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Review

Small-Signal Stability Criteria in AC Distribution Systems—A Review

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Abstract: AC distribution grid is prone to instability due to negative impedance and constant power nature of the load if it is dominant with power electronics-based components. There are various time-domain and frequency-domain modelling methods which use various methodologies and analytical tools. Also, there are many small-signal stability analysis (SSSA) methods and their different variants for different specific conditions and situation. This paper presents a review of SSSA methods in AC distribution grid using impedance-based models in a synchronous reference frame (SRF). By simplifying and converting the system into load and source subsystem, the impedances of both subsystems are determined by perturbation method. For a single-phase system, Hilbert transform can be used to derive the equivalent SRF model. Afterwards, the Nyquist stability criterion can be used for stability analysis.

Keywords: DC–AC power converters; frequency–domain analysis; impedance-based model; Nyquist stability analysis; phase–locked loop; small-signal stability analysis; synchronous reference frame

1. Introduction

Traditionally, electric power was generated in bulk by large generation units depending upon location and availability of resources. The power flow from the generation side to the load side was unidirectional. The distribution side used to receive power and distribute it to load centers. However, due to distributed generation and microgrid technology [1,2], loads are now neither linear nor passive. A distribution grid (DG) may consist of multiple generators and energy storage elements.

Power electronics helps us integrate nonconventional power with conventional sources while improving the efficiency by enabling bi-directional power flow at distribution level. However, the power system complexity increases [3–8] . The resulting system is prone to harmonics and instability due to negative impedance of constant power loads [9–18].

Power converters (PCs) play vital roles in DG as these can convert power form AC to DC and vice versa [19,20]. The dynamic behavior of PCs and their interaction with active loads in power systems may lead to oscillations and even instability of the system [21–23].

This has increased the importance and need for system modelling for stability analysis. The stability methods can be broadly categorized as the small-signal stability analysis (SSSA) methods and the large disturbance stability analysis methods depending on the nature of the disturbance [24].

There are various methods for long-term stability analysis of DG, droop control being most widely used. In this method, there are three control loops. The droop controller of devices in power electronics is slower than the inner control loops that regulate currents and voltages of storage elements. When the short-term dynamics are stable and within the acceptable range, the system reaches the slower stage [25,26]. One of the assumptions of the droop controller is that the current and the voltage are in a steady state [25]. However, this assumption is not necessarily valid because of possible interaction between short- and long-term dynamics.

There are various SSSA methods for system modelling and small signal stability analysis of AC DG dominated by active loads. These methods include impedance-based modelling in frequency-domain and state-space modelling in time domain [27,28]. The focus of this article is the impedance-based modelling in frequency domain using the SRF method.

In the past, numerical simulations were used to analyze complex system behavior [29,30]. Now, because of non-linear load and the active nature of DG, it is not practical to apply numerical simulations.

In impedance-based method system transfer function is obtained by dividing the system into the source side and load side, each with its own impedance. Then a stability criterion, mostly Nyquist stability criterion (NSC), is applied to interconnected system. Originally, the impedance-based system analysis was designed for DC grid system and was used for stability analysis of DC-DC converters along with their input filters [5] . Later, this method was extended and used for stability analysis of AC DG also. Now this is one of the most widely used methods for a stability study of AC grids. By using this method, more complex systems with multiple sources can also be studied by lumping together their sources into a single source. In the impedance-based method, the effect of making changes on the source side or the load side is only limited to the respective impedances. One of the advantages of this method is that unknown impedance can be found through simulations or experiments. This method not only works well with generators, transformers, and other conventional machine models, but also with modern nonconventional converters based on power electronics.

This article is organized as follows. In Section 2, small-signal stability methods are presented. Section 3 presents the modelling and analysis in frequency domain. Section 4 is based on impedance-based modelling and analysis. Section 5 describes modelling and analysis in SRF.

2. Small-Signal Stability Methods

The methodology diagram of different stability methods using various models in different domain is given in Figure 1 [31,32].

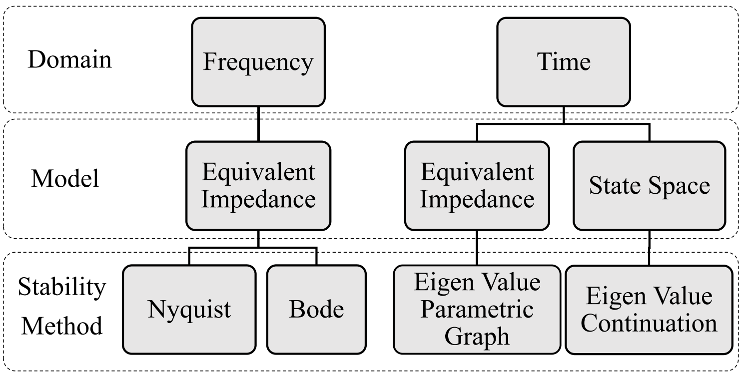

Figure 1. Methodology Diagram

SSSA methods in time domain or frequency domain involve linear or non-linear analysis. Linear analysis can be based on eigen values, state-space model, or impedance-based as given in Figure 1. However, the non-linear analysis can be based on either bifurcation theory or other probabilistic analysis methods [27].

