On-line and Off-line Fault Detection Techniques for Inverter Based Islanded Microgrid

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***Abstract*—To develop a stable and robust control that overcomes the challenges revealed by inverter based microgrid, it is very important to understand microgrid behavior when subjected to physical disturbances and associated power quality events. Microgrid faults leads to major power quality events and analysis of such faults will help in formulating a better control strategy. This article discusses an on-line and off-line technique using Park's Vector Trajectory (PVT) and Hilbert-Huang Transform (HHT) respectively to analyze fault transients in load current on occurrence of fault at the point of common coupling (PCC). From the analysis, it is observed that, detection of fault time and analysis of harmonic components can be performed using instantaneous frequency obtained from Hilbert-Spectrum of load current and PVT is useful in real-time detection of transients in load current.**

Keywords—Microgrid, Islanded, Line Faults, HHT, Park's Vector, Inverter

I. INTRODUCTION

Increasing integration of Distributed Energy Resources (DERs) in the grid, the dynamics of Renewable Energy Sources (RES) and ever-increasing demand for power revealed new stability and power quality issues. To solve these issues Microgrid concept is introduced [1]. Microgrid (MG) is better defined as a system with DERs and associated loads. MGs can be viewed as a subsystem of a grid that can operate in grid connected or islanded mode. Detection and classification of faults at an early stage in the MGs and solving these issues will improve the operational performance and reliability of the system [2]. However, to solve these issues it is of high importance to study the transients in MG when subjected to disturbance. Transmission line faults are such disturbances that cause serious stability and power quality issues and have a great impact on the overall system reliability [3]. Fault transient analysis is emphasized by the need for a deeper insight into system response to disturbance to formulate control strategy for robust, reliable, and stable MG operation. The most commonly used signal processing tool for analysis of fault transients is Fast Fourier Transform (FFT) [4]. Narrowed width of inter-harmonics and harmonics of load current signal and possible leakage in FFT algorithm results in submerged or false inter-harmonic and harmonics [5]. Another common tool to analyze the fault signals is Wavelet Transform (WT). A review of WT applications in power systems is presented in [6]. While high resolution decomposition is achieved using WT, its optimal performance depends on predetermined basis function [7]. Feature extraction using wavelet entropy is used to detect faults in [8] and in [9] fuzzy logic based fault detection using wavelet multi resolution analysis coefficients is presented. Initially introduced to analyze AC machines [10], park's vector transform is the principle behind PVT. Park's vector is commonly used for fault and airgap eccentricity detection in three-phase induction motor windings [11, 12], power electronic converters for variable speed drives for AC machines [13], *etc*. In [14] , location of fault in power grid is detected using Hilbert-Huang Transform (HHT). Applications of HHT in identifying the source of disturbance causing voltage sags and improved HHT for analysis of power quality events are discussed in [14] and [15] respectively.

Ability of a power system to regain its equilibrium post disturbance defines its stability. In the absence of a synchronous machine, a MG responds differently to a disturbance as opposed to stable power system with synchronous machine, where, post disturbance operates at new equilibrium point. Moreover, in case of fault in a islanded inverter based MG, the inverter should supply the fault current. Besides power converter and MG design, fault detection and analysis is also important for network protection. In [16] , limitation of fault detection methods used in conventional distribution network when applied to inverter dominated MG is discussed. Analysis of MG behavior, in case of three-phase balanced fault and line-line-ground fault is presented in [17]. One approach to identify a fault to enable a quick protection scheme is based on disturbances in d-q transformed voltage waveforms of MG [18]. But this approach does not provide any insight into the MG behavior with respect to transients in fault current waveform. HHT and PVT can be used to analyze the current waveform. HHT, presented as an offline technique in this paper, provides a better insight into the transients in current waveform and PVT, an online fault detection technique, can be leveraged for fast-real-time control and protection strategies. While, HHT and PVT have been investigated for fault detection in different power apparatus, its applications in MG is not demonstrated completely.

