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Review of Analyzing Techniques in Technical Challenges related to Distributed Generation

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Abstract
The need for alternate source of energy, to fulfill energy demand, necessitated introduction of Distributed Generation (DG) technologies. DG brings in many benefits such as high reliability, security, efficiency in operation, low power losses and low carbon emissions. But, the presence of DGs in the distribution grid also creates various technical challenges, in terms of power quality (harmonics, flickers, voltage swell and voltage sags), stability(voltage stability, transient stability and small signal stability) according to the penetration level and protection related issues (islanding, coordination, fault level, blinding of protection and false tripping).For efficient and accurate operation of distribution system with DG technologies, whether renewable or non-renewable, the above challenges need to be addressed through analysis and control. This paper provides an overview of different analyzing techniques for the technical issues that affect the operation of distribution system.

Keywords: Distributed generation, Power quality, Islanding, and Wavelets.

Introduction
Distributed Generation (DG) is basically a small scale power generating unit and located near the load centers/ consumers and these are connected to distribution grid to fulfill energy demand [1]. Integration of DG provides many benefits but causes many technical challenges that not only affect the planning but the whole operation of grid. These technical challenges are issues related to Power Quality (PQ), stability and protection. PQ term is used to define conditions in electrical grids that hinder the operation and damage the power electronic devices. These issues are harmonics, flicker, voltage swell and voltage sags. Most of the DG units are of smaller size compared to conventional generators. With low penetration level of DGs, the impact on transient stability of power system is negligible, however, if the integration is build on a larger scale, and the DGs will start affect the dynamic behavior of power system. These effects produce transient, small signal and voltage stability relates issues. Due to the instability of system the protection system gets affected and many issues such as islanding issues, coordination issues, fault level issues, blinding of protection and false tripping produces. DGs have ability to work either in a grid interconnected mode or isolated mode. But problems related to power quality, stability and protection could become the most prominent area to analyze when DGs are linked to the main grid [2].

Therefore, there is a need for appropriate analyzing technique to analyze different issues. This paper describes different technical challenges and reviews the analysis techniques for handling the issues. Section 2 focuses on analyzing techniques applied to analyze these issues. Section 3 deals with the conclusion.

Review of Analyzing Techniques - Power Quality
Merits of distributed generation force the power system utility to take measures for overcoming the technical challenges due to the integration of DGs. Incorporation of DG into existing transmission system accounts for various issues in protection, stability and power quality aspects [3].

1) Analyzing Techniques for Power Quality Issues
With the betterment in the power electronics and the digital control technology, the DG units can now be controlled to enhance performance and PQ of the system [4]. To enhance the power quality, the analysis of PQ issues like harmonics, voltage flickers, voltage fluctuations, sag or swell in voltage and the distribution system unbalance are very important. Most widely used digital signal processing techniques for the analysis are Fast Fourier Transform (FFT), Discrete Fourier Transform (DFT), Wavelet Transform (WT), and Short Time Fourier Transform (STFT) respectively. Hilbert-Huang Transform (HHT), Chirp Z-Transform (CZT), Multiple Signal Classification (MUSIC), and Modified Exact Model Order Estimation of Signal Parameters by use of rotational invariance technique are also adopted for PQ analysis.

FFT and DFT are applied in [5] to analyze harmonics in a microgrid. These techniques converts time domain signal into frequency domain. DFT is used for the periodic signal for finding the content of frequency, but it is not sufficient where the time information is necessary in the signal analysis. DFT of signal is defined as:

$$X_{DF}(k) = \sum_{n=0}^{N-1} x(n).\, e^{-j\left(\frac{2\pi}{N}\right)kn} \quad ,k = 0,1, \ldots.(N-1) \tag{1}$$

,where 'n' is nth data sample, 'N' is total number of samples, and 'k' is the frequency index. To focus on certain period of time DFT is applied with added windowing for non-stationary signals. However, it does not give the exact phase and amplitude for harmonics whose frequencies are different from that of window function.

