AKADÉMIAI KIADÓ

UNIVERSITY of DEBRECEN

International Review of Applied Sciences and Engineering

12 (2021) 2, 157–165

DOI:
10.1556/1848.2021.00215

ORIGINAL RESEARCH PAPER

A novel scheme for island detection in microgrids based on fuzzy c-means clustering technique

Amin Damanjani, Mohamad Hosseini Abardeh*,
Azita Azarfar and Mehrdad Hojjat

Department of Electrical and Computer Engineering, Shahrood Branch, Islamic Azad University, Shahrood, Iran

Received: December 5, 2020 • Accepted: February 12, 2021
Published online: April 14, 2021

ABSTRACT

Microgrids (MGs) are capable to work at different operation modes, namely grid-connected or islanded, which make a significant change in the network fault current level. These changes may lead to problems and should be detected fast to do the proper protection actions accordingly and prevent blackouts. Moreover, some island detection methods suffer from the drawbacks of high computation burden and time-consuming procedure of training data to detect the islanded mode. For this purpose, in this paper, a faster and less computation burden island detection scheme without the need for training data is proposed which detects the islanded mode by analyzing the fault current data obtained from a continuous sampling using the phasor measurement unit (PMU). The sampled data are utilized in the fuzzy c-means (FCM) clustering to determine the network operation mode. The proposed scheme works in two phases. In the offline phase, the root mean square (RMS) of the current amplitude for islanded mode is determined, and in the online phase, the center of the measured data is compared to the RMS value to detect the MG operation mode at a decision making procedure. It is proved that the proposed island detection scheme is an applicable technique for detecting the islanded mode in MGs.

KEYWORDS

microgrid, island detection, fuzzy c-means clustering

1. INTRODUCTION

A microgrid (MG) can be modeled by connecting distributed generators near the load together with main grid [1]. MG is capable of operating in both islanded and grid-connected modes. The transition between the two operation modes is done by the circuit breaker (CB) at the point of common coupling (PCC). The PCC isolated the MG from the grid. Changes in MG operation mode whether planned due to maintenance operation or load managing and unplanned due to faults may lead to change in the fault current levels and consequently cause protection problems. In grid-connected mode, the network is fed by an external grid while in islanded mode, the fault current level seen by the protective devices is only supplied by the sources in the MG, and the fault current magnitude is greatly reduced [2]. Consequently, the operational changes in the MG lead to new challenges in the protection system due to significant changes in the fault current levels.

So there is a need for a detection scheme to handle these situations and detect the network operation mode to adapt the protection system to the new situation and prevent protection problems. So far, various methods have been proposed to detect the islanded mode in the MGs.

These methods can be mainly classified into remote and local (i.e., active and passive) groups. The remote methods are fast and reliable but they are not economically viable due to

*Corresponding author.
E-mail: mohamad.hosseini@mail.um.ac.ir

AKJournals

expensive implementations [3]. So, active and passive methods are widely used for island detection.

Active methods inject a disturbing signal and analyze the system response [4]. These methods include low-frequency current injection [5], slip mode frequency shift (SMS) [6], Sandia frequency-shift (SFS) [7], active frequency drift (AFD) [8], frequency drift [9], and frequency positive feedback [10]. Also, some active methods have been proposed which utilize techniques such as current injection [11], injects a negative-sequence current [12], phase shift of current [13], and voltage monitoring at PCC [14].

Having a negative impact on grid stability because it acts as a disturbance and being disabling to detect an islanding operation when reverse power flows through the PCC due to high penetration of resources are the two main drawbacks of active methods [15]. Also, the injected disturbances due to applying active methods can reduce the electrical power quality at the PCC [16].

On the other hand, passive methods determine the islanding mode by measuring and analyzing the rate of variations of network parameters criterion. The rate of change in the voltage is the most popular criterion in passive methods [17–21]. Also, some passive methods have been proposed which utilized the rate of changes of voltage to frequency [22, 23]. Moreover, some passive methods are a combination of two or more measurement parameters. In [24] under/over voltage, under/over frequency, and phase jump are all utilized for island detection. Also, in other work, the dependency of the load on its associated voltage and frequency is considered as a technique for island detection [25]. Voltage and frequency [26], voltage and current [27], voltage and harmonics [28], and voltage and power [29] are some other hybrid passive methods in island detection.