This paper, presents the application of HHT and PVT in detecting the faults in a three-phase islanded MG with no presence of synchronous machine. Section II of the paper describes the model of MG under study followed by details of line faults and fault scenarios in section III. In section IV and V, PVT-the on-line and Off-line HHT fault detection techniques are discussed respectively. The results are presented in section VI of this paper. This paper concludes in section VII.

II. Microgrid Model Description

Three parallel connected inverters feeding a resistive load of 25 kW over an inductive transmission line is viewed as an MG in this study. Scope of the study is limited by using three identical six-pulse three-phase bridge inverters, each with a LCL filter and by not considering source and load dynamics. Active power sharing of this MG model is achieved by using conventional droop (*P-f/Q-V*) control given in each inverter and the switching frequency of power electronic converter is maintained at 50 kHz.

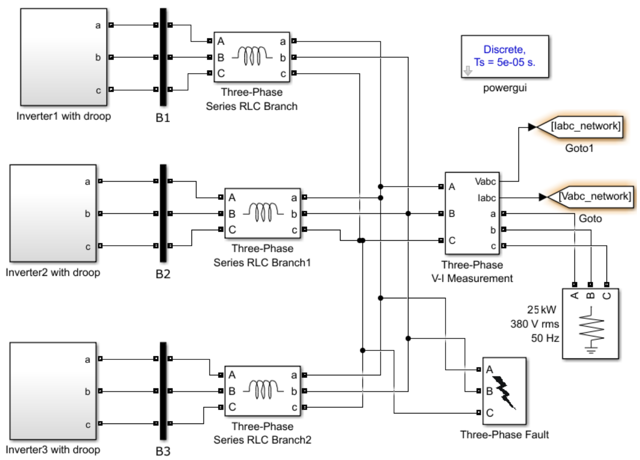

Fig. 1. Microgrid Model

The MG model designed and simulated in MATLAB/SIMULINK is shown in Fig. 1. The three-phase current at PCC sampled at 20 kHz is used for analysis using PVT and HHT.

III. Types of Line Faults and Fault Scenarios

Transmission line faults are mostly short circuit faults and are commonly classified as Symmetrical and Unsymmetrical faults. While, the symmetrical faults keep the system balanced, unsymmetrical faults tend to cause unbalance in the system. Three-phase symmetrical fault includes L-L-L fault where all three phases are shorted and L-L-L-G where all phases are shorted to ground. Single line to ground (LG), Double line to ground (LLG), Line to Line fault (LL) are common unsymmetrical line faults. Based on the frequency of the occurrence, Fig. 2 presents a comparison between symmetrical and unsymmetrical faults [19].

All faults cases, in this work, are simulated at 4.2 sec and cleared at 4.26 sec.

IV. Park's Vector Trajectory as Online Technique

Three phase load currents, taken as a three-dimensional vector obtained from simulation of different fault scenarios are

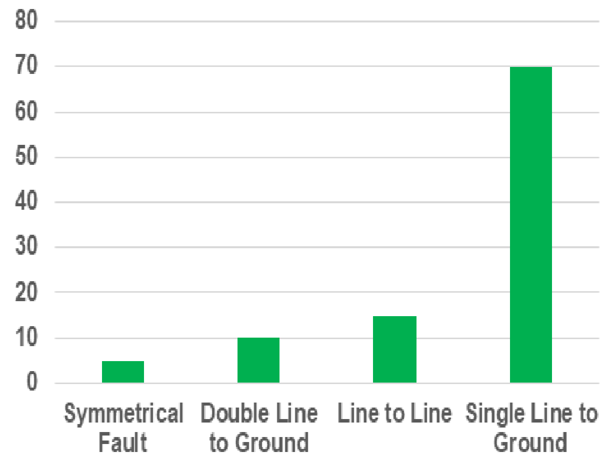

Fig. 2. Percentage frequency of fault occurrence

transformed into a two-dimensional parks vector using the following expression (1) [20].

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{-1}{\sqrt{6}} & \frac{-1}{\sqrt{6}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

By plotting i_β against i_α, Park's Vector Trajectory is obtained. The three-phase current waveform and the corresponding PVT under healthy case are shown in Fig. 3. It can be observed that the PVT is a circle for healthy systems.