The details of different stability tools in time domain are given in Figure 2 [31,32].

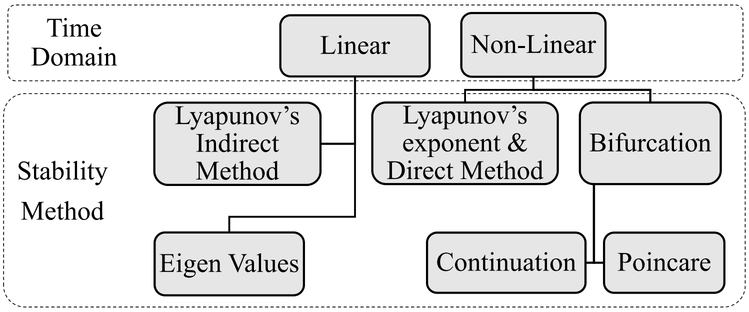

Figure 2. Tools for Stability Studies in Time Domain.

Non-linear analysis and linear analysis involving classical eigenvalues and Lyapunov tests are the main criteria in the time domain as given in Figure 2. However, non-linear stability can be studied by the Lyapunov criterion as a computational tool (i.e., with Lyapunov exponent). Moreover, the Lyapunov function and bifurcation points can be identified by continuation methods [31,32]. A comparative analysis of different time-domain SSSA methods for non-linear distribution systems is given in Table 1.

Table 1. Comparative Analysis of Different Stability Techniques in Time Domain.

Model	Detail	Advantage	Disadvantage	Ref.
Lyapunov indirect	Use eigenvalue to estimate stability	Can determine the stability of the entire system globally for an operating point.	It requires detailed modelling of entire system. Its converter model cannot identify the sustained harmonics.	[28–33]
Lyapunov direct	Use positive definite function and its derivative in state space	Can apply to small systems	Not suitable for large-scale systems	[29–33]
Probabilistic Numerical methods	Different types including Monte Carlo simulation method	Capable of analyzing a complex & large-scale system with high accuracy.	Time-consuming method. Huge computation efforts required	[34]
Probabilistic Analytical Methods	Cumulant-based method	Low computation efforts required so can deal with large-scale system.	Inaccurate in some situations due to inaccurate first order approximation	[34]
Probabilistic Approximate Methods	Point Estimation method (PEM)	Attains quick convergence, a low computational effort is required and can work for large-scale system	Applicability to large-scale system depends on applied scheme, requires complex formulation	[34]
Phasor Model	Estimate stability in time domain	Can be linearized using state-space methods if model is not large.	Dimensions are significantly higher. It is not differentiable often	[22]
Bifurcation	Apply mathematical approach to ordinary differential equations (ODEs) to extract eigenvalues	Performs very well for small system i.e., up to 2nd order ODEs	Slow for higher order ODEs	[35]

A comparative analysis of different frequency-domain SSSA methods for non-linear distribution systems is given in Table 2.

Table 2. Comparative Analysis of Different Stability Techniques in Frequency Domain.

Model	Detail	Advantage	Disadvantage	Ref.
Bifurcation	Apply Laplace transform to non-linear ODEs	Work well for higher order system as well	More complicated	[35]
SRF	Extract impedance using SRF technique to estimate stability	Detailed modelling is not required. It can deal with large system.	Only work for balanced 3-phase or pure single-phase	[22,28]
Harmonic Linearization	Extract impedance by injecting a specific harmonic component	Work for both unbalanced 3-phase and combination for 1-phase and 3-phase	Limited observability of certain states	[22,28]

It is necessary to build a linear time invariant (LTI) model for load as well as source side in both time-domain state space and frequency-domain impedance-based approach. It is easy to build such models for conventional components of power system. On the other hand, building such model for modern power electronics-based non-linear devices lacking fixed operation point is a major difficulty. This prevents the direct application of these LTI techniques. Thus, a fixed operation point is selected around which these models are linearized to apply these techniques. The details of different SSSA methods in AC system by linearizing the non-linear system are given in Figure 3 [22].

