Real Time Stability Enhancement for Islanded Microgrids

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***Abstract*—Highly fluctuating renewable sources create enormous stability issues in microgrids. Small signal and transient stability are the major classifications in microgrid stability. For small signal studies, eigenvalue analysis based on state space modeling is the most common method. Detailed dynamic modeling of the system is required for transient analysis. Since transient stability is related to larger disturbances, it creates power imbalance problem in microgrids. Therefore, calculation of power imbalance is an essential study for an islanded microgrid. This paper gives a review of the existing microgrid stability analysis methods. It also suggests a real-time stability monitoring method for islanded microgrids. A classification method along with feature extraction is presented to identify load disturbances based on the amount of load change by using frequency oscillation data. The method is validated using MATLAB simulations applied to a simple microgrid system.**

***Index Terms*—classifier, microgrid stability, real-time stability monitoring, signal processing, support vector machine.**

I. Introduction

Reduction of environmental pollution caused by electricity production with reliable and efficient supply of electricity has instigated the research towards microgrids. A microgrid is composed of distributed generations, loads, energy storage, secondary loads and controllers which cover the electrification of a small geographical area, and can be operated in grid connected mode as well as islanded mode[1]. Compared to the traditional grid, the microgrid has various stability issues due to unpredictable renewable sources and highly fluctuating demand[2][3].

The stability issues are often a concern in islanded microgrids. In grid connected mode, frequency and voltage of the microgrid are maintained by the larger grid. In case of islanded operation, frequency, voltage and power balance should be handled by the microgrid itself[4]. As distributed generations in microgrid normally rely on inverter based renewable sources, they do not have enough kinetic energy. This decrease in kinetic reserve in renewable based microgrids leads to stability issues [5].

When it comes to improving the stability limits for microgrids, traditional power system stabilizers and excitation systems are not useful because of the lack of spinning reserve in microgrids[3][6]. Further due to the low physical inertia of the microgrid, the dynamic response is much quicker than the conventional rotating machines, which makes the system potentially susceptible to oscillations, resulting from network disturbances [7].

Small signal stability issues in microgrids can be related to feedback controller, continuous load switching, power limit of the micro sources, etc. It can be improved by using supplementary control loops[2][8], coordinated control of DGs[9], stabilizers for DGs[10] and energy management system[11][12].

Transient stability studies should be carried out after any large disturbance. It can be achieved through nonlinear analysis methods[4]. Lyapunov's method is the most common method used in transient stability analysis of microgrids. Power imbalance issue may arise due to larger disturbance. Therefore, an accurate power deficit calculation is essential to be carried out and an appropriate load shedding has to be suggested to improve the transient stability. Conventional load shedding methods are not applicable for microgrids due to its low inertia issues [4][13].

This paper gives an in-depth review of small signal analysis, transient analysis in microgrids including methods of power deficit calculation for load shedding and the existing real-time stability monitoring methods with their limitations in section II. A modified method is suggested in section III. The proposed method has been applied to a standalone microgrid system in section IV and the results are discussed in section V. Conclusions are outlined in Section VI.

II. MICROGRID STABILITY ISSUES

Power imbalance is the key challenge in the stability of any power system. In islanded microgrids, highly fluctuating energy sources and demand frequently create imbalance issue, even if it is equipped with energy storage. Zhikang Shuai et al. [14] classified the microgrid stability into two major divisions, namely, small signal stability and transient stability, in both mode of operations, grid connected and islanded.

A. SMALL SIGNAL STABILITY ANALYSIS

Most of the small signal stability studies are carried by sensitivity analysis of system eigenvalue based on state space modeling of microgrid. A research conducted by Xisheng Tang et al. [15] studied the small signal stability problem for a microgrid with and without energy storage system. It was

978-1-5386-4950-3/17/$31.00 ©2017 IEEE

concluded that properly designed and controlled energy storage is an essential solution to this issue. The results are validated by using simulation and experiments. However, this study has only wind energy as renewable source and the method is complicated when applied to a multi-source microgrid system. In [16] small signal stability was investigated by optimizing the droop controller parameters. Inverter dynamics, network dynamics and load dynamics were considered in this study. By performing the eigenvalue loci analysis, it was demonstrated that the system's small signal stability is influenced by real and reactive power droop gain, proportional parameter of voltage, and integral parameter of current.

