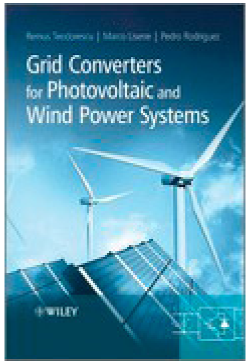

Grid Converters for Photovoltaic and Wind Power Systems

by R. Teodorescu, M. Liserre and P. Rodriguez

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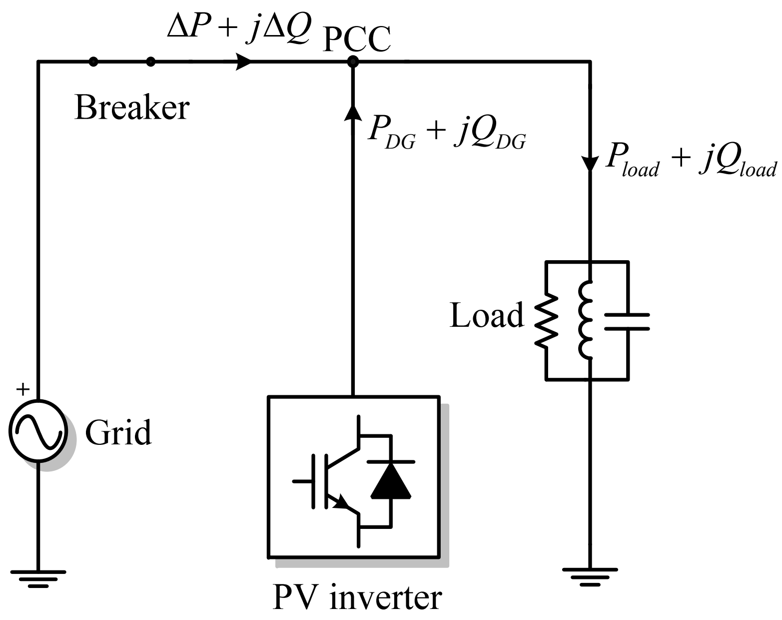
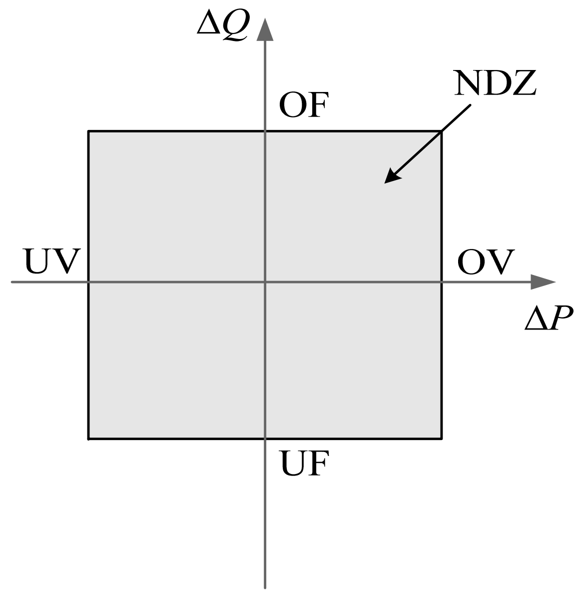
Chapter 5

Islanding Detection

Non-detection zone

The reliability of islanding detection methods can be represented by the non-detection zone (NDZ) defined in the power mismatch space (versus) at the point of common coupling (PCC) where the islanding is not detectable and the potential for parasitic trips.





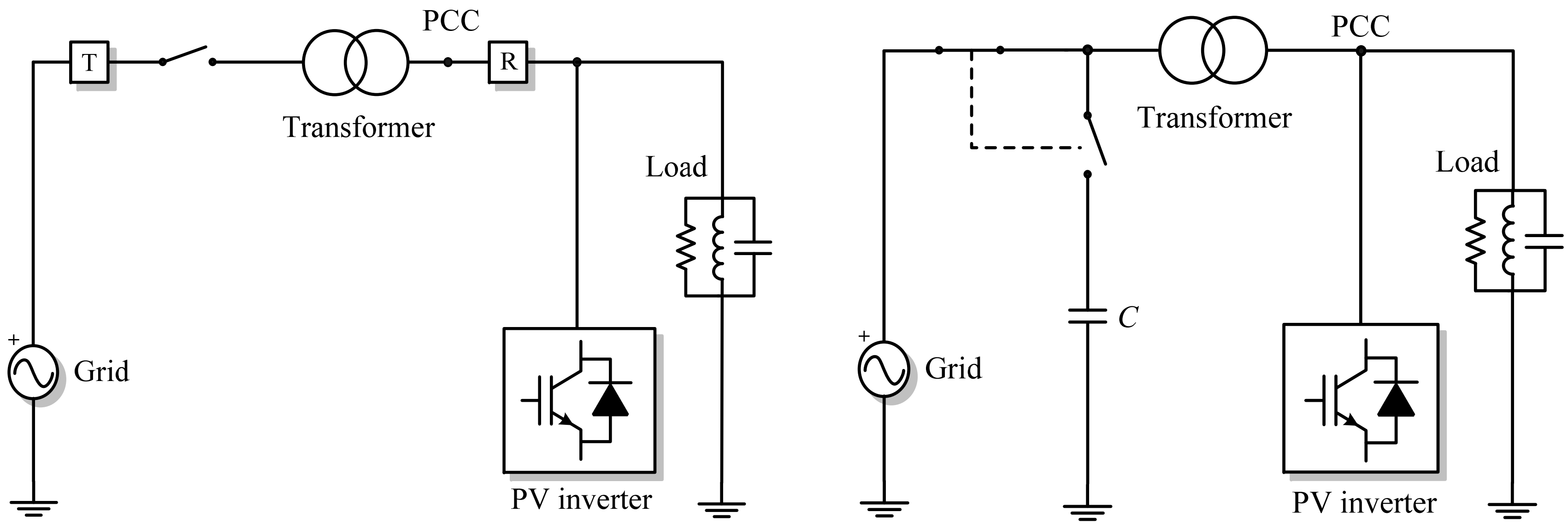
Overview Methods

There main approaches can be employed for islanding detection:

- Grid-resident detection
- External switched capacitor detection
- Inverter-resident detection

Overview Methods

- Grid-resident methods require either a communication system through the power line or a external switched capacitor at the PCC in order to detect the islanding condition accurately, which increases the system complexity and its economical costs
- External Switched Capacitor (ESC) Detection is based on the concept that an external capacitor periodical switched on in parallel with the grid would produce a zero-crossing delay proportional with the grid impedance



Overview Methods

Inverter-resident detection

It relies exclusively on software implementation inside the PV inverter control platform and can use:

- Passive methods
- Active methods

Overview Methods

- The passive methods are based on the detection of a change of a power system parameter (typically voltage, frequency, phase or harmonics) caused by the power mismatch after the loss of grid. Passive methods have non-zero NDZ and are typically combined with active methods to improve the reliability

- The active methods generate a disturbance in the PCC in order to force a change of a power system parameter that can be detectable by the passive methods. With active methods, the NDZ can be significantly reduced; however they have the potential to affect power quality and to generate instability in the grid especially if more inverters are connected in parallel

Passive methods: UOF-OUV detection

Voltage and frequency monitoring is typically used in order to trip the inverter in case of Over Under Voltage or Over Under Frequency. The worst case for islanding detection is represented by a condition of balance of the active and reactive power in which there is no change in amplitude and frequency.

Strengths

- Low cost option

Weaknesses

- Large NDZ

The minimum values for and that would hit the OUF or OUV can be determined analytically as:

$$q \cdot \left(1 - \left(\frac{f}{f_{\min}}\right)^2\right) \le \frac{\Delta Q}{P_{DG}} \le q \cdot \left(1 - \left(\frac{f}{f_{\max}}\right)^2\right)$$

for OUF

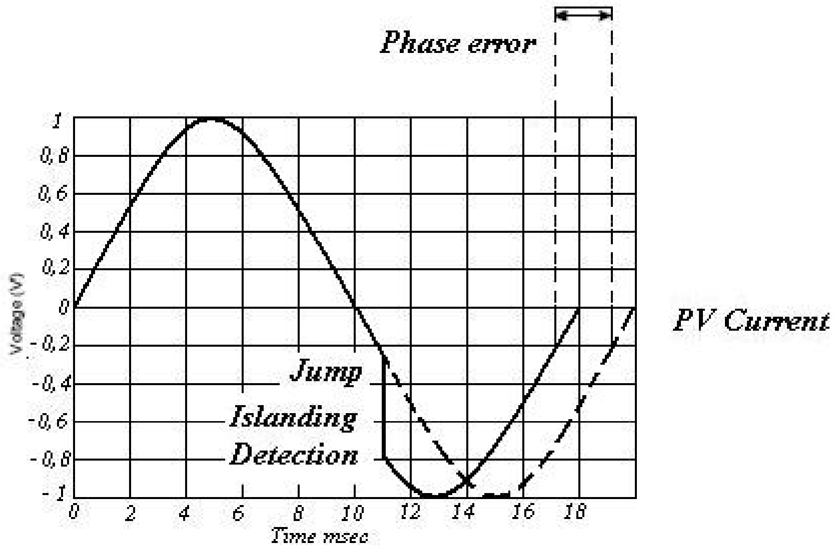
$$\left(\frac{V}{V_{\max}}\right)^2 - 1 \le \frac{\Delta P}{P_{DG}} \le \left(\frac{V}{V_{\min}}\right)^2 - 1$$

for OUV

Thus the NDZ can be precisely determined but in most cases this method is considered to be insufficient as anti-islanding protection complying with the PV standards

Passive methods: Phase Jump detection

This method observes the phase difference between the inverter terminal voltage and its output current that typically occurs during islanding due to reactive power mismatch. The phase can change much faster than the frequency, so much faster island detection is theoretically possible.



Strengths
- Fast Detection
- Easy to implement (using Zero-Croos detectic

Weaknesses
- Noise susceptibility

NDZ

A load with a zero phase angle at the utility frequency will not produce a phase error when the utility is disconnected

Passive methods: Harmonic detection

It is based on monitoring the voltage harmonic distortion to detect an islanding condition. In normal operation the voltage at PCC is controlled by the grid; Inislanding condition DG controls the PCC voltage and its harmonics. It is possible to consider al the harmonics using the Total Harmonic Distortion (THD) of the PCC voltage or only the main harmonics: the 3^{rd}, 5^{th} and 7^{th}.