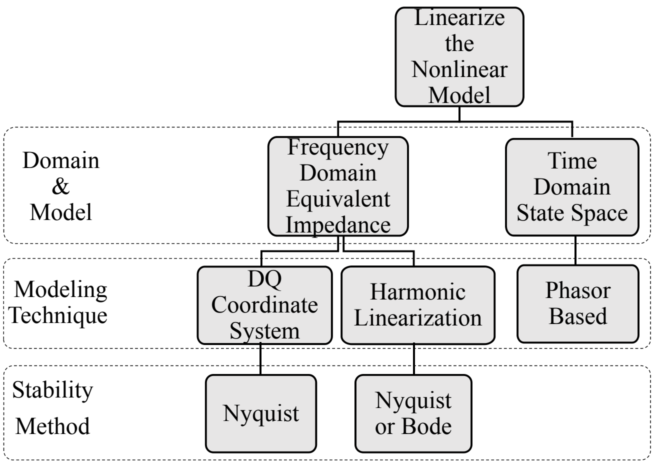

Figure 3. Different SSSA Methods in AC System by Linearizing the Non-linear System.

3. Modelling and Analysis in Frequency Domain

There are two frequency-domain impedance-based modelling methods. The one discussed here is transformation into dq reference frame. The other method is harmonic linearization [22,36,37]. NSC and Bode plots are the main stability criteria for SSSA in frequency domain as given in Figure 3. In harmonic linearization technique the time varying non-linear system, which can be composed of single or multiple harmonics, is converted to a small-signal impedance-based linear model. In this method, a system is perturbed by superimposing some specific harmonic components. The corresponding resultant output components are extracted by monitoring system response and by applying small-signal approximation along with harmonic balance principle [38]. The NSC or Bode stability criterion is applied after developing an impedance-based model. Studies on harmonic linearization are presented in [37–43]. There are various research articles in which this method is used to develop impedance-based models of various converters [44–48].

In the impedance-based method, non-linear systems are linearized first by using averaging linearization techniques [49], e.g., by using Taylor series and the likes. Transformation into synchronous reference frame (SRF) can be used for stability analysis of a balanced three-phase AC system [50]. Harmonic linearization, which divides the system into positive and negative subsystem, can be used for stability analysis of an unbalanced three-phase AC system [22]. This technique can perform the stability analysis on positive and negative subsystems separately in sequence domain by making use the property of LTI systems. For stability of the whole AC system, each component of sequence domain should be stable and there should not be any cross coupling between them. This method works well for both single and three-phase AC system and not only can handle balanced three-phase AC system but also unbalanced three-phase systems [22]. One disadvantage of this technique is that it requires lengthy algebra.

Transformation into SRF can either use frequency-domain technique along with impedance-based modelling method [51] or state-space technique by using time domain for analysis. Often, in SRF the frequency-domain technique along with impedance-based modelling method is preferred which uses NSC [22,33,52,53].

4. Impedance-Based Modelling and Analysis

Stability analysis of a DG dominated by non-linear loads can be evaluated by an impedance-based model. In this method, impedance is estimated by applying a proper relevant impedance estimation method first, and then an appropriate corresponding stability method is applied for stability estimation. The impedance-based stability analysis method to evaluate the stability of DG is well established for a DC type system when NSC is used. This method estimates the stability of a DC system by analyzing the locus of the impedance ratios of source and load in complex plane. In case of AC type DG system, the same impedance-based technique and stability methods are used. However, the techniques to extract the impedance and to apply the stability criterion are not the same [54]. Stability of a power system can be analyzed by considering it as a negative feedback control system as given below in Figure 4. Stability of this closed loop system can be evaluated by applying well-known NSC on transfer function of this system which is given in (1).

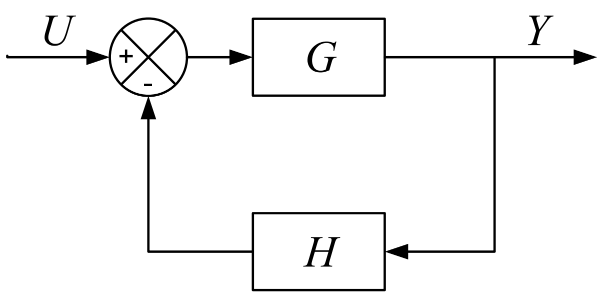

Figure 4. Negative Feedback Control System.

$$\frac{Y(s)}{U(s)} = \frac{G(s)}{1 + G(s)H(s)} \tag{1}$$

where $U(s)$ is the input, $Y(s)$ is the output, $G(s)$ is the forward gain and $H(s)$ is the reverse gain of the feedback system. Stability can be determined by only observing the Nyquist contour of open loop transfer function $G(s)H(s)$. This generalized criterion can be applied to a simplified power system shown in Figure 5. Transfer function of this power system can be determined in terms of input voltage V_s and output voltage V_l as shown in (2).