STFT (Short Time Fourier transform), reported in [5] is used to find the phase components and sinusoidal frequency of local sections of signal with change in time. The STFT for signal $x(n)$ is represented as:

$$X_{STF}(m, f_k) = \sum_{n=0}^{N-1} h(n-m)x(n)e^{-j\left(\frac{2\pi}{N}\right)kn}$$
$$,k = 0, 1, \ldots..(N-1) \quad (2)$$

,where 'f_k' stands for k^{th} harmonic frequency and 'm' stands for the integer that represents window position on the time scale. In this method, the signal is classified into very small fragments, where these segments can be assumed to be stationary in nature. The window function 'w' is taken for this purpose. In this spectrogram, or sonogram is used for visualizing the representation of spectrum of the frequencies. Spectrograms are usually created either by using STFT from the time signal, or by approximating as a filter bank resulting from a series of the band pass filters. They both actually form two different time-frequency distributions, but become equivalent under certain conditions. Stockwell transform (S-transform) using spectrogram analysis provides us with good visual analyzation of signal.

Wavelet transform (WT), [6] is another method to estimate the harmonics. It is suitable for both stationary and non-stationary signals. It is more suitable than Fourier techniques, if one is not assured about exact frequency components of the signal. WT is used to find the PQ disturbances e.g. voltage sags or swells oscillatory and impulsive transients, voltage fluctuations and notching. All the wavelet functions are extracted from the mother wavelet through scaling 'S' and translation 'T'. The Continuous WT is defined as:

$$X_{WT}(T, S) = \frac{1}{\sqrt{S}} \int x(t) \cdot \varphi(t) * \frac{(t-T)}{S} dt \quad (3)$$

,where $x(t)$ is the signal for analysis, $\varphi(t)$ is the mother wavelet. The discrete WT in a dyadic grid, $s = 2^m$, and $T = n\, 2^m$, n and m being integral values. By substituting value of 's' the mother wavelet is expressed as follows:

$$\varphi\, m.n\, (t) = \frac{1}{\sqrt{S}} \int \varphi * \frac{(t-n2^m)}{2^m} \quad (4)$$

The signal of grid voltage is captured at point of common coupling, and then is processed by taking a frame length comprising of desired sample points. Top level DWT is applied on the frame and the wavelet energy of detail coefficients is calculated. Wavelet energy is expressed as:

$$E_j = \sum_{K=1}^{N} |Djk|^2, j = 1, 2, \ldots L \quad (5)$$

,where 'Djk' is wavelet detail coefficients derived during the decomposition upto level 'N'. A total coefficient at each decomposition level is 'N', length of the sample is 'L' and at decomposition level 'j' is the energy of the detail coefficients is 'E_j'. The wavelet energy plot is drawn between wavelet energy and number of frames discrete WT is applied on the frames and further the wavelet energy of detail coefficients has been plotted. The event is observed through the wavelet energy plot. According to change in the wavelet energy level and number of frames the PQ events can be observed. At Point of Common Coupling (PCC), voltage signal of the grid is captured which is then processed through taking a frame length of 128 sampling points.

Hilbert-Huang Transform (HHT) is an appropriate method to carry out disturbance detection and harmonic analysis in [7]. It is a two stage analysis technique based on instantaneous frequency concept. It decomposes the data into the IMF (Intrinsic Mode Functions) by using shifting process, called EMD (Empirical Mode Decomposition). IMFs are adaptive basis functions derived from data itself. Decomposition process contains successive shifting to arrive at IMFs until the stopping criteria are met. The expression of signal $x(t)$ in terms of 'j^{th}' IMF 'C_j' can be represented as follows:

$$x(t) = \sum_{j=1}^{n} C_j(t) + r_n \quad (6)$$

In this method, the decomposition is continued until the last obtained component or residual is small or residual becomes a monotonic function. In second step, HT (Hilbert Transform) is applied on the obtained IMFs that provide information about the phase and amplitude, in both, time and frequency scales. IMFs can be represented as:

$$HC_j(t) = d_j(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{C_j(t')}{(t-t')} dt' \quad (7)$$

,where '$HC_j(t)$' is the Hilbert transform of any real valued function. 'D_j' is the Hilbert transform. The Cauchy principal value is represented by 'P'. The function HT and IMF is as follows:

$$Z(t) = C_j(t) + D_j(t) = A(t)\, e^{j\theta(t)} \quad (8)$$

,where $A(t)$ is the amplitude and $\theta(t)$ is the phase. This method has advantages over FFT and WT, such in terms of analyzing the non-stationary signal, good adaptive ability and inexistent choice of basis functions.