On occurrence of fault, transients in load current leads to deformation in the PVT which can be clearly distinguished from PVT formed under balanced condition. Based on different types of deformation caused by faults in PVT, classification of faults is possible. For the analysis purpose PVT is obtained for a sample set of 4-4.5 sec which includes the fault time.

V. Hilbert-Huang Transformation as Off-line Technique

Firstly, the Intrinsic Mode Functions (IMFs) of the signal are obtained using Empirical Mode Decomposition (EMD). Then, instantaneous frequency for every IMF is obtained by performing Hilbert-Transform on it.

A. Steps for EMD [21]

1) Given the signal *s(t)*, maxima and minima of the *s(t)* is identified. Spline method is then used for lower and upper envelope ($e_m(t)$ and $e_M(t)$ respectively) construction. Using equation (2), the mean values *m(t)* is calculated. New signal h(t) is then formed by subtracting *m(t)* from *s(t)* as shown in equation (3).

$$m(t) = \frac{e_m(t) + e_M(t)}{2} \quad (2)$$

$$h(t) = s(t) - m(t) \quad (3)$$

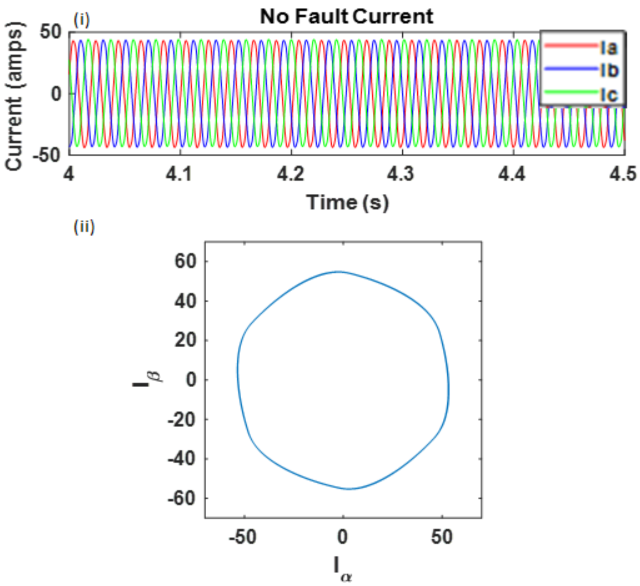

Fig. 3. (i) Load current and (ii) PVT for no fault current

2) Following two conditions are used to check if *h(t)* obtained from step 1 is an IMF.

a) Average of *h(t)* is zero

b) The local extrema are equal to number of zero crossings or differ at most by one.

If *h(t)* does not satisfy above condition, then it is considered as new sequence and step 1 is repeated for it.

3) Steps 1 and 2 are repeated till a latest *h(t)* satisfies the conditions given for an IMF.

4) All the IMFs taken out of *s(t)* are then used to calculate the residue *r(t)* given by following expression (4)

$$r(t) = s(t) - \sum_{i=1}^{n} IMF_i \qquad (4)$$

The process ends when function *r(t)* becomes very small or monotonic.

B. Hilbert-Transform

Hilbert-Transform of *s(t)* is given by

$$y(t) = \frac{1}{\pi} \cdot P \cdot \int_{-\infty}^{\infty} \frac{s(\tau)}{t-\tau} d\tau \qquad (5)$$

An analytical signal is then obtained using following expression

$$z(t) = s(t) + jy(t) \qquad (6)$$

Amplitude of *z(t)* is given by

$$a(t) = [s(t)^2 + y(t)^2]^{\frac{1}{2}} \qquad (7)$$

And the phase of *z(t)* is given as

$$\theta(t) = \tan^{-1} \frac{y(t)}{s(t)} \qquad (8)$$

Instantaneous frequency can then be calculated from phase of *z(t)* using,

$$f(t) = \frac{1}{2\pi} \frac{d\theta(t)}{dt} \qquad (9)$$

Instantaneous frequency gives the frequency time response which is used to analyze the fault transient in load current in this study. In this study HHT is performed for all phases of load current sampled from 4-4.5 sec. Frequency time response of phase A load current is presented in Fig. 4. It contains only 50Hz frequency component and that is why, no overshoot of is observed in case of No Fault (NF).