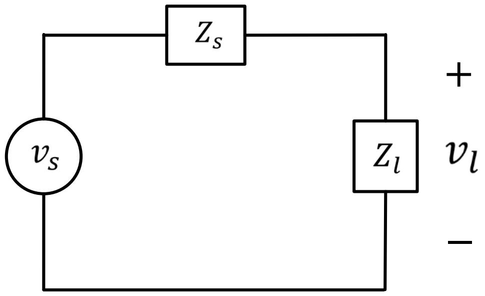

Figure 5. Simplified Power System as Feedback Control System.

$$\frac{V_l(s)}{V_s(s)} = \frac{1}{1 + Z_s(s)/Z_l(s)} \tag{2}$$

where Z_s is the source impedance and Z_l is the load impedance.

For stability analysis of the AC grid system, the system is divided into two subsystems; one is called source subsystem and the other is called load subsystem. The impedance measurement is achieved by injecting a small current perturbation in shunt, as shown in Figure 6, or small voltage perturbation in series, as shown in Figure 7, and then examining the system response [55,56].

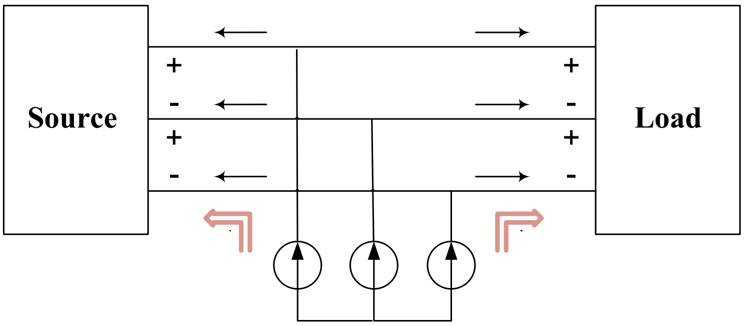

Figure 6. Current Perturbation Injected in Shunt.

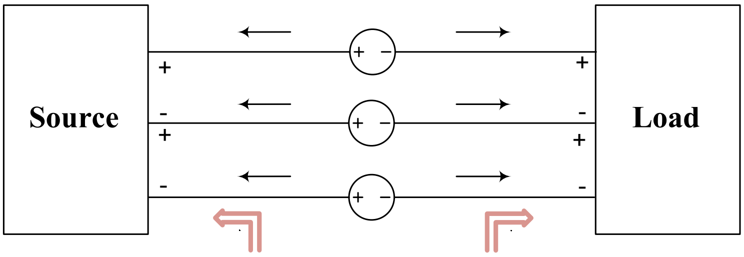

Figure 7. Voltage Perturbation Injected in Series.

A typical impedance measurement setup for both source and load side can be represented as shown in Figure 8 [57].

