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Probabilistic Analysis of Small Signal Stability of Power System with Penetration of Distributed Generation: A Review

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Abstract:
The liberalization of electricity markets, continuous increase in power demand, shortage in conventional generating and transmission capacities and the environmental awareness of consumers contribute to the wide application of Distributed Generation (DG) into power systems. The presence of DG presents system operators with new challenges regarding DG availability, integration and impact on system security and stability. Therefore, analysis of renewable energy penetrated power system using probabilistic approaches is of utmost importance in other to ascertain the impact of intermittency of the renewable generation on the power network. This work firstly reviews the problem of instability of power systems with a considerable share of renewable generation and its significant demand for probabilistic analysis, then, provides a critical evaluation of the available probabilistic methods that have been used for the assessment of power system small signal stability. Overview of frequently used methods are presented stressing their advantages and disadvantages with the aim of highlighting their strength and weaknesses. This paper, then proposes a method known as Stochastic Collocation Method that promises to be an effective probabilistic tool for the analysis of renewable energy penetrated power system.

Keywords: *Distributed generation, small signal stability, penetration, stochastic, probabilistic analysis*

1. Introduction

Global environmental awareness, liberalization of electricity markets, continuous increase in power demand, shortage in conventional generating capacities and inadequate transmission facilities have made the concept of integrating small and medium size generating units into power distribution networks a reality worldwide. These small and medium size generating units are known as Distributed Generation (DG). However, the presence of Distributed Generation (DG) presents power system Engineers with new challenges regarding some DG sources intermittent nature, integration and impact on system security and stability, hence the need for probabilistic analysis of the power system. Distributed Generation can be defined as an electrical power source connected directly to the distribution network or on the consumer side of the meter[1], [2]. It refers to small power plants at or near the loads, operating in a stand-alone mode or connected to a grid at the distribution or sub-transmission level and geographically scattered throughout the service area. It includes small, modular technologies for electricity generation located close to the load[3], [4], [5].

IEEE defines the generation of electricity by facilities sufficiently smaller than central plants, usually 10 MW or less, so as to allow interconnection at nearly any point in the power system, as Distributed Resources.

Electric Power Research Institute (EPRI) defines distributed generation as generation from a few kilowatts up to 50 MW.

International Energy Agency (IEA) defines DG as 'Power generation equipment and system used generally at distribution levels and where the power is mainly used locally on site'.

The International Council on Large Electricity Systems (CIGRE) defines DG as generation that is not centrally planned, centrally dispatched at present, usually connected to the distribution network, and smaller than 50-100 MW[6].While the term 'Distributed Generation 'has become very popular, there has been no consensus on its definition. Generally mentioned criteria are: not centrally planned and dispatched, usually connected to the distribution network with relatively small rating, from less than 100 kW up to several MW. Other characteristics mentioned in the literature to distinguish distributed generation from conventional generation are: fluctuations in its production and its production capacity in combination with the non-predictability of the production [7].The utilization of DG sources offers a number of technical, environmental and economic benefits for utilities and consumers due to their location close to the customers. Some of the benefits that can be derived from the integration of DG into the distribution network are: reduced line losses, voltage profile improvement, reduced emissions of pollutants, increased overall energy efficiency, enhanced system reliability and security, improved power quality, reduced operation and maintenance costs of some DG technologies, enhanced productivity, reduced health care costs due to improved environment, reduced fuel costs due to increased overall efficiency, reduced reserve requirements and the associated costs and increased security for critical loads [1], [8]-[16].As the electric power systems are riding the wave of decentralization through the deployment and use of 'distributed power' technologies, appropriate and efficient probabilistic analysis tools must be in place so that when fully deployed, distributed power technologies will create a decentralized power system within which distributed generators meet local power demand throughout the network with guaranteed system security and stability.

This paper, therefore, reviews the problem of instability of power systems with a considerable share of renewable generation and its significant demand for probabilistic analysis, then, provides a critical evaluation of the available probabilistic methods that have been used for the assessment of power system small signal stability. The outline of this paper is as follows: section 2 explores the technical issues associated with distributed generation. Section 3 captures the overview of power system small signal stability. Section 4 explains various computational techniques adopted for the analysis of probabilistic small signal stability. Section 5 presents the overview of the proposed stochastic collocation method while section 6 captures the conclusion.