Zhuoli Zhao et al. [17] worked on MV islanded microgrid by defining different zones, such as emergency zone, precautionary zone and stability zone in terms of frequency deviation and introduced a hierarchical frequency control. However, it is not applicable for decentralized control architecture. In [18] coupling control of n different microgrids to improve the small signal stability was suggested. Further, multi energy storage and critical clusters have also been suggested by other researches for small signal stability enhancement. By considering the complexity of the detailed state space modeling, Md. Rasheduzzaman et al. [19] suggested reduced order small signal model of the microgrid system using perturbation theory. Although the above linearized state modeling is simple and straight forward, it has several drawbacks, such as difficulty of implementation for a large microgrid, cannot take real time random factors into consideration, restricted to certain operating point, low efficiency, and complexity in obtaining accurate system parameters.

Instead of state space modeling, impedance modeling is also used in microgrid small signal analysis. In this context, each load and source is expressed by its input and output impedance[20]. Based on the forbidden region of impedance ratio, the stability status is decided. In [21], two source AC microgrid system has been studied for small signal problem by using impedance modeling. Nyquist plot and bode plot were taken to analyze the stability in real time operation as well. It was shown that even fixed parameters like filter coefficients can be adjusted by having some virtual impedance or active damping. However, difficulty in three phase model linearization and decoupling the output impedance in unbalance situation, affect the impedance modeling.

Identification of damping characteristics of small signal oscillations is achieved by some nonlinear methods. In [22] Kalman filter technique and in [23] Prony analysis are used to modal identification. In addition to that, different signal processing methods have also been considered for the above purpose. Various studies were carried out by using continuous and discrete wavelet transformation, wavelet packets, Fourier transformation, fast Fourier transformation, and S-domain analysis. Seyyed Ahmad Hosseini et al. [24], introduced a Fourier based wavelet approach by using Heisenberg's uncertainty principle and Shannon's entropy criterion to identify the damping characteristics. The equations have been derived theoretically and the parameters were optimized. Then, the proposed method had been applied on New England test system. The proposed method was proved to perform well in comparison with normal continuous wavelet transformation.

Probabilistic based small signal analysis is carried out in [25] for multiple wind turbine micorgrid system, where, second order polynomials and probability distribution functions are used to investigate the relationship between modes, damping ratio and multiple wind generations. Point estimation, forecasting and probability density function analysis are other methods used by researchers.

Recent microgrids are using open communication network to transfer information from a central controller. Delay in the communication severely affects the dynamic performance of the system. Saeed Golestan et al. [26] analyzed four different types of Phase Locked Loop (PLL) controllers and have suggested Enhanced Time Delay PLL (ETD-PLL) as the most appropriate controller to mitigate the delay. Ref[27] proposes a method to develop a cyber physical model of a microgrid to analyze constant and time varying delay. It also introduced an analytical method to determine the delay margin and the accuracy is validated based on simulation results. Time delay in communication is a crucial factor in stability analysis. Even minor delays may lead to instability in microgrids as their dynamic response is much quicker than the conventional rotating machines.

B. *TRANSIENT STABILITY ANALYSIS*

R. Belkacemi et al. [28] did an experiment to analyze the transient stability of a microgrid for different fault scenarios in islanded and grid connected modes. It was concluded that islanded mode operation is more vulnerable to faults and abnormal conditions than the grid connected mode. Yunqi Wang et al. [29] did a study on critical clearing time (CCT) of transient problems in microgrid. It is proved that the transient stability is affected by many other factors including DG penetration level, wind turbine crowbar protection and battery storage capacity. It is also shown that higher levels of wind energy penetration reduces the CCT, although they could contribute to transient stability improvement at lower penetration levels. However, with the higher amount of energy storage system, the CCT can be improved. Wavelet and Fourier transformation, line based models and numerical calculations are also used in transient stability studies to analyze the transients.

C. *LOAD SHEDDING*

Traditional load shedding methods of conventional system is not applicable for microgrids because of low inertia and mechanical power variation of energy sources with time. An adaptive load shedding scheme in[30] and multistage under frequency load shedding in[31] were based on conventional methods. In these, theoretical deviations of microgrids from conventional system were not considered well. A multi stage under frequency load sheding algorithms has been proposed to calculate the power deficit in [32]. However, it is not descriptive in terms of where to shed load and when to shed load.

Ajit A. Renjit et al. [33] presented a novel method to identify the power deficit in an islanded microgrid by using

Rate of Change of Frequency (ROCOF) and frequency nadir (The minimum value of frequency) of frequency oscillation. They used CERTS (Consortium for Electric Reliability Technology Solutions) islanded microgrid test bed for this study. All the testing and analysis have been applied to the CERTS test bed and state space Reduced Order Model (ROM) of the same microgrid. Both results are compared under different operating modes of energy storage and different generation set points. It was shown that the reduced order state space model performs well to calculate the power deficit of an islanded microgrid following any disturbance. Even though, the variation of mechanical power had been considered in their work, the equivalent inertia of the machines is fixed at a constant value all the times. Further, linearization for state space modeling is not applicable for larger disturbances.