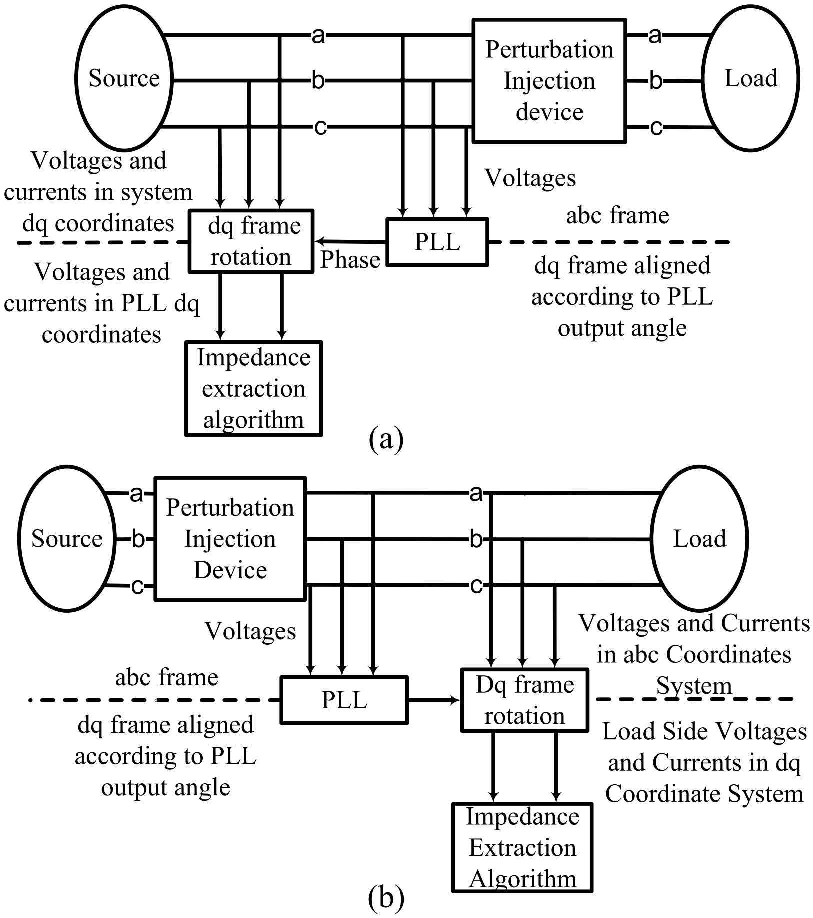

Figure 8. Impedance measurement setup in dq coordinates for (**a**) Source Side (**b**) Load Side.

NSC is then applied on input impedance of load subsystem and the output impedance of source subsystem. Middlebrook found out that system would be stable if Nyquist contour stays within the unit circle [5]. Later, in the 1970s, this criterion was further developed in [53,58]. In the 1990s it was extended and used for stability analysis of AC DG also. Attempts to develop and simplify this criterion for AC grid were made in [50,52,59]. Now it has become an important and basic tool for the stability analysis of AC type DG. Stability can be determined by only examining the open loop transfer function of source impedance and load admittance combined. Here contour would be the resultant of the product of source impedance and load admittance. A power electronics converter usually has a DC type power system on one side and an AC type power system on the other side. The first important step to evaluate the AC system stability is to determine the system impedance. A lot of research has been done in the past for DC systems stability and well established techniques are available for impedance extraction in DC grid system [5,11,52,60–63]. Input impedance at the AC interface also has the similar behavior of negative resistance [64]. So, the focus is being shifted toward AC because instability can occur at the AC interface as well [50–52]. The research related to AC impedance extraction is done in [5,7,33,52,55,56,65–82]. A comparative analysis of different shunt current impedance extraction techniques is given in Table 3.

Table 3. Comparative Analysis of Different Shunt Current Impedance Extraction Techniques.

Impedance Extraction Technique	Detail	Advantage	Disadvantage	Ref.
Bridge converter (three-phase)	Three-phase bridge converter or a shunt-connected power converter was used for current injection	The accurate control of the injected currents.	Limitations for measuring high frequencies. Pulse width modulation (PWM) needs to be a multiple of the injected frequency	[55,77]
Three-Phase Chopper Circuit	Modulates a three-phase shunt-connected resistive impedance using a three-phase chopper circuit	The switching frequency is set to the injected frequency and is very low compared to the full-bridge circuit.	The injected current will have considerable harmonics	[55,77]
Three-Phase Wound-Rotor Induction Machine (WRIM)	Used to inject a perturbation into the system. The machine injects onto all three phases as it rotates.	Can produce the same quality injection current as bridge converter and is suitable for low-, medium-, and high-voltage systems.	The WRIM must be at specific location. Induction machine must be sized for each application and power level.	[55,77]
Single-phase current injection	The impedance in SRF can be determined by injecting line-to-line current between two lines.	(1) Simpler to construct, requires less components, reduced cost, straightforward implementation. (2) Can be used for both ac and dc systems.	The injected current will have considerable harmonics (depending upon type of injection device)	[71,72]

The current injection techniques are based on electronic circuits or wound-rotor induction machines. The techniques based on electronic circuits use bridge circuits for low power systems and chopper type electronic circuits for high power systems [55]. The methods to extract the impedance can be based on current injection technique either in balanced three-phase system [55,56,70,73] or in single-phase line-line system [71,72,83]. Impedance can be measured by designing automated unit as presented in [67,73]. A comparative analysis of modern impedance extraction (other than the shunt current injection) techniques is given in Table 4.

The grid impedance extraction techniques have a long history [55,71,72,77,84–89]. These techniques can be broadly categorized as passive techniques [87], quasipassive techniques [89] and active techniques [55,71,72,77,84,88]. Passive techniques use already present signals in the system e.g., non-characteristic voltage and current harmonics whereas quasipassive techniques use hybrid techniques to extract the impedance. Since these methods are ineffective if applied disturbance is not large enough, active methods are preferred [84].