The major disadvantage with most of the passive island detection methods is that the islanding detection procedure needs a powerful analyzing system to compute the receiving data. This drawback which is known as high computation burden makes it difficult to use the existing passive island detection methods. Also, some heuristic methods are utilized in island detection methods which are based on the training procedure that exceeds the consuming time for final decision making.

To overcome these drawbacks, an applicable less-computation burden scheme is proposed in this paper which is independent of training data and highly integrates the passive methods based on continuous sampling and the fault current level criterion. In the proposed island detection scheme, the fault currents passing through the lines in the MG are sampled continuously by the phasor measurement units (PMUs) installed at the MG feeders and transformed to the MG control center (MGCC). In MGCC, a fuzzy c-means (FCM) clustering technique is applied to the sampled data to find the center of the samples. Finally, based on analyzing the FCM output and the root mean square (RMS) of the current amplitude, the MG operation mode is detected.

Compared with the aforementioned methods, the proposed passive island detection scheme has the following distinguishing features: 1) is accurate, and practical and also ensures the detection of the operation mode according to the online local data obtained from the network; 2) removes the drawbacks of complexity and time-consuming procedures of existing methods in applying and analyzing the data.

The article is organized as follows: Section 2 explains the proposed island detection scheme. Section 3 contains the procedure of sampling the data. Section 4 introduces FCM clustering and its application in island detection. Sections 5 illustrates the results of the proposed island detection scheme. Finally, Section 6 remarks the conclusions.

2. PROPOSED ISLAND DETECTION SCHEME

As mentioned before, for protection purposes, there is a need for an accurate and fast detection scheme capable to detect the MG operation mode. This paper proposes a mathematical technique that is capable of detecting the MG operation mode without requiring complex detection algorithms. For this purpose, PMUs are used for receiving data. PMU can measure amplitude and synchronized phasors of bus voltage and current in real-time for better observability of the power system [30]. PMU takes about 30–120 measurements per second and sends its measurements to a phasor data concentrator (PDC) through wireless communication [31]. This helps engineers to analyze dynamic events in the grid which is not possible with traditional supervisory control and data acquisition (SCADA) measurements in which the generation interval for measurement messages is 4 seconds [32]. PMUs send the local data measurements to the MGCC. The MGCC has the most important role for satisfactory automated operation and control of MG while working in grid-connected and islanded modes [33]. The main task of the MGCC in the proposed scheme is to determine the RMS value for the islanded mode and analyze the sampled data by the FCM technique for final decision making. Within MGCC, PDCs are implemented for data aggregation [34]. The designed MGCC provides an image of the current amplitude in real-time for operation mode detection purposes. The focus of the proposed scheme is on software intelligence for the detection of the operation mode. The procedure of the proposed island detection scheme is shown in Fig. 1. It can

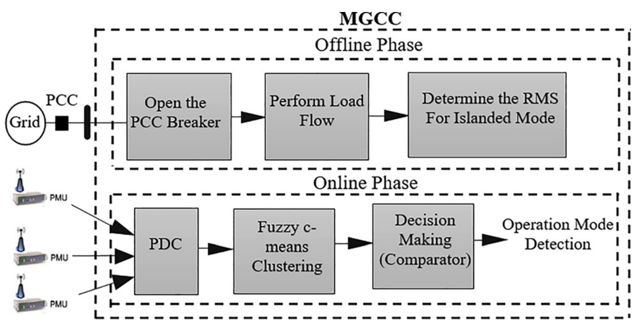

Fig. 1. The proposed island detection scheme

be seen from Fig. 1 that the proposed scheme works in two phases to detect the operation mode. In the offline phase, the RMS value for islanded mode is obtained by performing load flow. Then, in the online phase, the signals are obtained by the PMUs, which are located at the MG buses and are sent to the PDC. The PDC is used to aggregate all sampled values at a specific pre-defined cycle. Then, the FCM method is applied to determine the network operation mode by finding the center of data and compare it with the RMS value. In this paper, the FCM method is just used for finding the center of the sampled data in one cluster.