2. Technical Issues Associated with Distributed Generation

The question of power quality and distributed generation is not straightforward. On one hand, as highlighted in the introduction, distributed generation contributes to the improvement of power quality. For instance, in the areas where voltage support is difficult, distributed generation offers significant benefits for the voltage profile and power factor corrections. On the other hand, large-scale introduction of decentralized power generating units may lead to instability of the power system. The bi-directional power flow and the complex reactive power management can be problematic and lead to voltage profile fluctuation. Additionally, short-circuits and overloads are supplied by multiple sources, each independently not detecting the anomaly[17], [18], [19], [20]. Some of the renewables are stochastic in nature fluctuating with changes in weather. Examples of such are solar PVs and wind turbines. The fluctuation poses serious stability challenges to the grid even at low penetration levels[21], [22], [23], [24], [25]In most countries at present, stability is hardly considered when assessing DGs. However, this is likely to change as DG penetration increases and their contribution to network security becomes greater[26], [27], [28]. As the penetration increases, the network will be stressed because it was not designed to transmit power in a bi-directional way. Hence, the integration of DG transforms the distribution network into an active system involved in generation as well as bi-directional transportation of power to the grid. As a result, the distribution system is further stressed [29], [30]. When more DG will be integrated into the grid, the problem of large rotor excursion, small signal stability and voltage collapse will be a serious concern. This is because increasing the integration of DG will increase the complexity of the system thereby making system stability cumbersome for analytical approach to solve in real time. Presently, the concern of system operators is shifting towards delivering the results of stability assessment in real time or near real time in other to present accurate result of the complex power system [31], [32], [33]. Lack of suitable control strategies for electrical networks with high penetration levels of DG units poses a problem for the future systems. For instance, DG units are likely to affect the system frequency. As they are often not equipped with a load-frequency control, they will free ride on the efforts of the transmission grid operator or the regulatory body to maintain system frequency. Also, the dynamic interaction between high-voltage parts of the network from one side and DG units from the other side is an essential subject that needs extensive research. In spite of the benefits of utilizing DG units within power systems, such as the increase of the system efficiency and the improvements in the power quality and reliability [34], many technical and operational challenges have to be resolved before DG becomes commonplace. In the light of the above, analysis of power systems with a significant share of renewable generation requires probabilistic approaches in other to ascertain the impact of intermittency of the renewable generation on the power network.

3. Overview of Power System Small Signal Stability

Small signal stability analysis is about power system stability when subjected to small disturbances. Refs [35]-[43] define small signal stability as the ability of the power system to maintain synchronism under small disturbances. Conventionally, small signal stability analysis of a power system is carried out in frequency domain using the eigenvalue analysis method. The usual steps are: deriving a linear model of the nonlinear power system around a certain operating condition, solving for the eigenvalues and eigenvectors of the linearized system, then calculating the mode shape, sensitivity and participation factor based on the eigenvalue and eigenvector information[44], [45].Then, the power system can be represented by a state variable model after linearization as:

$\dot{x} = \mathrm{A}x + \mathrm{B}u$ (1)

$y = \mathrm{C}x + \mathrm{D}u$ (2)

where A is the state matrix, x is vector of state variables, u is vector of control variables, and y is vector of output variables. The process of finding the state matrix's eigenvalues corresponds to finding nontrivial solutions of:

$\mathrm{AV} = \Lambda\mathrm{V} \Leftrightarrow \mathrm{A}v_i = \lambda_i v_i$ (3)

where, if A is n x n matrix, V is a n x n matrix, whose columns are v_j , j = 1,…,n, and Λ = diag$\{\lambda_i\}$ is a n x n diagonal matrix. Λ and V satisfying the equation are vector of eigenvalues and matrix of right eigenvectors of A respectively [46], [47].The property of eigen values of the system is used to determine if the system is stable or not. For a system to be stable eigen values must be in left–hand side of the imaginary axis, otherwise, the system will be unstable. The indices of evaluating the system's eigenvalues includes the polarity, controllability, observ ability, participation factor, mode shape and sensitivity. [48].Meanwhile, the computation involved in the conventional small signal stability analysis is a time-consuming process for large networks which includes the load flow computation, the linearization at the operating point, and the eigenvalue computation. Now a days, an alternative method is to adopt model-free method such as neural networks (NN) which train the network using off-line historical data for different scenarios of critical eigenvalue prediction. By using NN, a fast computation of the eigenvalues is possible, provided that the network is properly designed and trained [49], [50]. Methods of Computational Intelligence (CI) can relieve the assessment of oscillatory stability rather than replace analytical tools and methods. Furthermore, they provide adaptability, fault tolerance and help to assist human reasoning. A very important step preparing the application of methods of computational intelligence to oscillatory stability assessment is the convenient selection of attributes for potential online use. It enables a fast assessment of the oscillatory stability within power system control [51]. When CI methods are implemented for a fast on-line oscillatory stability assessment, they always need feature extraction or feature selection based only on a small set of data. In general, results of CI methods are accurate enough for on-line oscillatory stability assessment[52]. Another method is the measurement-based analysis of small signal stability. This method is more popular for today's power system analysis because it uses real-time synchrop has or measurement obtained from Phasor Measurement Units (PMUs) that are installed at various buses to estimate the mode of oscillations based on prony method [48]. Since small disturbances is inevitable in power system operation, analysis of small signal stability is critical to the reliable operation of power systems[53]. If power system oscillations caused by small disturbances can be suppressed, such that the deviations of system state variables remain small for a long time, the power system is stable. On the contrary, if the magnitude of oscillations continues to increase or sustain indefinitely, the power system is unstable. It must be noted that any power system that is unstable in terms of small signal stability cannot operate in practice. In other words, a power system that is able to operate normally must first be stable in terms of small signal stability. Hence, one of the principal tasks in power system analysis is to carry out small-signal stability analysis to assess the power system under the specified operating conditions [54].

