updated over time using a recursive full-cycle technique (R-DFT), ensuring a consistent phase angle during steady-state conditions reducing calculation time, guaranteed by the voltage frequency reference input. The R-DFT current phasor at the $(r+1)^{th}$ instant can be calculated as:

$$I_{r+1} = [I_r + \frac{\sqrt(2)}{N} * (i_{N+r} - i_r)] * e^{j\frac{2}{N}\pi} \tag{1}$$

Where:
I_{r+1} is the new current phasor at the fundamental frequency.
I_r is the earlier current phasor at the fundamental frequency.
N is the number of samples over a cycle of the fundamental frequency.
i_{N+r} is the new current sample.
i_r is the outgoing current sample.
$e^{j\frac{2}{N}\pi}$ is the complex operator.

Subsequently, the positive sequence phase current is employed, with the positive sequence fault current calculated as the summation of fault currents. In microgrids where Inverter-Based Resources (IBRs) dominate, the effectiveness of directionality features that do not rely on positive sequence currents may be compromised, particularly in the presence of unbalanced fault conditions [14]. The Positive-Sequence block calculates the positive-sequence component, which includes the magnitude and phase, of the input 3 signal. The positive-sequence component of a three-phase current signal is calculated as:

$$I_p = \frac{1}{3} * (I_a + \alpha * I_b + \alpha^2 * I_c) \tag{2}$$

Where:
I_p is the current positive-sequence component at the fundamental frequency.
I_a, I_b, I_c are current phasors at fundamental frequency.
$\alpha = e^{j\frac{2}{3}\pi}$ complex operator.
$\frac{2}{3}\pi\ rad$ (radians) = $120°$ (degrees), is the phase angle.

C. Results in the frequency domain

The proposed model in Fig. 3 has several advantages over existing methods for current phasor measurement in microgrid protection. Firstly, it is based on a simple and efficient PLL approach that can be implemented in real-time. Secondly, it is effective in reducing errors in current phasor measurements caused by variations in the fundamental frequency. Simulation results will be presented in the next section to demonstrate the effectiveness of the proposed model.

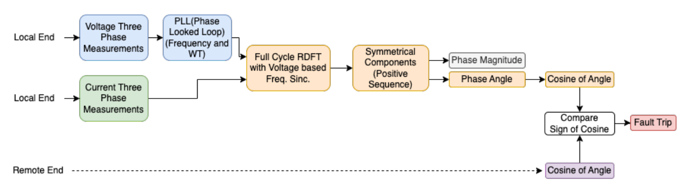


Fig. 3: Fault Detection Principle

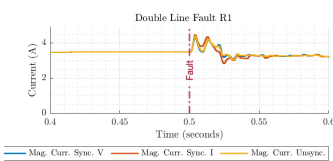
The results of the proposed model are presented in the frequency domain in terms of the phase magnitude and phase angle. The proposed model effectively reduces errors in current phasor measurements caused by variations in the fundamental frequency, leading to more accurate and reliable microgrid protection schemes that use DFT to go from the time domain to the frequency domain.

V. Simulation Results

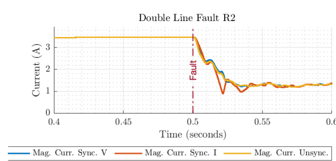
The model used consists of a 4-bus model in ring type of connection where 3 buses use VSC as generation source with local load, and 1 bus with entirely different kinds of loads, to share the load. The following plots show the difference between phase angle response after DFT transformation comparing the current response at each end of the line under an LLG(Line to Line and Ground) fault. Using the method described above, synchronizing on a set of variable frequencies, three-phase sinusoidal signals: Voltage-based synchronization, Current-based synchronization, and nominal off-frequency response as a periodic signal of the phase angles.