Using FCM, the center of the samples corresponded to the current amplitude is determined in each cycle of the sampling and consequently, the network operation mode can be detected. Applying the proposed island detection scheme helps the power system to monitor the system and perform proper protection actions.

3. SAMPLING PROCEDURE

The current signals applied to the terminals of the PMUs are sampled using an analog-to-digital converter (ADC). ADC can be used as a front end in PMU devices [35]. In ADC, the signal is taken as an input which is a continuous variable in amplitude and is transformed into a series of discrete values. This process is sampling, and the numerical output data from the ADC are known as sampled values. The process of sampling for a sinusoidal signal with the frequency of 2,000 Hz and the sampling interval of 4 is shown in Fig. 2.

Since the signal waveform in the power system is three-phase and in alternating current (AC) form, it needs to convert the signal to direct current (DC) form by RMS formula to be analyzed in the detection procedure. The value of RMS is the square root of the instantaneous value of a quadratic function. The term RMS is used only for time-varying sine waveforms (voltage, current, or a combination of the two). Therefore, the term RMS is not used in DC circuits. It should be noted that this value indicates how much DC voltage or current a time-varying sinusoidal waveform produces the same power that a pure DC value will produce.

In Fig. 2, the waveform is divided into n parts or n intermediate distances. The more we divide the waveform into parts, the more accurate the final result will be. Therefore, the width of each intermediate distance is equal to n and the height of each of them is equal to the "instantaneous value" of the waveform.

Each of the values of the intermediate distances is multiplied by its value (squared) and added to the next value. This method gives us the square part of the RMS expression. Then, these square values are divided by the number of intermediate intervals (n) and the mean part of the RMS expression is obtained. Therefore, the term RMS can be defined as the square root of the mean squares of the intermediate distances of the waveform as follows:

$$\mathrm{RMS} = \sqrt{\frac{\text{sum of squred values}}{\text{number of intermediate distances}}} \tag{1}$$

Accordingly, the RMS value of the fault current waveform (I_{RMS}) can be defined as the square root of the mean squares of the intermediate distances as follows:

$$I_{RMS} = \sqrt{\frac{i_1^2 + i_2^2 + i_3^2 + \ldots + i_n^2}{n}} \tag{2}$$

where (i_1, i_2, …, i_n) correspond to the samples of the fault current waveform.

4. FCM CLUSTERING

4.1. Definition of the FCM clustering procedure

FCM is a data clustering technique that is based on the degree of membership in which data belongs to a cluster by a membership grade and was introduced by Jim Bezdek [36]. In this technique, the basic c-means functions or their variations are optimized and the objective function is described as follows [37]:

$$J_m = \sum_{j=1}^{n} \sum_{i=1}^{c} u_{ij}^m d_{ij}^2 \tag{3}$$

where n, c, m, and u_{ij}, are the total number of samples ($X = x_1, x_2, \ldots, x_n$), the total number of clusters, the fuzzy factor, and the membership degree of x_j in cluster i, respectively