Active techniques can be based on either steady state methods or transient methods. The type of injected perturbation is periodic if a steady state active method is used. In this approach, Fourier technique is used for signal analysis. An example of the steady state method is presented [56] where a three-phase impedance analyzer is constructed in SRF. The authors present a cohesive solution addressing all critical issues simultaneously. That is not recommended in online applications though. For online applications design and implementation of impedance measurement unit up to 100 kW is presented in [73] which uses both series and shunt injection modes. SRF is only valid for extracting the impedance in three-phase AC systems. A method is proposed in [80] to extract the impedance of single-phase AC system by using the concept of Hilbert transformation.

Table 4. Comparative Analysis of Different Impedance Extraction Techniques Not Involving Shunt Current Injection.

Impedance Extraction Technique	Detail	Advantage	Disadvantage	Ref.
Maximum-length binary sequence (MLBS)	uses maximum-length binary sequence (MLBS) injection and averaging Fourier techniques to overcome the drawbacks of impulse injection	cost effective, easy data acquisition, can work under low SNR and tight amplitude restrictions, straightforward generation of sequence	Requires low noise floor	[84]
Discrete interval binary sequence (DIBS)	It is one class of pseudorandom sequences, in which the power spectrum can be specified by the user.	Energy at the harmonic frequencies can be increased up to eight times compared with MLBS, so perturbation injection is minimized	Strong grid conditions are required. Perturbation may create harmonics & nonlinearities.	[85]
Chirp Signal (also called a swept-sine signal)	Signal with wide bandwidth and low crest factor is injected into three-phase	Low crest factor so low perturbation level & wide bandwidth. Reduce measurement time.	More susceptible to noise	[67]
Recurrent Neural Networks Based Impedance Measurement	Random PWM signals and resistive chopper circuits are used to inject perturbation signals into the system	Much smaller number of online injections are needed. Impedance extraction is more consistent due to stable operating point. Reduces online test time.	Training is required to obtain impedance information at any frequency within the range of interest.	[86]

In case of transient methods, the injected perturbation is of impulse type. After injecting the impulse perturbation, the corresponding frequency component is extracted by using the Fourier analysis technique. This method works well for weak grids and is easy to implement, with limited accuracy [70]. Also, the injection of large impulse current perturbation is needed to be placed carefully between fundamental cycles. In [84], the use of a maximum-length binary sequence (MLBS) injection in place of the conventional impulse injection for online grid impedance measurement is proposed. A comparison of impedance extraction technique between SRF and harmonic linearization technique has been done in [36]. Converter control is either implemented in SRF or $(\alpha - \beta)$ reference frame. Derivation of input impedance is straightforward if converter control is implemented in SRF. The derivation is not straightforward if the control is given in $(\alpha - \beta)$ as has been discussed in [69]. Some authors have attempted to derive adaptive control techniques based on online grid impedance measurements, to provide constant damping ratio which can enhance the small-signal stability of distribution grid [88]. Design of single-phase shunt perturbation injections device in three-phase system presented in [74] is superior to simple H-bridge single-phase converter. As demonstrated in [79], admittance can be shaped by adjusting the controller parameters so as to get a positive real part which can help suppress the oscillations at certain frequency.

Most of the grid-connected PCs are designed to handle high power and already include those components capable of measuring impedances by using conventional methods. Such components can take very precise readings with a very low power requirement. However, the introduction of non-linear electronic devices has imposed certain restriction on impedance measuring devices. One restriction is that the impedance cannot be measured through old methods, thereby requiring new methods. To measure the impedances, perturbations of a reasonable magnitude are introduced into the system. Also, the perturbation injection equipment must be able to operate in the presence of power sources which can have significantly large power capacity.

At least two perturbations are required to build the 2×2 impedance matrix in SRF because only two equations can be generated though single perturbation [57]. A recent research proposed that the frequency of positive and negative sequence should be shifted twice that of fundamental for the impedance matrix extraction [36]. There are several experimentally verified impedance estimation methods [85,86,88,90] which can estimate the impedance in real time with low additional cost [54,91–94]. These impedance estimation methods are based on harmonic linearization [22,85,88] or SRF, [52,56,93,95]. Both models and impedance extraction techniques have certain advantage and disadvantage, but a comprehensive comparison is not done yet. Impedance models for specific and relatively simple system were built in [41,92,93,96] by using various stability criterion [97–100].

If system components are connected in various arrangements and these components come from various vendors, then their equivalent impedance can be used to evaluate the stability of overall system. Similarly, multiple rectifiers with high power factor connected in a power system can be converted into an equivalent single rectifier. Stability analysis for such a system can be performed by viewing it as a single input single output system [50,59] as proposed in [101] for the stability of parallel inverters. Some new impedance-based model analysis techniques proposed in [102] deserve more attention.