4. Methods of Probabilistic Analysis of Small Signal Stability

The traditional deterministic approach of analyzing power system small signal stability which evaluates the performance of a system based on a specific scenario neglects the uncertainties in power system operation, models and variables. That is, the deterministic assessment is carried out based on a set of specified system operating conditions. The solution obtained with such approach is correct only for the particular conditions of the system but unable to properly reflect the uncertainties existing in the realistic power systems, such as the fluctuations and the random factors in the variations of loads and generations, intermittence of renewable energy generations, changes in network configuration and the parameters as well as the errors in the measurement and the forecast parameters. In order to increase the reliability of the results obtained, the most stressed operating conditions of the system are commonly used for the stability assessment. Consequently, conservative results will be obtained which may be impractical for the purpose of power system economic operation and planning [55]-[58].Due to increased uncertainties associated with the operation of modern power systems, probabilistic approaches towards small-disturbance stability analysis have started to receive greater research attention. The benefits of the probabilistic approach are evident and result in more accurate depictions of the true modal variation [59]. Meanwhile, the accuracy of power system stability analysis depends on the accuracy of the models used. Using of more accurate models could result in increase in overall power system transfer capability and associated economic benefits. It is therefore important to attempt mathematical modeling and analysis of power system parameters probabilistically so that the system planners can gain a better understanding of the system stability margin[60].Various probabilistic methodologies used for small signal stability analysis can be classified into three; numerical approach, analytical approach and combination of numerical and analytical approach. The numerical approach for determination of probabilistic small signal stability is the Monte Carlo simulation (MCS). Basically, Monte Carlo simulation takes the variable that has uncertainty and assigns it a random value. The model is then run and a result is provided. This process is repeated again and again while assigning the variable in question with many different values. Once the simulation is complete, the results are averaged together to provide an estimate. The process starts from the initial stage of random number generation, followed by a loop of random input variables generation, load flow and system eigenvalue calculation, and the final stage of eigen analysis[61]. Despite the fact that the Monte Carlo Simulation approach has high degree of accuracy, it requires high computational effort which is its main demerit. A conceptual framework for probabilistic power system stability analysis consists of the following three eigen analysis of uncertain input variables and operating conditions, applying probabilistic computational methods and calculation of probabilistic stability indices [50].Over four decades ago, probabilistic analysis was introduced to load flow studies [62], power system dynamic stability studies [63] and later applied successfully to both load flow and stability studies[64] - [76].Table 1 presents various applications of probabilistic computational techniques in power system small signal stability assessment. It shows the intensity of previous research in applying a probabilistic method in small signal stability analysis.

Probabilistic Computational Techniques	Modelled Variables
Probabilistic Collocation Method	Transmission system [77], Sparse grid points [78], [88], Wind and photovoltaic [79], Load [86], [106], parameter and operational uncertainties [87], Wind [117]
Point Estimate Method	N random parameter [58], Generator and load [59], Voltage source inverter [84], Wind [89], [93], [95], [102] Wind and photovoltaic [99],
Cumulant-based method	Solar photovoltaic [80], [81], [82], [83], Load and generated power [85], Wind [91], [92], [111], [113] Wind [94], [129],[130], [131], [133],[135], Generated power [98], [100], [101], [103], [105],[126], [132], [134], Voltage phasor measurements [104], Load [107]
Neural Networks/Clustering approaches	VSC-HVDC [114], Load [119], Wind [120], [122],[125], Generated power and load [121],
Latin hypercube sampling	Generation and demand [61], wind-hydro-thermal [90], Wind [96], [97], [115], [124], [127], [128], Load [108], [112], [116], [118], [123], Plug-in electric vehicles (PEVs) and wind [109], Wind and solar photovoltaic [110]
Monte Carlo based Simulation	