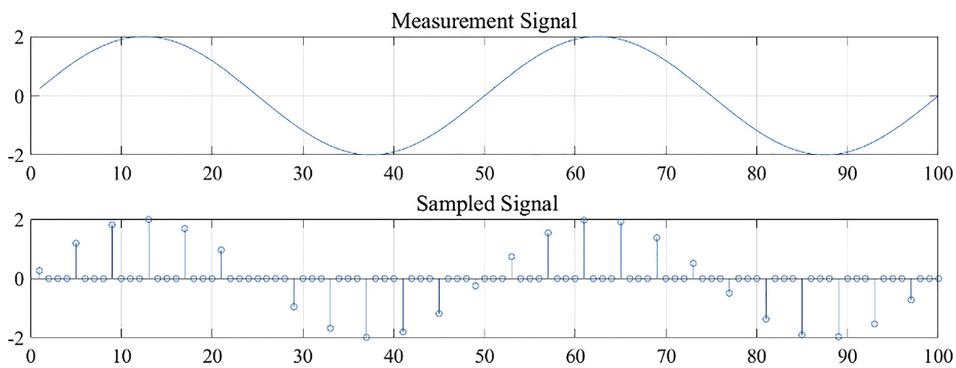

Fig. 2. The sampling procedure

[37]. Also, d_{ij} is the distance between the jth sampled data (x_j) and the center of the cluster (v_i) that can be defined as follows [37]:

$$d_{ij} = \|x_j - v_i\| \tag{4}$$

Also, in (3), m is a scaler number greater than 1, which in most cases 2 is chosen for m. If m set as 1, the objective function of FCM clustering changes to non-fuzzy classification. From u_{ij}, the u matrix can be defined which has c row and n column, and its components can choose any value between 0 and 1. Although the components of the matrix u can be any value between 0 and 1, the sum of the components of each column must be 1 as follows [37]:

$$\sum_{i=1}^{c} u_{ij} = 1, \quad 1 \le j \le n \tag{5}$$

The FCM procedure is discussed as follows [37]:

Step 1: Initialization of the centers by determining the value of c and m.
Step 2: Calculation of the center of data (v_j) based on the initial random membership values (u^0) using the equation:

$$v_i = \frac{\sum_{j=1}^{n} u_{ij}^m x_j}{\sum_{j=1}^{n} u_{ij}^m} \tag{6}$$

Step 3: Calculation of the distance between the data points and the centers (d_{ij}). Then, the membership values should be modified. The modification is based on the proximity of the data to the centers of the clusters so:
Step 4: Update the new membership matrix by the equation:

$$u_{ij} = \frac{1}{\sum_{i=1}^{c} \left[\frac{d_{ij}}{d_{ij}}\right]^{\frac{2}{m-1}}} \tag{7}$$

The degree values that are considered randomly, should be revised here. This revision is based on nearing the data to the centroids.

Step 5: Returning to step 2 unless there are no changes in the centers.

4.2. FCM application in island detection

In the proposed scheme, the sampled data corresponding to the fault currents are aggregated from all PMUs and utilized as inputs of the FCM. In FCM each sample is evaluated with the center of the cluster. In other words, in the proposed scheme, the FCM is set to just one cluster and the goal of using the FCM is just to find the center of the samples with the minimum distance to each sample.

Since the fault current waveform is three-phase, it needs to convert the waveform to DC form by calculating the RMS value as discussed in Section 3. Then, a parameter must be defined for the comparison purpose and final decision of the MG operation mode. For this purpose, the center of the data which is found by applying the FCM technique is utilized. This value is named as α. To find α, an optimization problem is performed in FCM. The objective of the problem is to minimize the sum of distances of the samples as defined in (3). Then, both the value of α which is obtained in the online phase, and the RMS value of fault current waveform in islanded mode ($I_{RMS\text{-}Islanded}$), which is determined in the offline phase, are taken into account in the decision making procedure. In this procedure, if α is bigger than $I_{RMS\text{-}Islanded}$, then the network is known as grid-connected mode, otherwise, the network is operated in islanding mode. In other words, the FCM method is a part of the detection procedure. In the detection procedure, the FCM output (i.e., α) and the $I_{RMS\text{-}Islanded}$, which has been stored in the MGCC memory, are utilized to detect the MG operation mode. Therefore, the final decision about the MG operation mode is taken by comparing the output of FCM (i.e., α) and the value of $I_{RMS\text{-}Islanded}$. The mentioned details are given in the island detection flowchart as shown in Fig. 3.