The results show the comparison of an operational grid with the methodology proposed in contrast to the methodology without the voltage-based frequency proposed adaptation, and also the current-based frequency synchronization. It is at the same time clear that Synchronizing the frequency of R-DFT current measurements with the voltage signal characteristics ensures a stable phase angle response, eliminates periodicity, and facilitates the detection of load variations and faults. The use of voltage measurements for synchronization enhances detection capabilities in comparison to current synchronization and unsynchronized or frequency-mismatched measurements. All types of faults were studied, Line-line (LL) in Fig. 4, Line-line-ground (LLG) in Fig. 5, Line to Line to Line (LLL) in Fig. 6, Line-ground (SLG) in Fig. 7 and Line-line-line-ground (LLLG). Where the short circuit fault that happens at $0.5sec$ of simulation is presented as a red dotted line, the blue line corresponds to the positive sequence voltage-based frequency synchronization method, while the orange line represents the positive sequence current-based frequency synchronization approach method used for validation. In contrast, the yellow line depicts the positive sequence response obtained without synchronization under off-nominal frequency conditions, as initially presented in [5]. The upper figure showcases the magnitude response, providing insight into the amplitude characteristics of the measured quantities. Moving on to the middle figure, presents the phase angle response, offering valuable information about the phase shift and relative timing between the signals. Lastly, the lower figure displays the cosine of the angle, enabling a clearer visualization of the phase direction relationship and its consistency.

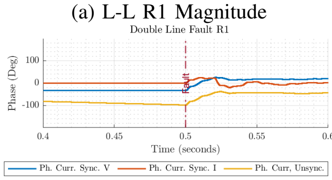
A tap load response was analyzed in Fig. 8, where a load was added at $0.6sec$ of simulation on distribution line 1, within the protection zone of the differential relay technique. Consistent with the case study, the response curves are depicted in each of the figures. Where the blue line corresponds to the voltage-based synchronization, the orange line represents the current-based synchronization, and the yellow line illustrates the response obtained without synchronization under off-nominal frequency, typically observed in islanded microgrids. These figures provide a comprehensive overview of the different synchronization methods for differential relay studies, allowing for a direct comparison of their performance in terms of magnitude, phase angle, and cosine of the angle.



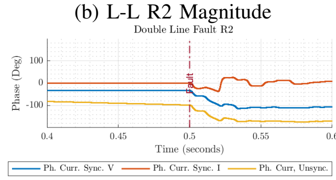
(a) L-L R1 Magnitude



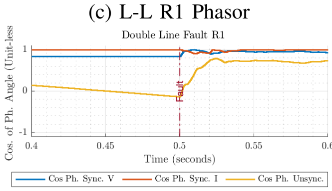
(b) L-L R2 Magnitude



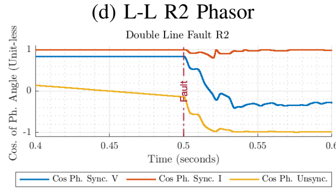
(c) L-L R1 Phasor



(d) L-L R2 Phasor



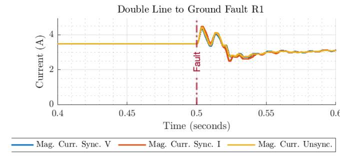
(e) L-L R1 Cosine



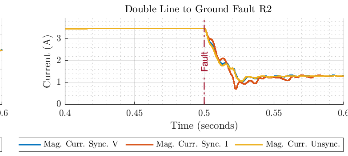
(f) L-L R2 Cosine

Fig. 4: L-L Fault Response

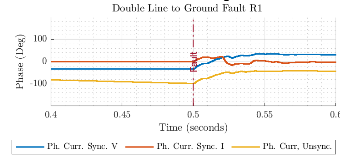
In the simulation figures, we present a comparative analysis of the phase angle response at both ends of line 1, focusing on the protection zone under study. The methodology employed follows a differential relay response approach, wherein