Chirp Z-Transform (CZT) with seven term B Harris Window is used in [8] for the estimation of harmonic in the distributed PV System under low and high and low irradiance. It is an efficient and fast technique as compared to DFT in computational point of view, for prime length transforms, and also in computing subset of DFT for a sequence. CZT determines the Z-transform with the spiral contours in the *z*-plane for a given sequence input. The CZT is forced to operate with unit circle, but can determine Z-transform along with the contours described as follows:

$$Z_e = AW^{-L}, L = 0, 1 \ldots \ldots M^{-L} \quad (9)$$

The complex starting point is $'A'$, complex scalar that defines complex ratio between given points on contour is $'W'$, and length of transform is $'L'$.

Multiple Signal Classification (MUSIC) is a parametric method of noise subspace is reported in [9] to calculate frequencies present in the signal. This algorithm is used for estimating the directions of arrival (DOA) of various signals. By the spectral peak searching method, frequencies of the various incident signals are computed. To create the super-resolution approach, the variance of MUSIC algorithm uses the Cramér– Rao bounds. The steering vector according to the harmonic frequencies is represented as:

$$a(\omega) = [1\ e^{j\omega} \ldots \ldots \ldots .\ e^{j(p-1)\omega}] \quad (10)$$

where is $'p'$a scalar integer. Based on the steering vector and orthogonal characteristics of noise subspace:

$$f(\omega) = a^{H}(\omega).V_n.V_n^H a(\omega) = 0 \quad (11)$$

Pseudo power spectrum PMUSIC is defined as:

$$P_{MUSIC} = \frac{1}{f(\omega)}, \omega = 1,2, \ldots \ldots M \quad (12)$$

Then, the harmonic frequencies can be computed from minima the $f(\omega)$ by searching over $'\omega'$ with fine grid.

Fast harmonic phasor measurement method, [10] derives MEMO-ESPRIT (Modified Exact Model Order-Estimation of Signal Parameters by use of Rotational Invariance Technique), harmonic phasors. The harmonic phasors are calculated with respect to nominal fundamental signal, which is then synchronized with global positioning system, hence giving, real-time synchronized harmonic phasors. This method is advantageous in the fault diagnosis and analysis point of view.

Smart Meters (SM), reported in [11] implements the PQ - framed aggregation algorithm. In this algorithm, real time values of the voltage parameters are analyzed to allow the optimal network operation in real time. These meters can be used in calculating the voltage quality. The data is in time stamped for Supervisory Control And Data Acquisition (SCADA) system, known as Synchro-SCADA helps in controlling active network, such as, preserving the quality of voltage at the end–user level.

2) Analyzing Techniques for Stability

For the reliable operation of power system, system has to remain in stable or in synchronism after being subjected to disturbances. Stability in power system deals with the voltage, transient and small signal stability issues.

Voltage Stability

A comprehensive analysis on the effects of penetration of the DG on voltage stability in a low voltage secondary meshed network has been discussed in [12]. The VSM (Voltage Stability Margin) depends on the penetration of DG. The penetration will cause positive effects on VSM, and negative effects may occur, in some cases, where VSM is lowered by large induction type DGs. A Distributed TDSVA (Transmission Distribution Coupled Static Voltage Stability Assessment) is developed in [13] to check the voltage stability of the integrated system. In this approach, distributed continuation power flow algorithm is designed which posses a distributed transmission distribution corrector, a distribution equivalencing-based predictor and a step length regulator. It needs limited amount of data exchange between TSO (Transmission System Operator) and DSO (Distribution System Operator).

Transient Stability

The analysis of transient stability of an islanded microgrid under varying load conditions is reported in [14]. In this, the load coordination technique is implemented and the stability against dynamic and fixed loads is analyzed. In cases with higher penetration of DGs Projective Integration Method (PIM) is applied in [15] to determine the transient stability. It adopts mixed explicit-implicit integration methods to gain both, numerical stability and efficiency. Moreover, the stability of PIM is independent of its parameter but is dependent on the step size.