As can be seen from Fig. 3, the MG operation mode is determined at each cycle. In other words, the MG operation mode will be detected sequentially using the FCM at each decision cycle (T). Also, the procedure will continue up to the next decision cycle ($T + 1$) and it is expected the accuracy can be higher because more system measurements are used by the FCM to cover the unintentional islanding due to three-phase faults. This procedure will continue until a pre-determined cycle of load flow. Consequently, the decision-making for MG operation mode is taken in each cycle of the performing load flow. So, for continuous sampling and performing the load flow at each cycle, the maximum number of cycles (T_m) is set to an infinity value that leads to performing the FCM in each cycle for the detection procedure. Besides, the decision cycle, no longer time needs, and the time of the decision-making mechanism for island detection is refreshed at the beginning of the next cycle.

5. IMPLEMENTATION AND DISCUSSIONS

5.1. Case study

The proposed island detection scheme is implemented on a hybrid photovoltaic (PV) and wind turbine (WT) power system known as HPW [38] which is shown in Fig. 4. A WT with 1 MW capacity and a PV array are connected to a 25-kV distribution system. The HPW exports power to a 25-kV grid through a 100-km feeder. Both the WT and PV systems are connected to the DC bus using a DC/DC converter. When the PV is collapsed or the WT speed is decreased from 15 m/s (rated value), the CB of PCC is closed and the load is fed by the grid. The HPW is simulated using MATLAB/SIMULINK.

5.2. Applying the proposed detection scheme

To achieve a desirable performance of the proposed island detection scheme, the FCM technique is implemented in a proper AI tool to detect the MG operation mode. The FCM inputs for detection purpose, are the samples that are