Strengths

- Detection islanding under a wide range of conditions

Weaknesses

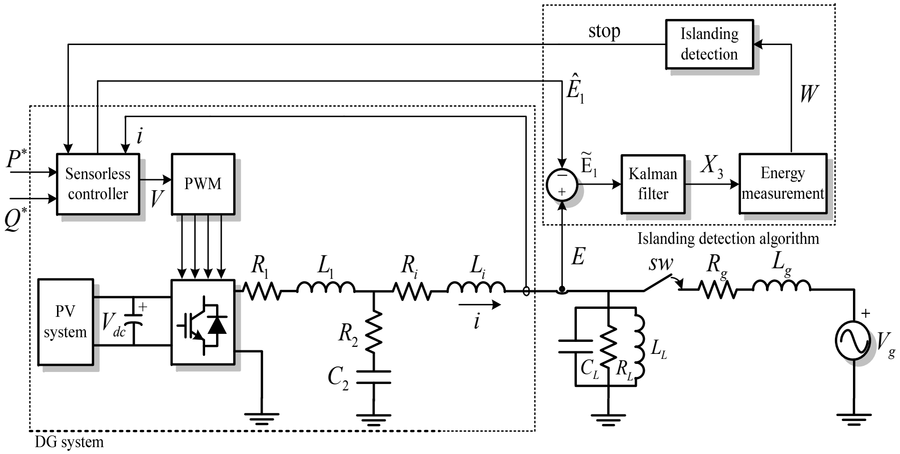
- Connection/disconnection of non-linear loads may change the harmonic condition and can be interpreted as event of islanding
- No-loaded transformers that are known for generating high amount of 3^{rd} harmonic
- Some DG-inverter may increase the voltage background distortion in the effort to inject “clean” currents

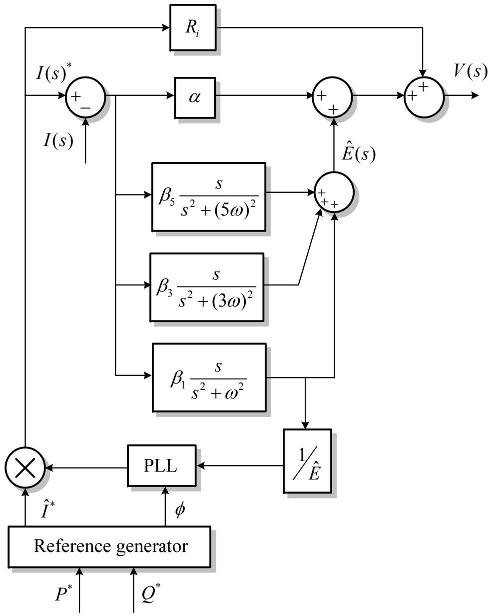
NDZ

It can theoretically reduce to zero

Passive methods: Harmonic detection

Kalman filter based method based on the natural sensitivity to disturbances of a grid voltage sensorless control





The algorithm evaluate the variation of the spectrum power density (energy). The contribution of the harmonic compensators can be considered as an estimate of the background distortion and compared with the measured one in order to determine islanding condition

Weaknesses

- It is dependent on control strategy

Passive methods: Evaluation

The reliability of passive methods is limited as there will always be a non-zero NDZ for small power unbalance. Thus passive methods are often combined with active methods.

Method	NDZ	Trip time (power balance)
OUV	-17 %$\leq \Delta P \leq$24 %	Not applicable
OUF	-5%$\leq \Delta Q \leq$5%	Not applicable
PJD	-5%$\leq \Delta Q \leq$5%	Not applicable
HM	Absent	It can be less than 200 ms

Active methods

The active methods are based on the generation of small perturbations at the output of the PV inverter generating small changes in one of the power system parameter (frequency, phase, harmonics, etc.).

The most commonly used techniques are based on:

- Frequency drift
- Voltage drift
- Grid impedance estimation
- Phase injection

Active methods: Frequency drift Methods

Active Frequency Drift (AFD)
When disconnected from the utility, the frequency of PCC is forced to drift up or down, augmenting the “natural” frequency drift caused by the system seeking the load’s resonant frequency.

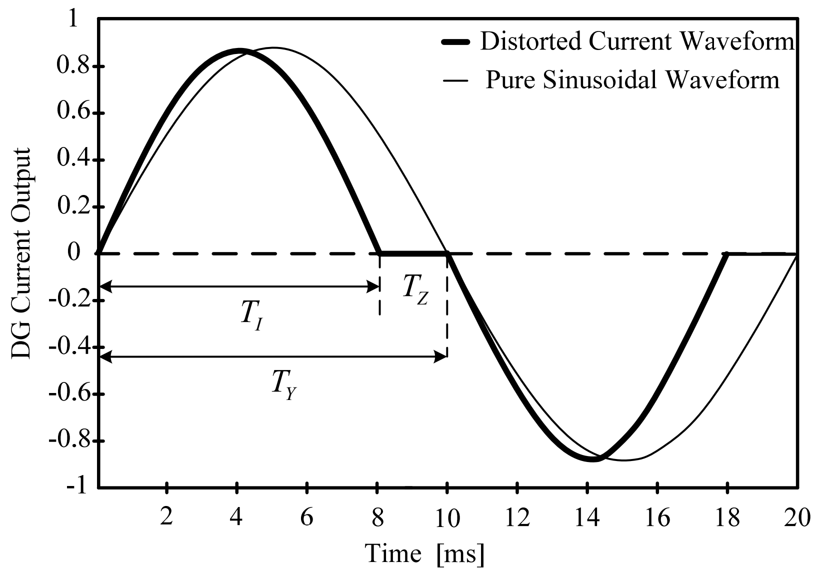
Current reference

$$i_i = \sqrt{2} I \sin\left[2\pi\left(f + \delta f\right)\right] t$$

$$\theta_{AFD} = \pi f T_z = \frac{\pi \delta f}{f + \delta f}$$

Chopping factor

$$cf = \frac{2T_z}{T} = \frac{\delta f}{f + \delta f}$$



Weaknes: NDZ depends on Q

Ropp, M.E.; Begovic, M.; Rohatgi, A., "Analysis and performance assessment of the active frequency drift method of islanding prevention," IEEE Transaction on Energy Conversion, vol.14, no.3, pp.810-816, Sep 1999