With the addition of non-linearity, any change in magnitude and frequency of AC system makes the system non-stationary with periodic tendencies. Stability study is not possible in SRF if more than one sinusoidal component are present in a three-phase system because the resulting system is time varying in dq coordinate system.

5. Modelling and Analysis in SRF

In SRF impedance extraction can be done both in single-phase or three-phase AC system. Originally SRF was designed for balanced three-phase AC system though. Later, it was extended to single-phase AC system.

5.1. Modelling and Analysis of Three-Phase AC Impedance

For balanced three-phase systems, the rotating SRF involving the well-known *Park*'s transformation is used. To calculate the system impedances in SRF, voltages and current are measured in three-phase AC system first and then converted to SRF [65,77] at the point of injection.

It was first proposed in 1929 [103,104]. The SRF is so called because 0-axis component remains zero all the time for balanced three-phase system, so it can be ignored. This method cannot be applied to a system with significant load on only one phase, because 0-axis component becomes non-zero making linearization impossible as 0-axis component changes periodically. Additionally, when the system is unbalanced because of fault or other abnormal system conditions the operating point is lost. It becomes difficult to linearize the system by using SRF, therefore system should be balanced to apply SRF for stability study.

At the beginning, SRF was used for control loop of rectifier and filter design in [64,105]. Then, later, its application in impedance-based stability analysis was found. The first major impedance-based stability analysis by using SRF was proposed in [50]. SRF is a virtual frame of reference that does not actually exist. Actual sensors cannot be connected to d- and q- axis terminals because they do not exist physically. This artificial frame of reference is derived in real time through real-time processing. Impedance is measured through an analyzer, a component of converter, in an artificial frame of reference through real-time processing unlike a conventional analyzer.

It is essential to establish a stable frame of reference before taking a measurement in SRF. PLL is used to achieve the alignment during park transformation to convert from three-phase to SRF. This technique has been used extensively to synchronize PCs with grid [106–109]. Techniques to achieve grid synchronization by using PLL are described in [69,93]. In [56], an analyzer is designed which provides impedance measurement through variable bandwidth PLL. Change in bandwidth of PLL under weak grid condition can lead the converter system to instability [94]. Some other techniques can also be used for grid synchronization. In the case of [63] induction machine is used, instead of PLL, to align the signal at the same reference frame.

The perturbation is first injected into q-axis and then into d-axis, the source and load impedances are then extracted at the frequency of interest. It is often not possible to explain the coupling between d-axis and q-axis or interpret the impedance physically. Some researchers have attempted to simplify the impedance-based stability criterion in SRF by only taking into account the impedance of d-axis by using unity power factor load [50,59]. In an SRF there are three channels, d, q, and zero and usually zero channel is ignored in a balanced system. As impedance occur and is represented in the form of a matrices, so source and load system cannot be created separately. There is a coupling between load and source subsystems. If a perturbation is introduced into the d-channel, it cross-couples from q-channel and then back to q-channel to produce a voltage response. The ratio of the response voltage to the injected current can be used to measure the impedance.

5.2. Modelling and Analysis of Single-Phase AC Impedance

The single-phase AC systems are different from three-phase AC systems because they are non-transformable into other reference frame. Also, these systems are different from DC systems because their operating point is not constant, so linearization is not possible.

Some approximations are required to make the stability analysis of such a system possible. One possible solution is to use harmonic linearization by neglecting the dc link dynamics [45,110,111], another possible solution is to construct an artificial three-phase AC system as described in [68] and [80]. The Hilbert transform is applied to single-phase AC systems for transforming them into fictitious qd reference frame. The research on idea of single-phase impedance is presented in [68,72,80].

To transform the single-phase AC system it is necessary that one or more fictitious phases are introduced into the system. There are two methods to introduce fictitious phases in the single-phase AC system. One method is fixed time delay which introduces a fixed phase shift of 90° between signals. The time delay method is easy to implement, but it considers only the fundamental frequency component of the system. The stability of the system should be studied for wide range of frequency so this method in not appropriate for accurate results. Second method is to use Hilbert transform. It is a mathematical technique which shifts the whole frequency spectrum by 90° but retains the amplitude of original signal. The Hilbert transformed signals used in single-phase AC systems are mentioned in Table 5.

Table 5. The Hilbert Transform of sine and cosine functions.