VI. Results and Discussion

All the fault scenarios are simulated in MATLAB/SIMULINK and the three-phase load current sampled at 20 kHz from 4-4.5 sec in all simulations is presented in Fig. 5.

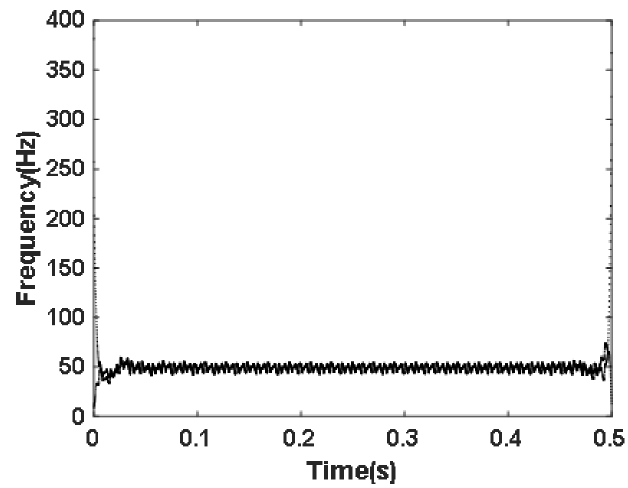

Fig. 4. Frequency-time plot in case of no fault obtained from HHT

A. Detection based on PVT analysis

In the park's transformation pure circle can be obtained only in case of pure sine wave output; which occurs in NF case in this study. During the fault duration the deduced α and β components of load current gets distorted. So, their magnitude will be no longer the same. Hence, the circular trajectory gets deformed during fault duration. This indicates that the eccentricity value which is zero for pure sine wave changes and its values purely depends on the absolute values of i_α and i_β during the fault. For example, in Fig. 6, 'region a' generates a circle and 'region b' generates an ellipse or other distorted trajectory.

Park trajectory obtained for various faults for the microgrid model in this paper are shown n Fig. 7. It is observed from the trajectories that for different line fault scenarios the extent to which the components get deviated are different.

Moreover, since Park's vector transformation can be performed for instantaneous values of phase currents, PVT can be realized in real-time with minimal computational overhead.

B. Detection based on HHT analysis.

During the fault, the frequency-time plots show various natures for different fault cases. Again, the frequency distribution and magnitude are different in pre-fault and post-fault duration which has been indicated as 'region 1' and 'region 2' in Fig. 8. For LLG and LLL fault the frequency component magnitude are found to be higher compared to other two faults and in no fault case. While for post fault, frequency magnitude is found to be more in case of L-L fault.

HHT analysis is performed for each phase current of three phase load current data for all fault scenarios considered in this study and corresponding frequency-time response is presented here.

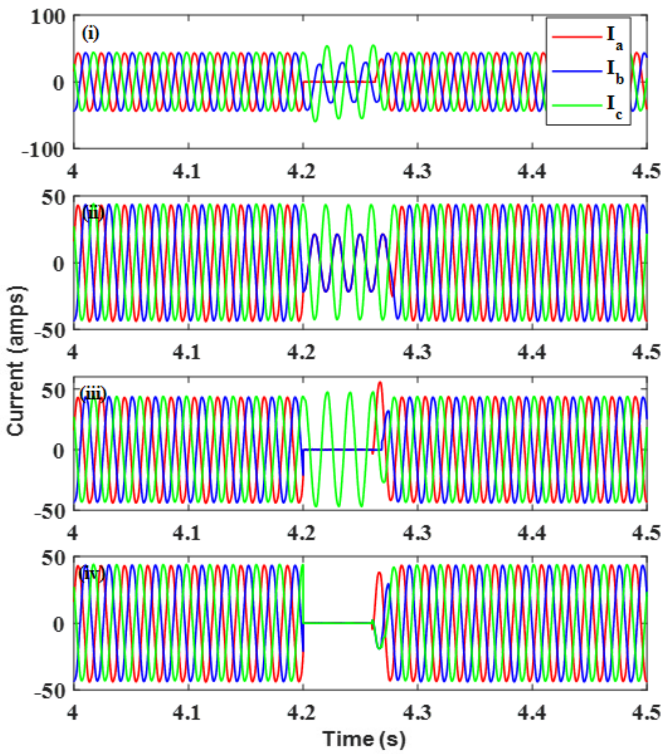

Fig. 5. Load current for different fault scenarios are shown in (ii)LG fault, (iii) LL fault, (iv) LLG fault, and (v) LLL fault