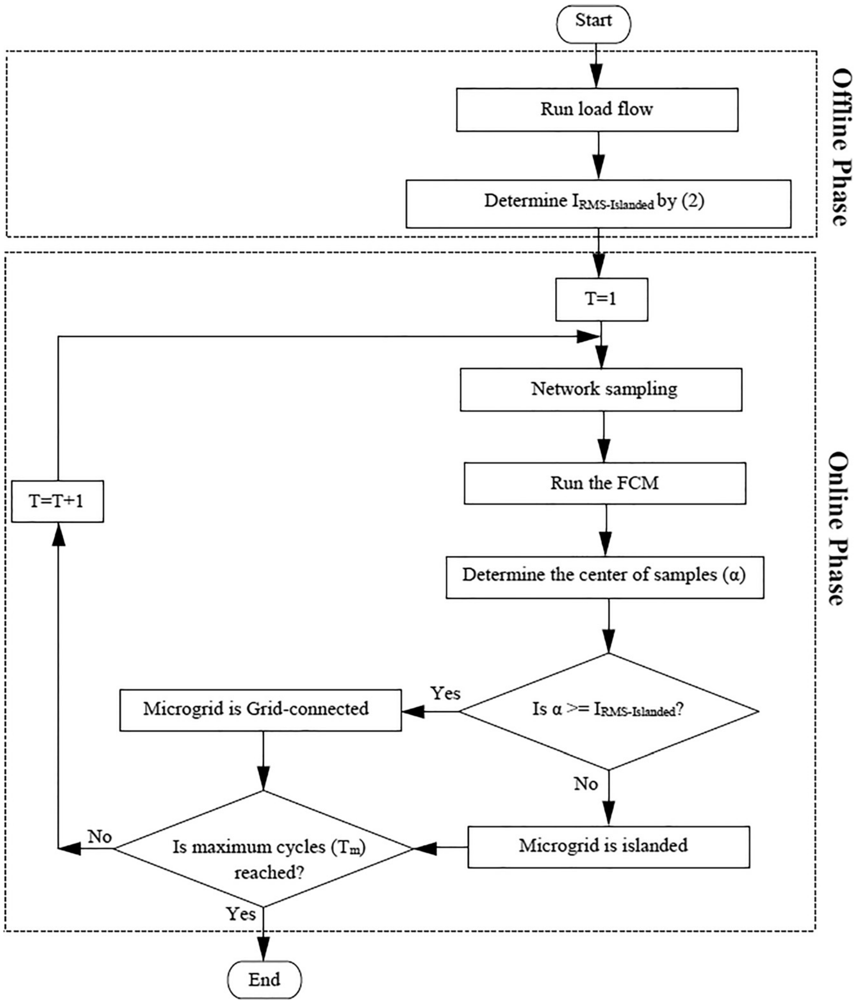

Fig. 3. The island detection flowchart

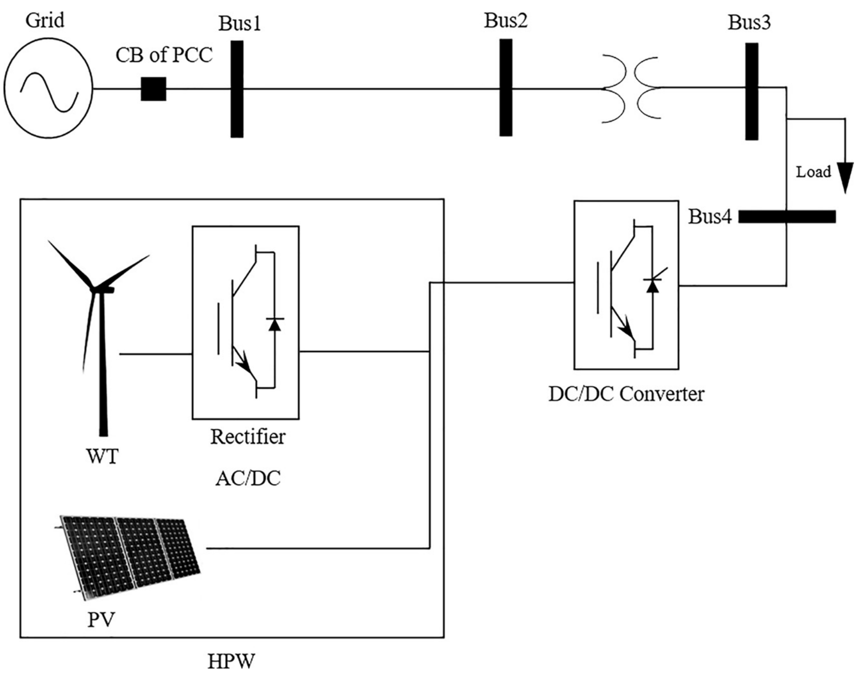

Fig. 4. The HPW connected to the grid

obtained from the fault current waveform. Also, the output of the FCM is used to determine the MG operation mode. In the proposed scheme, the MG operation mode can be detected by sampling the fault current amplitude.

Figure 5 shows fault current amplitude of the MG under study for islanding condition as a result of an islanding occurrence at $t = 0.03$ second. Also, Fig. 5 shows that upon islanding occurrence at $t = 0.03$ second, the amplitude of fault current changes and experiences a significant reduction. This reduction in transition between grid-connected mode to the islanded mode illustrated the effectiveness of the selected criterion (the fault current amplitude) for the islanding detection procedure.

As it is mentioned in Section 3, to analyze the three-phase fault current waveform for the island detection procedure, the RMS value of the AC waveform must be calculated. The details of waveform statists including the maximum amplitude of the fault current (I_{max}), the minimum amplitude of the fault current (I_{min}), and the RMS values of the fault current waveform for both the islanded and grid-connected modes are obtained and given in Table 1.

By obtaining the fault current waveform characteristics, the MG operation mode can be detected in the proposed detection scheme.

To evaluate the proposed scheme, the sampling procedure is performed in grid-connected mode to determine the inputs of the FCM. The two dimensions of samples for applying in the FCM procedure are shown in Fig. 6. As can be seen from Fig. 6, the samples of fault current waveform in grid-connected mode are in the range of [I_{min}, I_{max}] as given in Table 1. In this study, the sampling rate is set as 2,000, meaning that the sampled waveform contains 2,000 individuals of the total number of data.