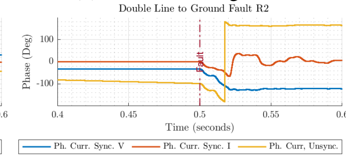
(a) L-L-G R1 Magnitude



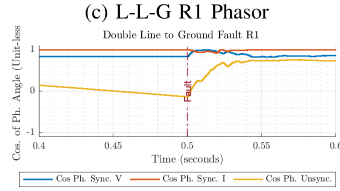
(b) L-L-G R2 Magnitude



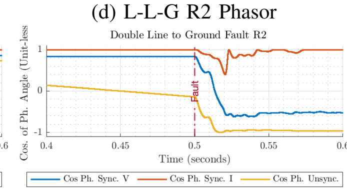
(c) L-L-G R1 Phasor



(d) L-L-G R2 Phasor

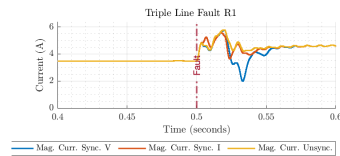


(e) L-L-G R1 Cosine

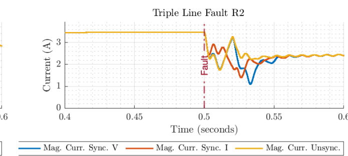


(f) L-L-G R2 Cosine

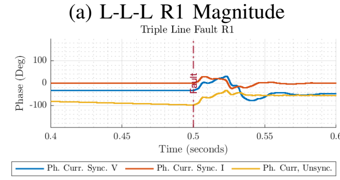
Fig. 5: L-L-G Fault Response



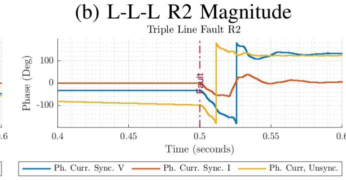
(a) L-L-L R1 Magnitude



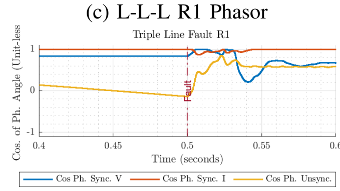
(b) L-L-L R2 Magnitude



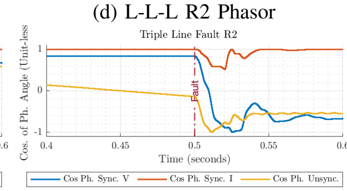
(c) L-L-L R1 Phasor



(d) L-L-L R2 Phasor



(e) L-L-L R1 Cosine

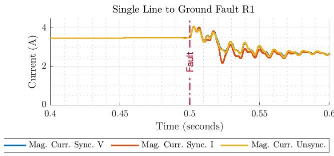


(f) L-L-L R2 Cosine

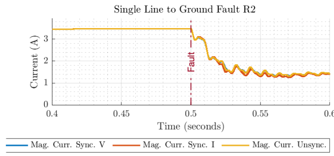
Fig. 6: L-L-L Fault Response

a comparison is made between the two ends of the line. The measurements encompass three-phase voltage and current readings. The response curves are depicted in each of the figures, with distinct color coding for clarity. In the case of the unsynchronized R-DFT method (yellow line), the presence of periodicity in the sinusoidal response is clearly evident. Conversely, when employing the proposed synchronization methods, the periodicity is effectively eliminated, resulting in stable and reliable phase angle responses. This is observed through the consistent behavior exhibited by the blue and orange lines.

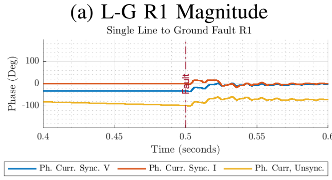
By comparing the different synchronization approaches, it becomes apparent that the Voltage Synchronization method (blue line) yields a more favorable and precise response, enabling accurate monitoring and detection of phase angle variations. The Current Synchronization method (orange line) also demonstrates improved performance compared to the unsynchronized R-DFT method, albeit with slight differences in the response characteristics. The results also show that the proposed method is effective for segregating a fault from a tap load, which is very critical for microgrid operation, avoiding unnecessary tripping.