Table 1: Probabilistic Computational Techniques

4.1. Probabilistic Collocation Method

The Probabilistic Collocation Method (PCM) is an approximate method that establishes a polynomial approximation between the uncertain parameters and the desired output of the system. It is a technique by which uncertainties in intensive power system computations can be related to parametric uncertainties using only a small number of simulations. It essentially creates polynomial models relating the uncertain parameters of the system to the outputs of interest. The power of the PCM method lies in its ability to select appropriate simulation points to create a polynomial model which has the same moments as a higher order model. It is computationally efficient and can significantly reduce the computation burden without compromising the result accuracy[136], [137], [138], [139].The simulation requires the following steps: reducing the number of considered uncertainties based on a ranking algorithm (to due explosive computational burden with high numbers of uncertainties), establishing orthogonal polynomials to represent system uncertainties based on desired model and the input distributions, determining collocation points for each system uncertainty, where it considers the roots of higher order orthogonal polynomials and order based on the joint probability density associated with the operating point; completing a large number of deterministic studies to calculate all coefficients for the PCM model, selecting the most probable collocation points, and calculating output moments or produce a pdf based on the obtained data set [55].The application of PCM was illustrated on small disturbance stability studies in [77-79, 86-88, 106, 117] to determine the effects of a supplementary power oscillation damping controller installed on a VSC-HVDC line in the presence of parameter and operational uncertainties, to evaluate the uncertainty in state estimation of power systems, to investigate the power system small signal stability of a power system consisting of wind and PV power generation. The simulation outputs show that the method is computationally efficient for small numbers of uncertainties and requires reduced computational time.

4.2. Point Estimate Method

The point-estimate method (PEM) is a simple but effective technique for evaluating the moments of functions of random variables. That is, it requires calculating input concentrations for each uncertainty, performing deterministic studies at each concentration, calculating the output raw moments; based on the deterministic simulation outputs and weights, calculating output central moments and standard moments to generate the required pdfs. Despite its simplicity, it can be accurate in many practical situations[140], [141]. It has a good balance of accuracy and computational burden. PEMs are superior to the simulation methods because it only needs few deterministic power flow runs [142]. It was applied to small signal stability analysis in [58, 59, 84, 89, 93, 95, 99, 102]. The outputs show that the tradeoff between the simulation precision and the computing speed can be implemented effectively while the stability probabilistic assessment and the probabilistic indices analysis can be carried out with less computational efforts to determine the small signal stability of a renewable energy penetrated power network.

4.3. Cumulant-based Method

Cumulant-based methods require: calculating uncertain input cumulants based on input mean and input central moments, establishing the system input-output sensitivity, calculating the cumulants of the change in system output directly, calculating the central moments of the system output, and obtaining output standard moments and generating pdfs. It is effective at obtaining the moments of output variables and rebuild the distributions of the same with asymptotic expansion theory such as Gram–Charlier expansion, Edgeworth expansion and Cornish–Fisher expansion [55], [143]. It has interesting properties and is computationally inexpensive. For large transmission networks, it is very adequate because of its low computational requirements. It has the disadvantage of the necessary linearization but it may be generalized for dependent random variables[144]. In the analysis of power system probabilistic small signal stability analysis, cumulant-based methods were applied in [80-83, 85, 91, 92, 111, 113] and the results show that this method gives a satisfactory result and can be used for further eigenvalues studies.

4.4. Neural Networks/Clustering Approaches

Neural Networks/Clustering approaches involve training of Neural Networks (NN) such as multilayer feed-forward, Fuzzy Logic, Self-Organizing Map by a set of training patterns and store the input-output relationships in weights. Once a NN is properly trained, it is able to approximate highly non-linear functions. Some of the advantages of the method are good interpolation behavior, improved speed of operation and usage of a small set of system data. This technique was used for the analysis of small signal stability of renewable resources penetrated power networks in [94, 98, 100, 101, 103 - 105, 107, 126, 129, 130 – 135] and the results demonstrate high efficiency, accuracy and less computation time.