Small Signal Stability

The concept of 'critical cluster' in the microgrids controlled by inverter based droop has been used in [16] to determine the margin of small signal stability of given system. Clustering is a technique of data mining that makes useful cluster of objects having similar characteristics by using the automated technique. The formation of clustering between distributed generators begins from electrical connection with lowest impedance, known as "critical line". Initially it is performed for determining the modes of oscillations. The eigen-value analysis of models provides the correlation amongst the locations of their eminent individual connections between low frequency modes and neighboring inverters. Further, a sensitivity analysis is done for calculating the active power droop gain with respect to the parameters of the network that ascertains previous findings and depicts the prominent effect of critical line impedance. The state-space model for small-signal stability has been developed in [17] for inverter based DGs. Particle Swarm Optimization (PSO) algorithm has been applied for optimizing the control parameters.

The analysis of small signal stability in distribution networks is carried out with electric springs installed at the consumer supply points in[18]. Vector control of these springs along with reactive compensation is carried out to ascertain the compatibility with other components' standard stability models. A liberalized state-space model is developed with multiple energy storages of the distribution network which can be extended to include DGs which are inverter-interfaced, active loads, equipment with energy storage, etc. This analysis is carried out for various scenarios covering dense urban or sparse rural distribution network and low to medium voltage levels.

3) Analyzing Techniques of Protection Issues

The main purpose of a protective system is to recognize abnormalities present in the system which can cause damage to the equipment if undetected. It also takes corrective measures e.g. isolating the faulty component and restoring the remaining part of the grid to normal operation. Protection issues in the presence of DGs are mainly on islanding and improper relay co-ordination. Islanding refers to the condition of safe isolation of the DG fed system to have minimum intervention from the fault.

Islanding Detection

Islanding detection deals with detection of disturbances and deriving suitable strategies to isolate the system. WT is used in [19] to detect disturbances in the hybrid power system connected to the grid. Use of WT causes disintegration of the transients in a series of wavelet components with specific frequency band. The detailed information and approximations related to fault voltages are extracted from original signal. When utility grid gets isolated, the variation within decomposition coefficient of voltage signals occurs. The voltage signal is captured at the PCC and is applied on a sequence analyzer to get the negative sequence voltage and is then passed through the mother wavelet. Disturbance detection is done by the increase in energy or standard deviation. The limitation of wavelet transform based analysis method is that it fails to detect notch under noisy conditions (20 dB) but Stockwell -Transform (S-transform) works effectively under both normal and noisy conditions is reported in [20] to detect the islanding situations. It provides better resolution as a function of frequency and is based on a scalable localization of the Gaussian window.

Data mining based intelligent scheme is reported in [21] for DG protection. In this method, dominating properties are extracted from the time varying signal e.g. voltage at PCC using DFT based pre-processor at the end of DG. Once these features are retrieved, the decision tree is made. On the basis of decision tree data-mining models are created to identify the events of islanding from the non-islanding conditions, including those conditions which are close to the islanding situation.

Islanding detection based on mathematical morphology is used in [22]. The extraction is done with a predefined set called Structuring Element (SE), where the SE shape is predefined considering the previous knowledge of the signal shape. The two base operations used in mathematical morphology are dilation and erosion. Hybrid Islanding Detection Approach (HIDA) is proposed in [23]. The Slip Mode Frequency-Shift (SMS) is used in active method and in the passive method the inputs from over/under frequency relay and Rate of Change of Frequency (ROCOF) relay are used. In the absence of electrical network, the SMS uses positive feedback to destabilize inverter-based DGs. The ROCOF relay operates to activate SMS when islanding condition is suspected.

Improper Relay Co-Ordination Detection

The main purpose of a coordination technique is to ensure that minimum healthy portion of the grid is interrupted during isolation of a fault or overload, anywhere in the system.