Identification of 1) when to shed load, 2) where to shed load and 3) how much load to shed is very important to efficiently run the system technically and economically. Conventional load shedding schemes are implemented with the only consideration of rate of change of frequency. But, this is not enough for microgrids, as it is very sensitive to minor changes. Therefore, a fast and reliable load shedding strategy, independent to the microgrid parameters would be a better solution for islanded microgrids.

D. EXISTING REAL-TIME STABILITY ANALYSIS FOR MICROGRIDS

Geir Kulia et al. [34] developed a software platform to analyze the real-time electrical voltage and current waveforms for islanded microgrids. Hilbert Huang Transformation based Empirical Mode Decomposition (HHT-EMD) was used as a key building block for the above analysis. It was concluded that measurement based analysis in real-time is sufficient to acquire, analyze and detect the microgrid problems. However, the results analyzed the frequency pattern only and did not determine the exact frequency values for short samples. In [35], a real-time prediction of energy management by using probabilistic algorithms was presented for microgrids. The future energy demand in real-time was predicted by collecting sensor data and reconstructing missing data. However, there is no discussion on stability enhancement. Instantaneous frequency tracking of harmonic distortion was studied in [36]. An adaptive Kalman filter technique was used for harmonic identification and stability improvement. Further, steady state impedance model was used to estimate the parameters correctly.

All the above research studies are related to specific issues in microgrids that may not necessarily enhance the stability, although they may have the capacity for this. This paper introduces a real time monitoring approach especially for analyzing the stability of islanded microgrids.

III. PROPOSED METHODOLOGY: REAL TIME STABILITY ANALYZER FOR ISLANDED MICROGRID

The primary objective of this study is to develop a real-time stability analyzer and decision maker to enhance the stability of islanded microgrids. Determining the type of stability issue and amount of power imbalance could be achieved using signal processing techniques and machine learning methods.

Most of the existing stability enhancement methods for microgrids are restricted to certain operating points. Further, they are almost following the conventional stability enhancement methods. Because the microgrid is too sensitive and rely on time varying parameters, real-time random factors should be taken into the consideration. As islanded microgrid has limited number of generating units, load feeders and buses. This makes it possible to collect frequency and voltage oscillation data at all the nodes and in all combinations of disturbances over a wide range. Therefore, a disturbance classifier needs to be developed to identify the behavior of islanded microgrids for each disturbance by using collected data. When a new disturbance data goes into the classifier, it should be able to,

- Differentiate the data based on types of disturbances (load change, generation change, any fault, etc.)
- Identify the location of the disturbance (load feeder, generation plant, faulty line etc.)
- Identify the amount of disturbance (amount of load change, amount of generation change etc.)
- Calculate the amount of power imbalance

Based on the type, location, amount of disturbance and power imbalance, stability of the system can be analyzed. The decision from the classifier can be sent to the central controller/proper protection relay to maintain the system stability and reliability. In this work, as a first step, load disturbance classification based on the amount of disturbance is carried out by using support vector machine classifier.

IV. INITIAL TESTING OF THE PROPOSED METHODOLOGY

As an initial step towards implementing a real-time stability analyzer and decision maker, a wind based microgrid system with 1150kW wind generation, synchronous condenser, 1000kW base load and (0 – 300) kW secondary load, shown in figure 1 is simulated in MATLAB/SIMULINK and used for data collection.

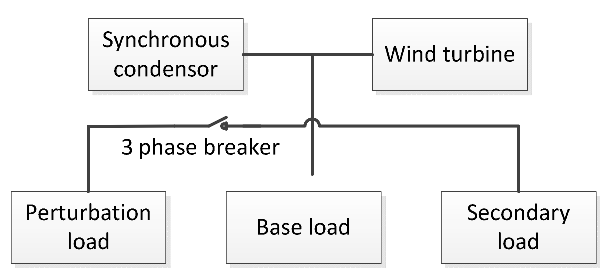

Figure 1. Microgrid architecture

It is a three phase, 400V and 50Hz microgrid. The secondary load can be adjusted automatically based on the availability of generation and base load. There is an option to connect and disconnect a perturbation load throughout the running time by a three-phase breaker.