Table 1. Fault current waveform statics for both MG operation modes

Waveform characteristic	Islanded mode		Grid-connected mode	
	Value (KA)	Time (s)	Value (KA)	Time (s)
I_{max}	4.75	0.035	65.16	0.005
I_{min}	-4.71	0.04	-65.19	0.015
I_{RMS}	3.34		46.06	

Then, the center of the samples must be optimally determined for operation mode detection. For this purpose, the objective function (3) in FCM is applied to the samples to update the center of the total samples and determine the value of α for the operation mode detection procedure.

In what follows, we are running FCM results to minimize the objective function to find the center of data. In this paper, the partitioning-based of the FCM algorithm is set to 1 ($c = 1$), the fuzzy parameter is set to 1 ($m = 1$), and the number of iterations is set to 100, which is used as the termination criterion of the FCM procedure. The convergence of the optimization results is shown in Fig. 7. Also,

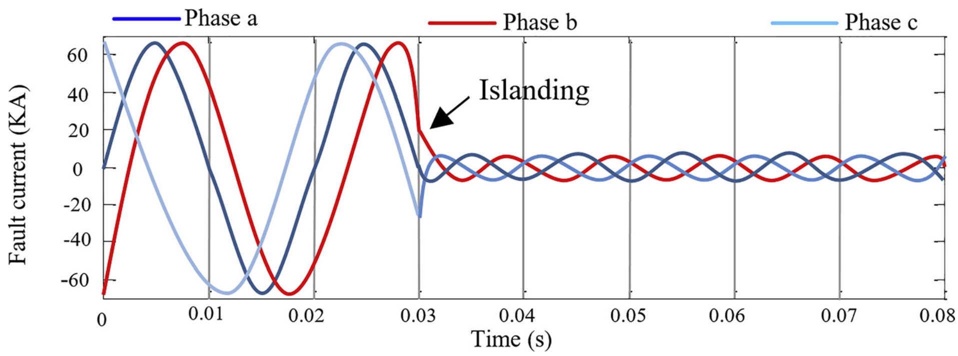

Fig. 5. Fault current waveform during the transition between grid-connected mode to islanded mode

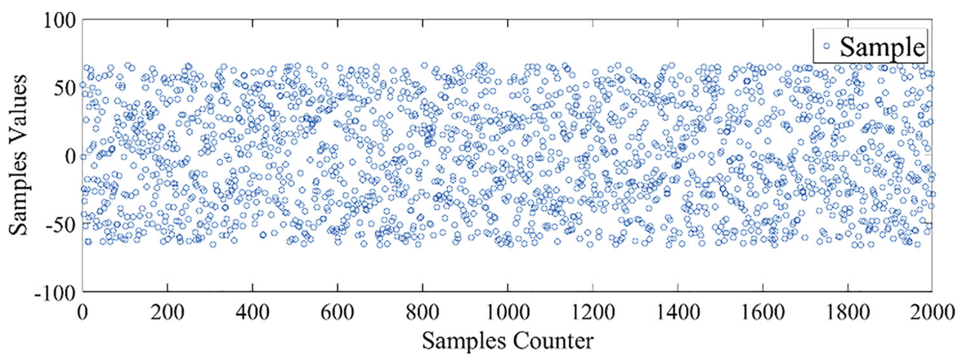

Fig. 6. Sampled data of fault current waveform on a unit square

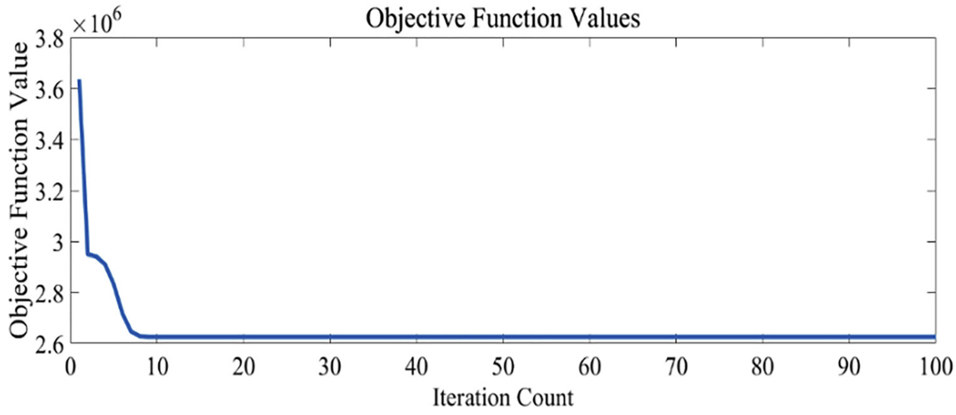

Fig. 7. Objective function J_m by performing the FCM

Fig. 7 shows that the FCM obtains a good solution, and the convergence process is very robust without getting stuck in the local optimum.