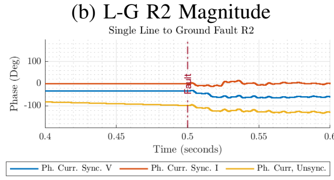
(a) L-G R1 Magnitude



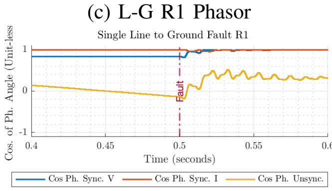
(b) L-G R2 Magnitude



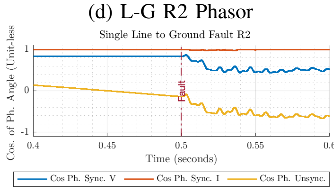
(c) L-G R1 Phasor



(d) L-G R2 Phasor

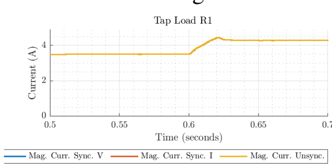


(e) L-G R1 Cosine

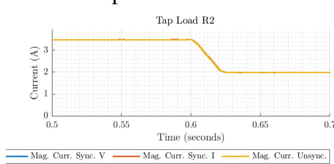


(f) L-G R2 Cosine

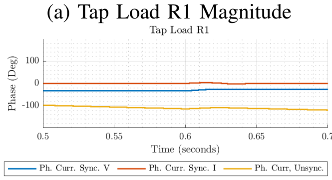
Fig. 7: L-G Fault Phase Response



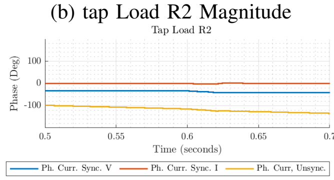
(a) Tap Load R1 Magnitude



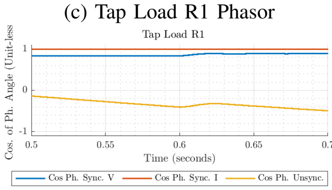
(b) tap Load R2 Magnitude



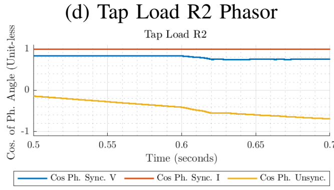
(c) Tap Load R1 Phasor



(d) Tap Load R2 Phasor



(e) Tap Load Cosine



(f) Tap Load Cosine

Fig. 8: Tap Load Response

VI. Discussion and Conclusion

The frequency of the voltage in a three-phase circuit with an inverter as a VSC may be different from the frequency of the current due to the switching frequency of the inverter, the varying load impedance, and the inability of the VSC to directly control the current frequency. This new proposed scheme offers inherent immunity to harmonics and noise generated by power electronics, non-linear loads, transients, and measurement errors.

When performing recursive Discrete Fourier Transform (DFT) measurements without synchronizing the frequency to the nominal value, the phase angle response can be affected by mentioned issues among them periodicity response issues, particularly when dealing with non-linear loads. This means that the phase angle may exhibit variations at regular intervals, which can affect the accuracy of the measurements. Causing false tripping by the method proposed in the microgrid. However, when the frequency for recursive DFT current measurements is synchronized precisely to the same current signal, the phase angle variations disappear, and the periodicity issue is resolved. This synchronization ensures that the measurements align precisely with the frequency of the current signal being analyzed.

In this context, it is important to note that the absence of variations in the phase angle does not necessarily indicate the absence of other problems, such as load and tap load additions or short-circuit faults. These issues may require further investigation using different techniques or measurements to identify and address potential problems in the electrical system. Since they are overseen by the method.

When voltage measurements are used for synchronizing the frequency for recursive DFT measurements, the ability to detect loads, tap loads, and faults is enhanced. This suggests that the voltage measurements provide a more reliable frequency reference for synchronization, allowing for the accurate identification of load variations and fault conditions with linear and non-linear loads. The results show how the cosine of the angle response is directly influenced by the phase angle response, and show how the yellow line response, based on voltage-based R-DFT has better resolution.