Active methods: Frequency drift Methods

Slip-Mode Frequency Shift (SMS)

A positive feedback is applied to the phase of PCC voltage to destabilize the inverter by changing the short-term frequency. If the utility is tripped and the frequency of PCC voltage is distorted, the inverter phase response curve increases the phase error and hence, causes instability in the frequency. This instability further amplifies the perturbation of the frequency of PCC voltage and the frequency is eventually driven away until it hits OUF protection.

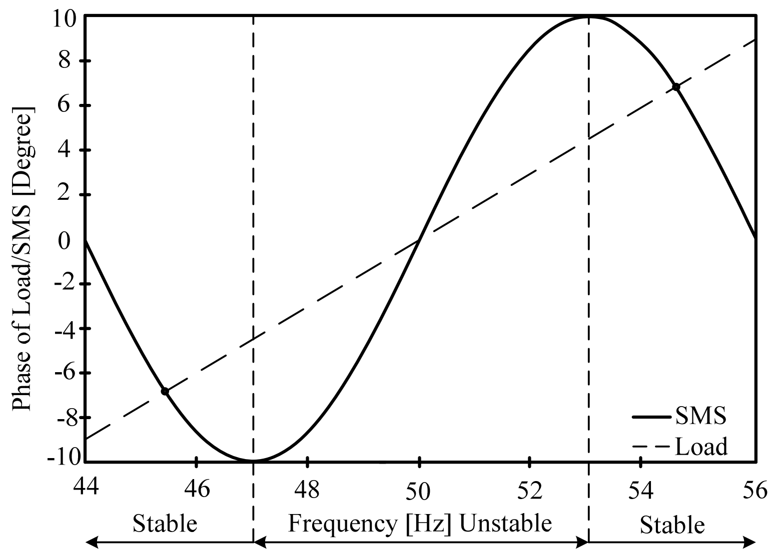
Current reference

$$i_i = \sqrt{2} I \sin\left(2\pi f t + \theta_{SMS}\right)$$

$$\theta_{SMS} = \theta_m \sin\left(\frac{\pi}{2}\right)\frac{f_i - f}{f_m - f}$$

To obtain zero NDZ for a given Q

$$\frac{\theta_m}{f_m - f} \geq \frac{12Q}{\pi^2}$$



W.Bower, M.Ropp: "Evaluation of Islanding Detection Methods for Utility-Interactive Inverters in Photovoltaic Systems",Sandia National Labs., Albuquerque, NM, SANDIA Report SAND2002-3591 Nov. 2002 (online ordering: http://www.doe.gov/bridge)

Active methods: Frequency drift Methods

Sandia Frequency Shift (SFS) also called Active Frequency Drift with Positive Feedback (AFDPF) is an extension of the AFD method, and is another method that utilizes positive feedback. In this method, it is the frequency of voltage at PCC to which the positive feedback is applied. To implement the positive feedback, the "chopping fraction" from AFD is made to be a function of the error in the line frequency.

Acceleration factor k

$$cf = cf_0 + k(f - f_n)$$

NDZ can be reduced to zero by choosing

$$Q < 4.8 \qquad cf_0 = 0.05 \qquad k = 0.01$$

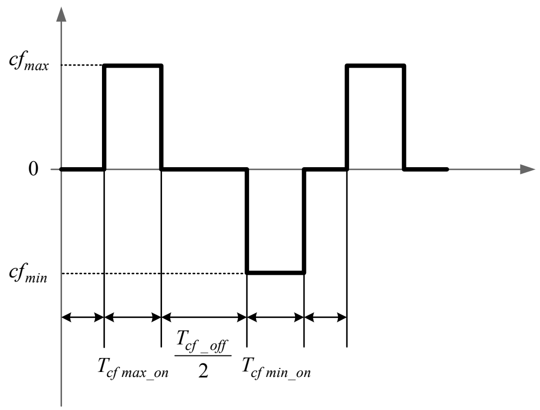
Lopes, L.A.C.; Huili Sun, "Performance assessment of active frequency drifting islanding detection methods," Energy Conversion, IEEE Transaction on, vol.21, no.1, pp. 171-180, March 2006

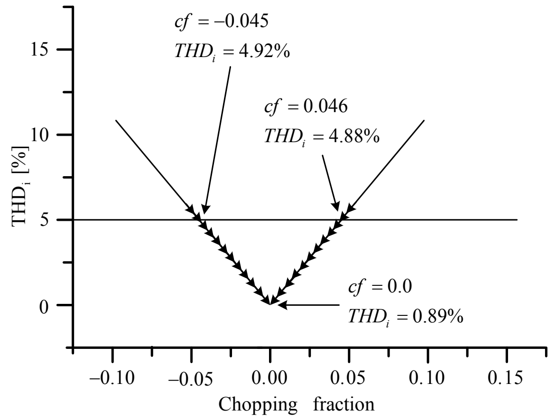
Active methods: Frequency drift Methods

Active Frequency Drift with Pulsating Chopping Factor (AFDPCF) is an improved SFS method is reported where the chopping factor instead of depending on a gain, has an alternating pulse shape leading to faster frequency drift during islanding.