A. DATA COLLECTION

Load disturbance is created at 5th second as shown in figure 2 in a wide range, ±15% (-150kW to +150kW) of base load in steps of 0.1% (0.1kW). Frequency oscillation data for 45 seconds following the disturbance is obtained for each disturbance. A total of 3000 data files were collected with 1500 each for load increment and load decrement. The sampling frequency used here is 8.15 kHz

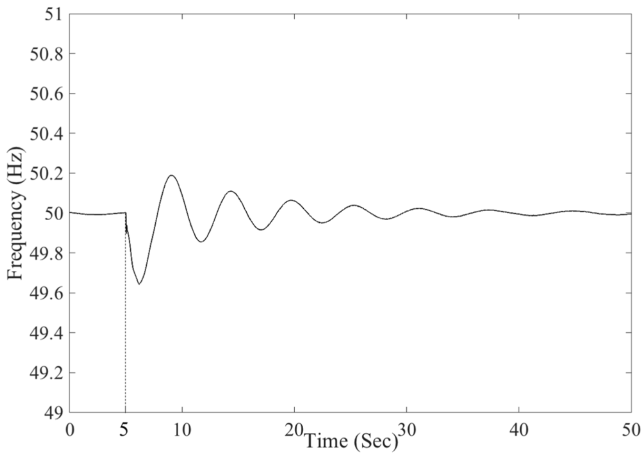

Figure 2. Frequency oscillation for 100kW load increment

B. FEATURE EXTRACTION AND CLASSIFICATION

In order to classify the data collected for various load changes, a feature extraction algorithm followed by a classifier is implemented as shown in figures 3 and 4.

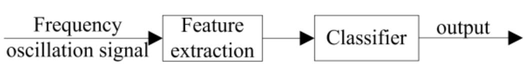

Figure 3. System overview

Figure 4 shows the feature extraction process. The Fast Fourier Transform (FFT) of the signal is obtained and magnitude of the FFT is retained. The FFT bins are grouped into 10 equal sub-bands. Average energies are calculated for each sub-band, thus providing 10 energy values (E_0,E_1……..E_9). The log energies are smoothed using Discrete Cousine Transformation (DCT) to obtain 10 dimensional features (C_0,C_1……..C_9). In addition, the peak value of the oscillation is also taken into consideration as a 11th feature.

There are 9 different classifications based on the number of classes tested as shown in table I. Type 1 has 2 classes, load increment (0 to +150kW) in one class and load decrement (0 to -150kW) in another class. Type 2 has 4 classes, i.e., load increment (0 to +75kW), load increment (+75kW to +150kW),

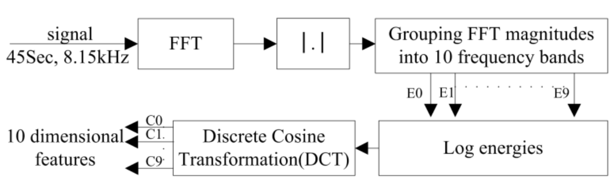

Figure 4. Feature extraction

load decrement (0 to -75kW) and load decrement (-75kW to -150kW). Likewise, Type 9 has 30 classes in 1kW intervals, with 15 classes each in load increment and load decrement. Their accuracy levels are obtained with independent test data. Support Vector Machine (SVM) classifier is used to classify the data.

V. RESULTS AND DISCUSSION

As per the results, shown in table I, load increment and decrement is classified with 95% of accuracy in the first type of classification. Percentage of accuracy is gradually decreasing with number of classes, since the number of data in each class is also reducing while number of classes is increasing. However, it is able to classify up to 1% (10kW) step change in load with 80% of accuracy considering 30 classes. By increasing the number of data in fine-tuned intervals, the accuracy level could be improved further.

TABLE I. SVM CLASSIFICATION AND ACCURACY

Types	No. of classes	No. of training data	No. of test data	Classification accuracy (independent test data)
Type 1	2	1400×2	100×2	95.00%
Type 2	4	700×4	50×4	94.50%
Type 3	6	450×6	50×6	89.33%
Type 4	8	325×8	50×8	87.50%
Type 5	10	250×10	50×10	81.60%
Type 6	12	200×12	50×12	79.83%
Type 7	20	120×20	30×20	77.83%
Type 8	24	100×24	25×24	79.66%
Type 9	30	90×30	10×30	80.10%

VI. CONCLUSION

Microgrid stability issues and currently available enhancement methods are discussed in terms of small signal stability, transient stability and amount of power deficit calculation. Since most of the stability analysis has been done on the static model of the microgrid system, the real time random factors were not taken into consideration. Thus, real time measurement based stability analysis method could be a solution for the above drawback. To overcome the shortcomings in the existing methods, a real-time stability analyzer for islanded microgrid is introduced. A novel feature extractor is proposed to classify the large amount of load disturbance frequency data based on the amount of load change. The results obtained from the proposed methodology shows better accuracy. Therefore, the proposed method could be applied for the stability enhancement of an islanded microgrid in real-time.

The method could be further validated by collecting a huge amount of frequency and voltage oscillation data in all the scenarios of disturbance from a renewable based multi-source microgrid.

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