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References

[1] A. G. Phadke and J. S. Thorp, "Synchronized phasor measurements and their applications Springer Science+Business Media, LLC, New York, 2008. [Online] Available: Springer Ebook.

[2] C. Zhang, S. Zheng, J. Zhou, H. Qin, J. Zhao and D. Lv, "Key Technology of Multifunctional Wide Area Synchronous Phasor Measurement Terminal Device in Distribution Network," 2020 2nd ICAML , Changsha, China, 2020, pp. 17-22, doi: 10.1109/ICAML51583.2020.00013.

[3] S. Tian, K. Li, H. Fang, S. Liu, S. Wei and Y. Fu, "Situation Forecasting Method for Distribution Network Based on Phasor Measurement Unit," 2019 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Macao, China, 2019, pp. 1-5, doi: 10.1109/APPEEC45492.2019.8994472. [13]

[4] S. Hampannavar, D. B and S. M, "Micro Phasor Measurement Unit (PMU) Placement for Maximum Observability in Smart Distribution Network," 2021 IEEE PES/IAS PowerAfrica, Nairobi, Kenya, 2021, pp. 1-5, doi: 10.1109/PowerAfrica52236.2021.9543234.

[5] J. Nsengiyaremye, B. C. Pal and M. M. Begovic, "Microgrid Protection Using Low-Cost Communication Systems," in IEEE Transactions on Power Delivery, vol. 35, no. 4, pp. 2011-2020, Aug. 2020, doi: 10.1109/TPWRD.2019.2959247.

[6] M. Adamiak, W. Premerlani, and B. Kasztenny. "Synchrophasors: Definition, Measurement, and Application", GE General Electric, pp. 57-62.

[7] J. Nsengiyaremye, B. C. Pal, and M. M. Begovic, "Low-Cost Communication-Assisted Line Protection for Multi-Inverter Based Microgrids," in IEEE Transactions on Power Delivery, vol. 36, no. 6, pp. 3371-3382, Dec. 2021, doi: 10.1109/TPWRD.2020.3039176.

[8] F. Li, R. Li, and F. Zhou, "Monitoring and energy management of the microgrid", in Microgrid Technology and Engineering Application, Academic Press, 2016, pp. 91-113, doi:10.1016/B978-0-12-803598-6.00006-1.

[9] A. Karaki, M. Begovic, S. Bayhan and H. Abu-Rub, "Frequency and Voltage Restoration for Droop Controlled AC Microgrids," 2019 2nd International Conference on Smart Grid and Renewable Energy (SGRE), Doha, Qatar, 2019, pp. 1-6, doi: 10.1109/SGRE46976.2019.9020914.

[10] X. Liu, M. Shahidehpour, Z. Li, X. Liu, Y. Cao, and W. Tian, "Protection scheme for loop-based microgrids," IEEE Trans. Smart Grid, vol. 8, no. 3, pp. 1340–1349, May 2017.

[11] I. Poonahela, S. Bayhan, H. Abu-Rub, M. Begovic and M. Shadmand, "On Droop-based Voltage and Frequency Restoration Techniques for Islanded Microgrids," IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society, Toronto, ON, Canada, 2021, pp. 1-8, doi: 10.1109/IECON48115.2021.9589772.

[12] J. I. D. Cisneros-Saldana, S. Samal, H. Singh, M. Begovic and S. R. Samantaray, "Microgrid Protection with Penetration of DERs - A Comprehensive Review," 2022 IEEE Texas Power and Energy Conference (TPEC), College Station, TX, USA, 2022, pp. 1-6, doi: 10.1109/TPEC54980.2022.9750716.

[13] Dean Banerjee, PLL Performance, Simulation and Design, 5th edition, Texas Instruments, SNAA106C, May 2017.

[14] A. Hooshyar and R. Iravani, "Microgrid protection," Proc. IEEE, vol. 105, no. 7, pp. 1332–1353, Jul. 2017.