Actually the frequency is pushed to increase in one period and then to de-crease in the second period. The positive and negative value of the chopping factor can be set using analytical calculation by imposing a certain grid current THD as required by standards. Thus, complying with power quality standard can be guaranteed. Also the potential for parallel operation is higher than the previous AFD base method.

$$cf = \begin{cases} cf_{\max} & \text{if } T_{cfmax\_on} \\ cf_{\max} & \text{if } T_{cfmin\_on} \\ 0 & \text{otherwise} \end{cases}$$

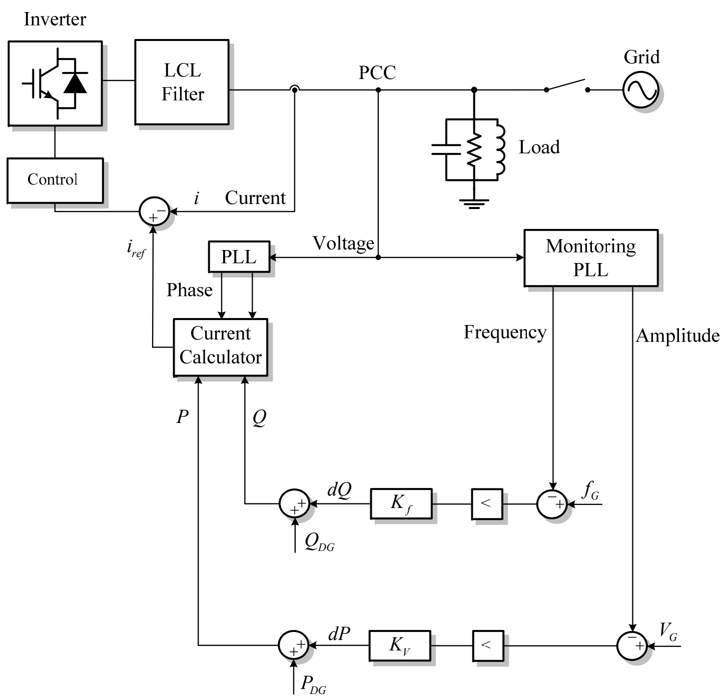


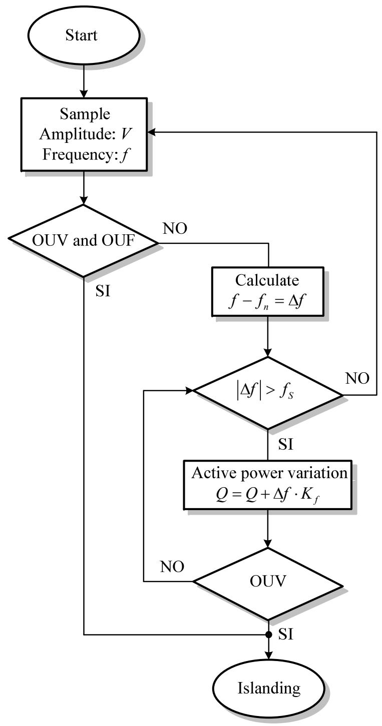


Jung, Y.; Choi, J.; Yu, B.; So, J.; Yu, G., "A Novel Active Frequency Drift Method of Islanding Prevention for the grid-connected Photovoltaic Inverter," Power Electronics Specialists Conference, 2005. PESC '05. IEEE 36th , vol., no., pp.1915-1921, 2005

Active methods: Frequency drift Methods

GE Frequency Shift (GEFS) is another frequency drift AI method based on positive feedback like SFS. Here the reactive current reference is augmented with a positive feedback derived from the frequency estimation with proper filtering and gain in order to maintain the stability. Increasing the reactive current reference will lead to higher reactive power which in case of islanding on RLC load will further increase the frequency so the frequency is quickly pushed outside the OUF limits.





Ye, Z.; Walling, R.; Garces, L.; Zhou, R.; Li, L.; Wang, T. "Study and Development of Anti-Islanding Control for Grid-Connected Inverters" NREL/SR-560-36243. Golden, CO: National Renewable Energy Laboratory. May 2004

Active methods: Frequency drift Methods

Reactive power Variation (RPV)

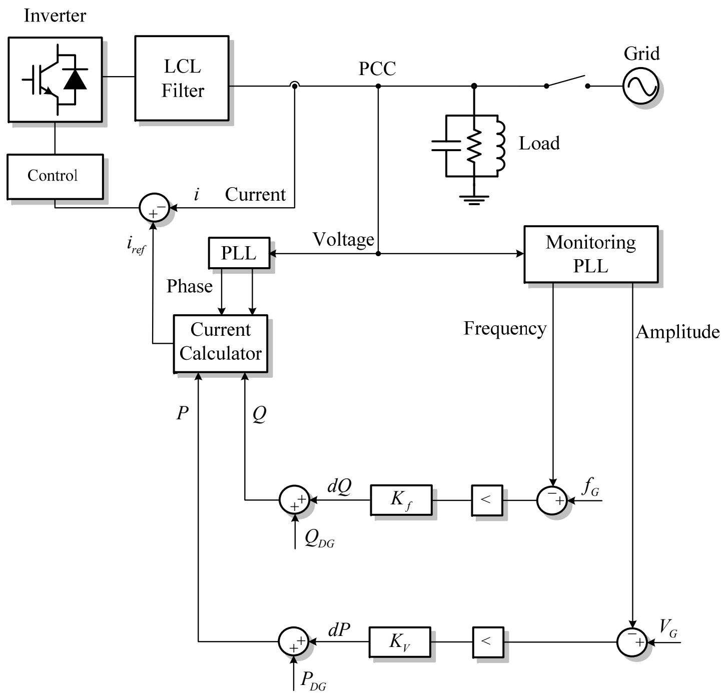
The concept here is to add a harmonic disturbation signal (typically low frequency) in the reference of the reactive current. In the presence of the grid, this disturbance will try to modulate the voltage frequency with the disturbing one but will not be able due to the stiff character. In islanding situation, the voltage will depend linearly with the current and the frequency variations will be present and can be detected.