4.5. Latin Hypercube Sampling

Latin hypercube sampling (LHS) was inspired by the concept of 'Latin square' from combinatorial mathematics, where an n-by-n matrix is filled with n different objects [145].The basic idea of LHS is similar to the generation of random numbers via the inverse probabilistic transformation. The difference is that LHS creates the values of F not by generating random numbers dispersed in chaotic way in the interval (0; 1), but by assigning them certain fix values. The interval (0; 1) is divided into several layers of the same width, and the x values are calculated via the inverse transformation (F−1) for the F values corresponding to the center of each layer. With reasonably high number of layers (tens or hundreds), the created quantity x will have the proper probability distribution. This approach is called stratified sampling [146], [147], [148]. Meanwhile, Latin Hypercube Sampling is typically used to save computer processing time when running Monte Carlo simulations. Studies have shown that a well-performed LHS can cut down on processing time by up to 50 percent (versus a standard Monte Carlo importance sampling) [149]. Analysis of renewables integrated power system small signal stability in [114, 119, 120 – 122, 125] was carried out using Latin Hypercube Sampling and effectiveness came to the fore front in terms of high speed and accuracy.

4.6. Monte Carlo Based Simulation

One of the most common and accurate stochastic methods is Monte Carlo Simulation (MCS). It is recognized to be a system-size independent approach and is used when the system is highly nonlinear, complicated or has many uncertain variables[150].Monte Carlo simulation involves repeated random sampling of system uncertainties in order to obtain a large dataset from which the distribution of an unknown probabilistic entity, that is, output probability density function (PDF) can be determined. The method is very flexible and virtually limitless for analysis and the algorithms can be easily extended and developed [56]. Though Monte Carlo Simulation method handles uncertainty variables very accurately, the method is computationally complex[151], nevertheless, Since MCS impose no limitations on the number or statistical properties of input parameters, they usually serve as a yardstick against which the performance of other approaches is compared[152].Application of Monte Carlo based Simulation was illustrated on power system small disturbance stability studies in [61, 90, 96, 97, 108 - 110, 112, 115, 116, 118, 123, 124, 127, 128]. The uncertainties considered include; generation, demand, Plug-in electric vehicles (PEVs), wind, small hydro and solar photovoltaic. The results were characterized with high degree of accuracy and shows that power system small signal stability may either be enhanced or deteriorated depending on the penetration of renewable energy resources. Strengths and weaknesses of the reviewed probabilistic computational methods is presented in Table 2.

Probabilistic Computational Techniques	Advantages	Disadvantages
Probabilistic Collocation Method	It reduces the computational burden without compromising the result accuracy	Not suitable for a system with large number of uncertainties.
Point Estimate Method	Quick convergence hence low computational effort is requirements. Provides accurate results	Not suitable for the analysis of large power systems.
Cumulant-based method	Accurate results are attainable. Low computational effort required. Finds application in the analysis of large-scale power systems.	Accuracy may be low in some situations due to inaccurate first order approximations.
Neural Networks/Clustering approaches	Fast and accurate. Good interpolation behavior. Requires small set of system data.	High variation in objective function values affect accuracy
Latin hypercube sampling	It is computationally efficient.	High computational burden Time consuming
Monte Carlo based Simulation	High degree of accuracy. Suitable for large-scale power systems.	

Table 2: Summary of Probabilistic Computational Techniques

5. Overview of Stochastic Collocation Method

Stochastic collocation (SC) method offers a computationally feasible alternative to traditional Monte Carlo approaches for assessing the impact of model and parameter variability [153]. It has been successfully used in computational electromagnetics[154], in medicine to quantify the effects of heart position in Electrocardiographic(ECG) forward simulation [155] and in modeling uncertainty in diffusion simulation due to microstructure variability[156].The method can be seen as a 'sampling' extension to generalized polynomial chaos, which represents the stochastic process as a linear combination of orthogonal polynomials of random variables, that is, it approximates N-dimensional integrals using quadrature rules with a properly chosen set of collocation points or nodes and a corresponding set of collocation weights. Since stochastic collocation builds statistics based on deterministic solutions for sampled stochastic parameter values, it only requires a standard discrete solver for the problem of interest. This makes for easy implementation and allows its use on problems with complicated governing equations for which a non-sampling generalized polynomial chaos formulation would be difficult or impossible. [153].

6. Conclusion

This paper reviews the problem of instability of power systems with a considerable share of renewable generation and its significant demand for probabilistic analysis, then, provides a critical evaluation of the available probabilistic methods that have been used for the assessment of power system small signal stability. Merits and demerits of the existing probabilistic methods were brought to the forefront because application of the appropriate methods of probabilistic analysis of power system small signal stability is critical to ensuring the stability and efficient operation of future power system. Meanwhile, the growth of grid integrated distributed generation which has changed the operation dynamics of power system necessitates more accurate probabilistic analysis, therefore, this paper proposes a method known as Stochastic Collocation Method that promises to be an effective probabilistic tool for the analysis of the small signal stability of renewable energy penetrated power systems.

7. References

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