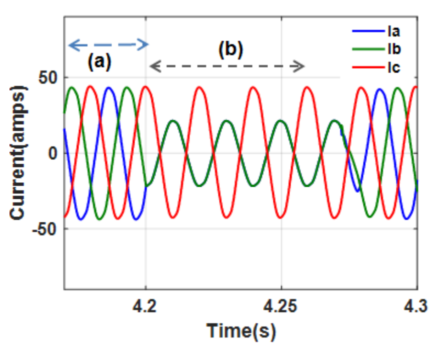

Fig. 6. Distorted load current.

Table I, presents the Normalized Maximum Instantaneous Frequency (NMIF), obtained from the frequency-time response plots for different phase currents around the fault time, for different fault scenarios. Stem plots corresponding to Table I is presented in Fig. 9. It can be observed that the NMIF around the fault duration is greater than zero and can be distinguished only for faulted phase current. For example, in LG, LL, and LLG NMIF of phase C current is almost zero, but, the NMIF of currents in faulted phase is relatively higher. This is attributed to the high frequency contents in faulty phases and it can be concluded that distortions in current during fault results in higher number of IMF decomposition steps to get the residue and higher NMIF. Based on observations made from Table I and Fig. 9, relative difference in NMIF between different phase currents during different faults are presented in Table II, where, IF_{Px} (at fault) and IF_{px} (after fault clearance) represents NMIF of phase 'x' current.

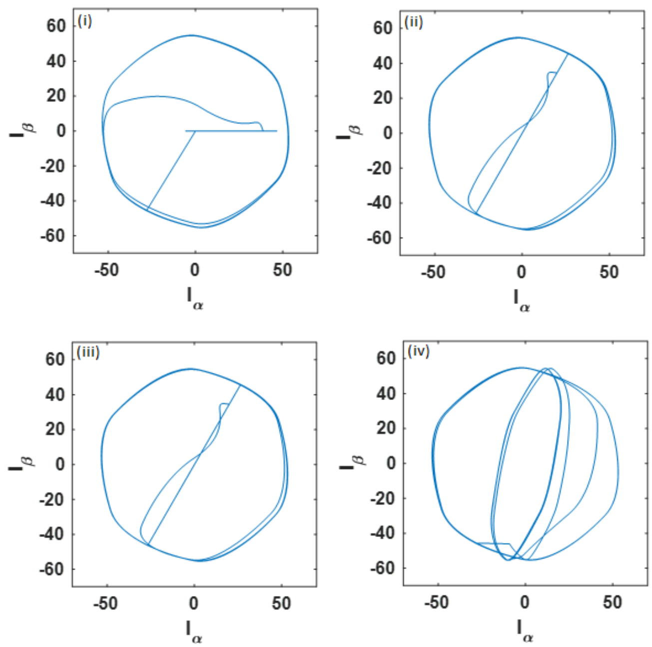

Fig. 7. Park trajectory in case of differetnt faults as (a) LLL (b) LLG (c) LL and (d) LG