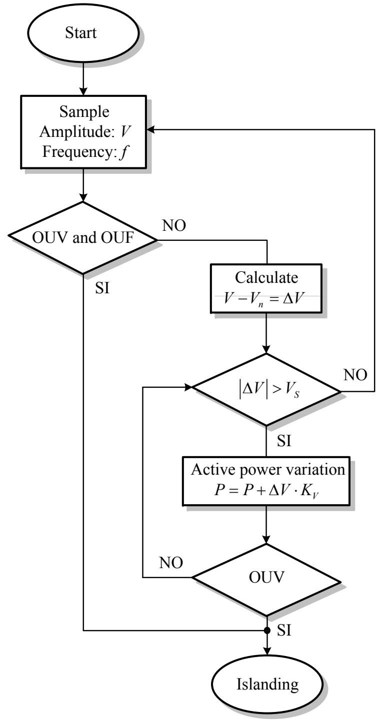
For ex 1 Hz – 1% harmonic current is added to the reactive current reference with very reliable detection not-sensitive to the grid impedance. A frequency deviation detector is used to count the half periods between zero crossing that deviates from the rated frequency. After a predetermined count the trip signal is generated. Shorter detection times can be obtained by increasing the frequency of the harmonic current if desired but keeping low its amplitude.

G. Hernandez-Gonzalez; R. Iravani, "Current injection for active islanding detection of electronically-interfaced distributed resources," IEEE Trans. on Power Delivery, vol.21, no.3, pp.1698-1705, July 2006

Active methods: Voltage Drift Methods

Sandia Voltage Shift (SVS) is an islanding detection method which uses positive feedback in the amplitude of the grid voltage. If there is a decrease in the amplitude of PCC voltage (usually it is the RMS value that is measured in practice), the PV inverter reduces its current output and thus its power output. If the utility is connected, there is little or no effect when the power is reduced. When the utility is absent and there is a reduction of the voltage in PCC. This reduction leads to a further reduction in PV inverter output current, leading to an eventual reduction in voltage that can be detected by the UVP.





W.Bower, M.Ropp: "Evaluation of Islanding Detection Methods for Utility-Interactive Inverters in Photovoltaic Systems",Sandia National Labs., Albuquerque, NM, SANDIA Report SAND2002-3591 Nov. 2002 (online ordering: http://www.doe.gov/bridge)

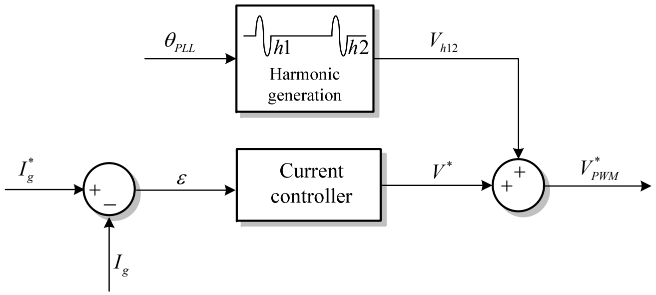
Active methods: Grid impedance estimation

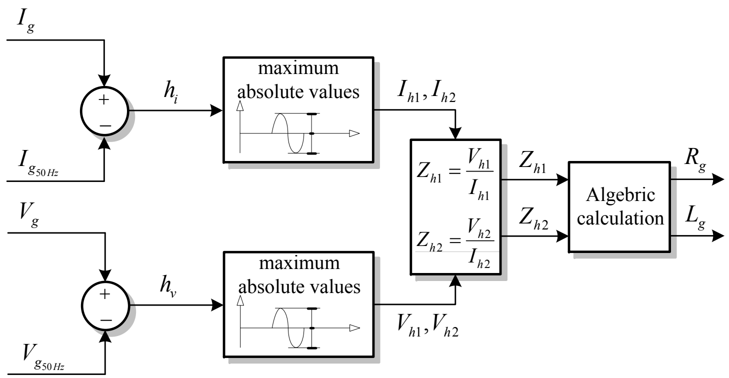
The concept is that a certain disturbance, such as harmonic injection or variation are used to estimate the grid impedance based on the response of the grid

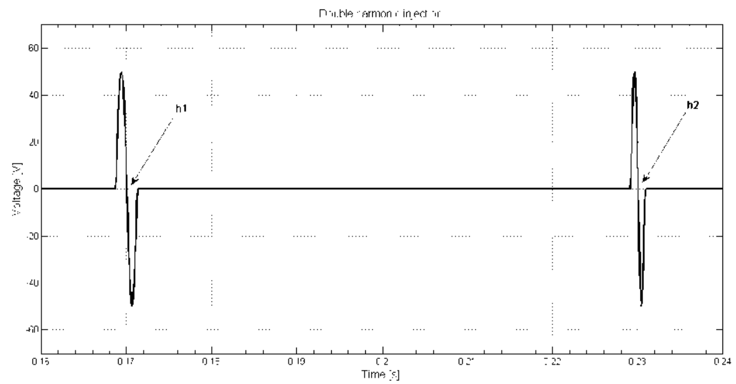
- Harmonic Injection (HI)
- Grid Impedance Estimation by Active Reactive Power Variation (GIE-ARPV)