In the presence of DG, some problems in coordination of protection devices will occur due to change in short circuit level at different points. ADAS (Advanced Distribution Automation System) is reported in [24] to monitor the status of operation of line switches and Wind Generators (WGs). It is used for collecting the status of line switches and for operating them for carrying out the load transfer among feeders and its terminal units and collect the status of line switches. It communicates to Master Station (MS) through optic fiber communication. A topology processor is installed at MS for updation of the configuration of distribution network with respect to the operational status of line switches and connectivity attributes. In addition, ADAS monitors the operation of all the WGs to find the power capacities and the locations of all operated WGs.

Results-Comparative Analysis of All Techniques

A summarized view of the different analyzing techniques is presented in Table I.

Table 1: Comparison Table for different control techniques

Type of Issues	Analyzing Techniques	Merits	Demerits
Power quality (Harmonics / Voltage fluctuations / Sag / Swell)	Fast Fourier Transform (FFT) and Discrete Fourier Transform (DFT)	Suitable for stationary signal. Used for periodic signal to find out its frequency content Applied to non-stationary signals but with added windowing to focus on certain period of time.	Does not provide time information of signal. Does not provide exact amplitude and phase values for harmonics whose frequencies different from window function frequency.
	Stockwell Transform(S-Transform)	Provides better resolution in time-frequency domain. Provides information about relative amplitude of various sinusoids in signal at any time.	Fixed width of window Poor time resolutions of high frequency events.

Contd…. Power quality (Harmonics / Voltage fluctuations / Sag / Swell)	Short Time Fourier Transform (STFT)	Used to find the phase components and sinusoidal frequency of local sections of signal with change in time.	Fixed resolution at all the time.
	Wavelet Transform (WT)	Suitable for stationary signal and non-stationary signals. Used for time-frequency analysis.	High computational burden Interpretation complexity limits
	Hilbert-Huang Transform (HHT)	Provides information about the phase and amplitude, in both, time and frequency scales. Good adaptive ability.	Accuracy is dependent on spline fitting and it requires over sampled data for exact definition of instantaneous frequency.
	Chirp Z-Transform (CZT)	Efficient and fast technique Flexibility on data sampling	Extra Storage requirements
	Multiple Signal Classification (MUSIC)	Good accuracy with shorter length of data High resolution	High storage requirements and takes more time
	Modified Exact Model Order Estimation of Signal Parameters by use of rotational invariance technique	Advantageous in the fault diagnosis and analysis point of view. No storage requirements High resolutions	High computational burden and takes more time

Islanding	Wavelet Transform (WT)	Insensitive to regular signal behavior but sensitive to disturbances or irregularities	It has batch processing step. It fails to detect notch under noisy conditions (20 dB).
	Stockwell Transform (S-Transform)	Works in both normal and noisy conditions. Better performance.	Fixed width of window
	Data mining based intelligent scheme	Fast in detecting islanding	Proper selection of features to be extracted is
	Mathematical morphology	Helps in extracting the exponential decaying DC	Complex technique Needs more
	Hybrid Islanding Detection Approach (HIDA)	Detects islanding efficiently with high quality factor.	Only applicable to inverter based DGs
Relay coordination	Advanced Distribution Automation System (ADAS)	Used to find the power capacities and the locations of all operated WGs.	Proper relay setting is quite difficult
Voltage stability	Transmission Distribution Coupled Static Voltage Stability Assessment (TDSVA)	Provides accurate assessment.	Limitation in amount of data exchange Applicable to integrated system only
Transient stability	Projective Integration Method (PIM)	Works for fixed and dynamic loads. Helps to gain numerical stability and efficiency.	Performance is dependent on step size

Small signal stability		Provides effective margins of small signal stability Gives information about modes of oscillations.	Eigen value analysis of small signal model required More complex

Conclusion

In this paper, a comprehensive review on various technical challenges faced in grid operation, and the techniques that are used for the analysis in the DG integrated distribution grid are discussed. Though, DGs have potential for achieving increasing demand of energy, still there are some barriers viz. economical, technical and operational which are to be overcome to utilize the DG technology to the full extend. A comparative analysis of various techniques, highlighting the limitations is brought out in the paper. This review enlightens the researchers to select the suitable technique for analyzing the effect of power system issues in integrated operation and then motivates further to select a suitable control strategy in mitigating/ minimizing the effect in grid operation.

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