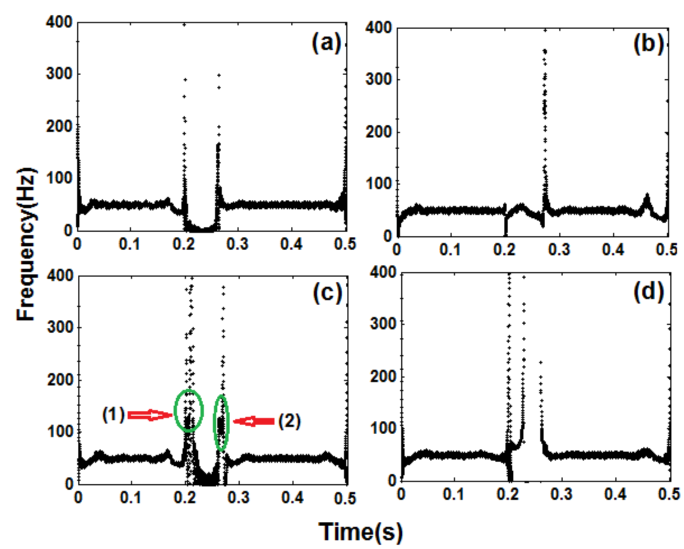

Fig. 8. Frequency-Time plot for different faults as in (a) LG (b) LL (c) LLG and (d) LLL

TABLE I. NORMALIZED MAXIMUM INSTANTANEOUS FREQUENCY

Fault case	**At Fault**			**After Fault Clearance**		
	A	***B***	***C***	***A***	***B***	***C***
LG	1	0.0009	0	0.235	0.001	0.0001
LL	0.003	0.061	0.0004	0.881	1	0
LLG	0.174	1	0	0.0271	0.313	0.0001
LLL	1	0.212	0.435	0	0.014	0.533

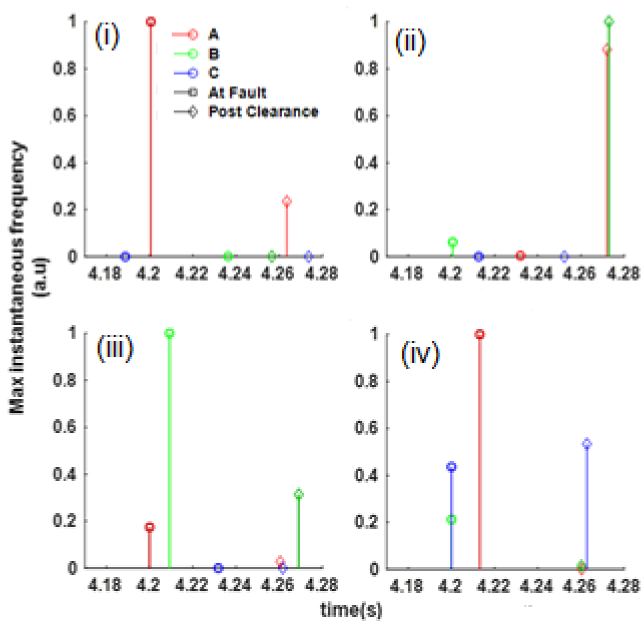

Fig. 9. Normalized maximum instantaneous frequency of different phase currents during (i) LG, (ii) LG, (iii) LLG, and (iv) LLL faults

TABLE II. OBSERVATIONS BASED ON TABLE I AND FIG. 9.

Fault Case	**At Fault**	**After Fault Clearance**
LG	$IF_{Pa}>>IF_{Pb}>IF_{Pc}$	$IF_{pa}>>IF_{pb}>IF_{pc}$
LL	$IF_{Pb}>IF_{Pa}>IF_{Pc}$	$IF_{pb}>IF_{pa}>IF_{pc}$
LLG	$IF_{Pb}>>IF_{Pa}>>IF_{Pc}$	$IF_{pb}>>IF_{pa}>>IF_{pc}$
LLL	$IF_{Pa}>IF_{Pc}>IF_{Pb}$	$IF_{pc}>>IF_{pb}>>IF_{pa}$

VII. CONCLUSION

Analysis of transient fault current is important to handle the power quality events in an islanded MG. Fault analysis of the three-phase load current for symmetrical and unsymmetrical transmission line faults in MG using an On-line and Off-line technique is demonstrated in this paper. However, the source and load side dynamics and its impact on the fault analysis are not within the scope of this study. From the analysis it is observed that Park's Vector Trajectory can be used as an on-line technique for real-time realization with relatively minimum overhead. While frequency-time response obtained using HHT can also be used for fault detection, it takes more computation time which can be attributed to the steps involved in EMD and HT, and hence it is viewed as an Off-line technique in this article.

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