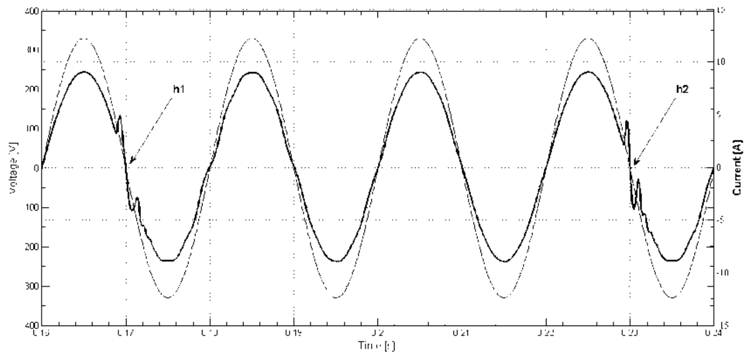
Active methods: Grid impedance estimation

Harmonic Injection (HI) is based on injection of non-characteristic harmonic current (ex 75Hz, 400, 500 Hz) and extraction of the resultant voltage harmonic which is dependent on the grid impedance at that frequency.









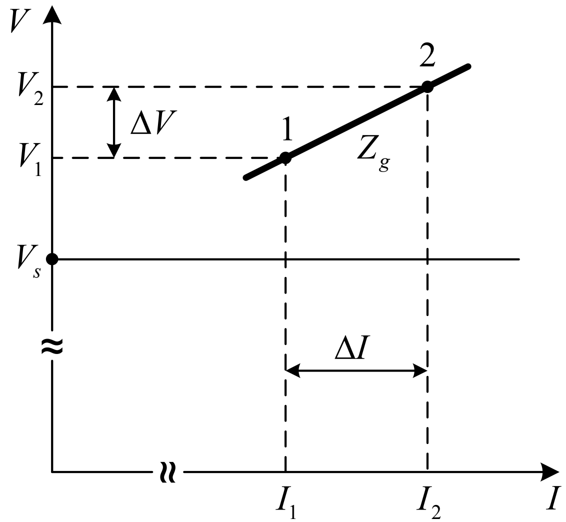
Ciobotaru, Mihai; Teodorescu, Remus; Blaabjerg, Frede, "On-line grid impedance estimation based on harmonic injection for grid-connected PV inverter," Industrial Electronics, 2007. ISIE 2007. IEEE International Symposium on , vol., no., pp.2437-2442, 4-7 June 2007

Active methods: Grid impedance estimation

Grid Impedance Estimation by Active & Reactive Power Variation (GIE-ARPV)

This method is based on the fact that the grid impedance can be calculated by using 2 stationary working points and solving the Voltage Kirchhoff Law.

Usually small pulse variations of P are used to determine the resistive part and small Q variations to determine the inductive part of the grid impedance.



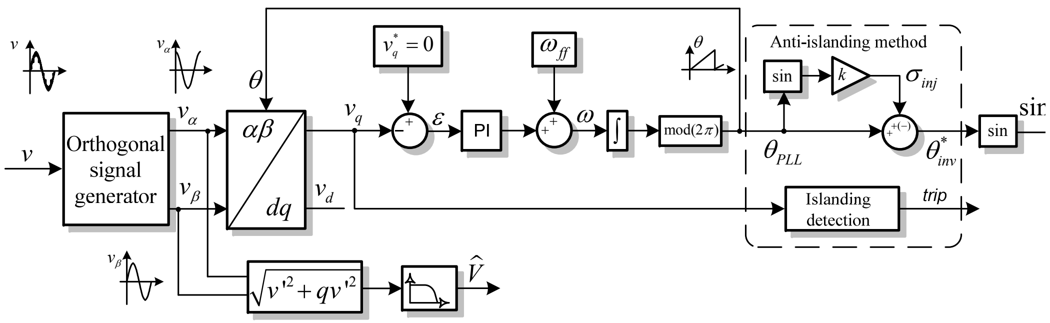
$$\begin{cases} R_g = \dfrac{\Delta V_d \cdot \Delta I_d + \Delta V_q \cdot \Delta I_q}{\Delta I_d^2 + \Delta I_q^2} \\ L_g = \dfrac{\Delta V_q \cdot \Delta I_d - \Delta V_d \cdot \Delta I_q}{\left[\Delta I_d^2 + \Delta I_q^2\right] \cdot \omega} \end{cases}$$

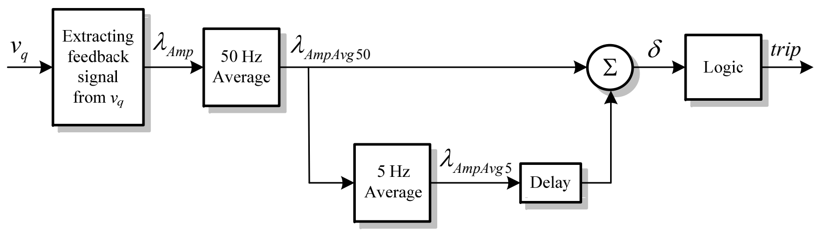
In PV and WP plants applications, P is continuosly changed and in close future Q too!