Signal $= u(t)$	**Hilbert Transform** $= H(u(t))$
$sin(t)$	$-cos(t)$
$cos(t)$	$sin(t)$

The transformation for sine and cosine signals is shown in Table 5. The single-phase AC system, represented by $u(t)$, can be defined as in (3)

$$u(t) = A.cos(\omega t + \phi_m(t)) \tag{3}$$

In (3) A is amplitude ω is the frequency and ϕ_m is the phase of the signal. The Hilbert transformation of (3) is shown in (4)

$$H(u(t)) = A.sin(\omega t + \phi_m(t)) \tag{4}$$

The basic concept of working of Hilbert transform in frequency domain is to shift the negative and positive frequency component of given signal by $-90°$ and $90°$. The major advantage of Hilbert transform is that it guarantees the orthogonality of the fundamental frequency signal as well as the injected signal for perturbation from input signals. The single-phase AC systems are transformed into two phase AC system using Hilbert transform by using the phase difference of 90° as shown in Figure 9.

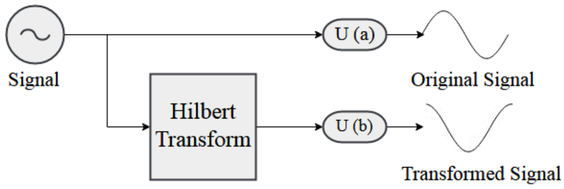

Figure 9. Single to Three-Phase Conversion by Hilbert Transform.

After applying Hilbert transformation single-phase AC systems can transform into q-d reference frame. The transformation from Hilbert to q-d reference frame is shown in (5).

$$\begin{bmatrix} U_q \\ U_d \end{bmatrix} = \begin{bmatrix} cos(\theta) & sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix} \begin{bmatrix} U_a \\ U_b \end{bmatrix} \tag{5}$$

where U_a and U_b are the components of voltage/current in three-phase, whereas U_q and U_d are the components of voltage/current in q-d frame. According to (5) the original as well as fictitious phase currents and voltages are transformed into q-d frame. Most systems are non-linear, so it is crucial to calculate the admittance or impedance of the system. The NSC discussed earlier needs the impedance matrix of the AC system. The system under consideration is single-phase AC system with an additional fictitious winding. The impedance matrix consists of four elements as shown in (6).

$$Z = \begin{bmatrix} Z_{dd} & Z_{qd} \\ Z_{dq} & Z_{qq} \end{bmatrix} \tag{6}$$

The (6) shows that impedance matrix consists of four elements. The solution of four elements required four simultaneous equations so, to obtain four simultaneous equations two set of measurements are required. Two sets of perturbations are injected in q-d frame to calculate the impedance of system as shown in (7) to (10)

$$V_{q1} = Z_{qq} I_{q1} + Z_{qd} I_{d1} \tag{7}$$

$$V_{d1} = Z_{dq} I_{q1} + Z_{dd} I_{d1} \tag{8}$$

$$V_{q2} = Z_{qq} I_{q2} + Z_{qd} I_{d2} \tag{9}$$

$$V_{d2} = Z_{dq} I_{q2} + Z_{dd} I_{d2} \tag{10}$$

V_{d1}, I_{d1}, V_{q1} and I_{q1} are the components of voltages and current after injecting the first perturbation. Whereas V_{d2}, I_{d2}, V_{q2} and I_{q2} are the components of voltages and current after injecting the second perturbation.

The set of simultaneous equations are solved to find the elements of impedance matrix. These impedances are used to build a simplified power system as shown in Figure 5. Afterwards, the NSC can be applied to evaluate the stability of the system.

6. Future Work

The way to apply SRF method to a system which is a combination of three-phase and single-phase system is yet to be determined. Similarly, it is yet to determine that for an unbalanced grid dq0 reference frame should be used or harmonic linearization is a better option. The relation of different input indices and other parameters such as distance, penetration, and size of active load with the stability and stability margins for the unbalanced DG is yet to be determined. Eventually the grid must switch toward hierarchical control structure, so integration of different components e.g., energy storage elements to improve the DG stability should be properly assessed. Also, there is a need to assess the SSSA in different grid conditions such as in emergency and during islanding to develop a comprehensive stability model.

7. Summary

This paper presents a survey of stability methods of AC type DG by using different time and frequency-domain SSSA methods especially focusing on impedance-based stability analysis in frequency domain by using SRF. There are many different types of SSSA methods in AC systems and each of these SSSA methods has advantages and disadvantages, but the most widely used method is impedance-based model in SRF. In impedance-based stability analysis first step is to find out the impedances of the system by dividing the system into source and load subsystems. The technique of SRF, by using PLL method, is used to build the impedance matrix. For this purpose, perturbations are used to disturb the system and then impedance is evaluated from the response of the system. There are various methods to inject perturbation into the system. Hilbert transform is used to convert single-phase AC into virtual SRF. Finally, NSC is applied for stability analysis by using impedance matrix and considering the system as negative feedback control system.

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