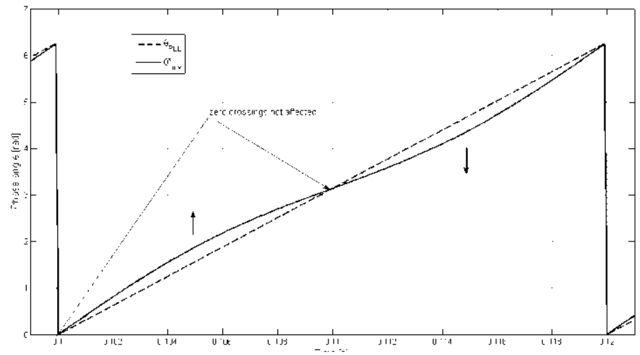
Ciobotaru, M.; Teodorescu, R.; Rodriguez, P.; Timbus, A.; Blaabjerg, F., "Online grid impedance estimation for single-phase grid-connected systems using PQ variations," Power Electronics Specialists Conference, 2007. PESC 2007. IEEE , vol., no., pp.2306-2312, 17-21 June 2007

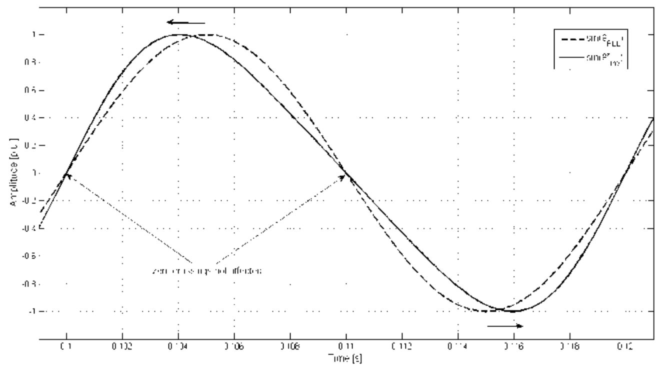
Active methods: PLL based islanding detention

This method takes advantage of the existing PLL structure responsible for the synchronization of the inverter output current with the grid voltage and is based on the deliberately alteration of the derived angle of the inverter current angle .A feedback signal is then extracted from the voltage at the PCC (namely from) as a consequence of the injected signal The signal injection can be done with either positive or negative sign.









Ciobotaru, M.; Agelidis, V.; Teodorescu, R., "Accurate and less-disturbing active anti-islanding method based on PLL for grid-connected PV Inverters," Power Electronics Specialists Conference, 2008. PESC 2008. IEEE , vol., no., pp.4569-4576, 15-19 June 2008

Active Methods: Evaluation

AI active method	Reliability	Maintaining Power Quality	Suitability for parallel inverter operation	Potential for standardization
Active Frequency Drift - AFD	Medium as it is not able to eliminate the NDZ	Low as it introduces low harmonics	Low as it can not handle concurrent detections	Low. More likely for the AFD with positive feedback
Slip Mode Frequency Shift – SMS	Medium as it is not able to eliminate the NDZ	Medium as PF is affected but no harmonics are injected	Low as it can not handle concurrent detections	Low
Sandia Frequency Shift (SFS+SVS)	High it can eliminate NDZ but it is susceptible for parasitic trips	Medium – with continuously drifting the PQ can be affected	Medium. It can work with parallel inverters but PQ can be affected.	Medium. More likely for the improved AFDPCF or GEFS
Active Frequency Drift with Pulsating Chopping Factor AFDPCF	Medium High – usually it leads to longer detection times as AFDPF but stability is controlled	High – it introduces harmonics but THD can be controlled	High, but limited in case one inverter is increasing frequency while another is decreasing it	High – as both stability and THD degradation can be controlled
General Electric Frequency Shift – GEFS	Very High – as NDZ can be eliminated and stability can be controlled.	Very High – practically no influence on THD	High but not unlimited. According to GE more research is needed	High as no degradation of THD is made

Petrone, G.; Spagnuolo, G.; Teodorescu, R.; Veerachary, M.; Vitelli, M., "Reliability Issues in Photovoltaic Power Processing Systems," Industrial Electronics, IEEE Transactions on , vol.55, no.7, pp.2569-2580, July 2008

Active Methods: Evaluation

AI active method	Reliability	Maintaining Power Quality	Suitability for parallel inverter operation	Potential for standardization
Reactive Power Variation - RPV	Moderately High – It can eliminate NDZ	High as no harmonics are injected, only the PF can be slightly reduced	Low as frequency changes at PCC can be also caused by other inverters	Low due to low suitability for parallel operation
Grid Impedance Estimation – Harmonic Injection GIE-HI	High as NDZ can be eliminated. There is potential for parasitic trip depending on grid impedance	Medium – depending on time between injections	Low – readings can be influenced during parallel injection	Low as ENS has softened now the requirements and accept IEEE1547 as alternative
Grid Impedance Estimation – External Capacitor Switching –- ESC	High- It can eliminate NDZ	Low – It introduces low harmonics	Low for inverter level implementation. It can be implemented as one unit for a group of inverters	Low – as for inverter level can not compete with software anti-islanding methods
Grid Communication (GC)	Very High – as long as communication is good. It does not depend on PQ mismatch	High (no influence on PQ)	Very High – just as it is dependant on communication reliability	Moderately High – on long terms due to cost issues

Petrone, G.; Spagnuolo, G.; Teodorescu, R.; Veerachary, M.; Vitelli, M., "Reliability Issues in Photovoltaic Power Processing Systems," Industrial Electronics, IEEE Transactions on , vol.55, no.7, pp.2569-2580, July 2008