Applying the FCM, the final value of α, which is shown with the black sign in Fig. 8, is obtained and can be used to detect the mode of operation through the island detection flowchart that is presented in Fig. 3. As a result of performing the FCM and what can be seen from Figs 7 and 8, the objective function value is 2.6×10^6, and the value of α is 17.79. So, applying the decision-making procedure discussed in the island detection flowchart (Fig. 3), it can be concluded that the obtained value for α is bigger than $I_{RMS\text{-}Islanded}$ and the MG is in grid-connected mode.

Consequently, applying the proposed detection scheme to the MG, the mode of operation can be detected continuously by overcoming the drawbacks of complexity and computation burden in existing island detection methods.

5.3. Comparison with other methods

Previous island detection studies can be divided into mathematics-based and heuristic-based methods.

The mathematics-based methods suffer from the computation burden. On the other hand, the heuristic methods then developed to metaheuristic search, are based on network parameter features which are extracted at the specific conditions to be analyzed to detect the islanded mode. The metaheuristic methods such as graph search algorithm (GSA) [15], the combination of genetic algorithm (GA) and artificial neural network (ANN) [19], and support vector machine (SVM) [18], used training process which created a major problem when handling a large amount of data. On the other hand, the training process in multilayer networks is time-consuming and there is no guarantee to obtain the global minimum.

By comparison given in Table 2, the proposed island detection method utilizes the advantages of both the less computation burden and no complexity of analyzing in the existing mathematics-based methods along with removing the time-consuming procedure of training data in the metaheuristic-based methods.

Moreover, utilizing the PMU technology in the proposed scheme provides a faster sampling of current amplitude with more sampling rates that are not available with traditional SCADA measurements. Applying this technology in this paper and utilizing the advantages mentioned in Table 2, along with the island detection criterion (fault current amplitude) which was obtained directly by the measuring devices in the network with no need for supplementary computations, the islanded mode can be detected effectively and rapidly in 20 milliseconds (one cycle of each phase). As it is illustrated in Fig. 5, phase *a* is completed during 0.02 seconds (one cycle), and since

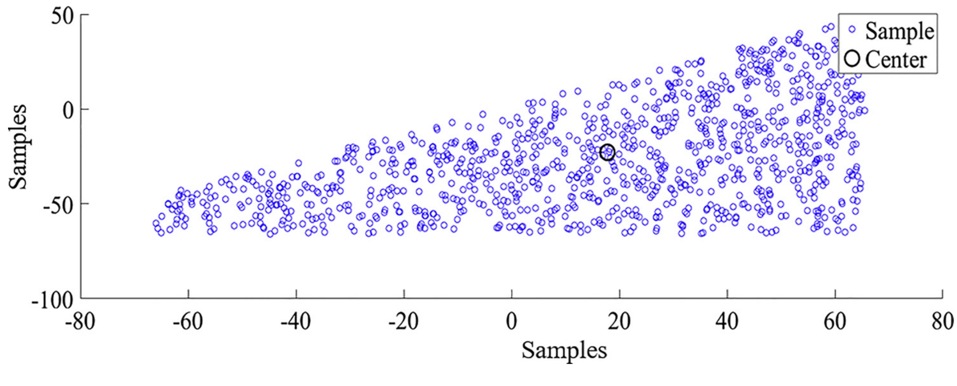

Fig. 8. Determination the center of the samples

Table 2. Comparison of the proposed island detection method and the other methods

Characteristic	Methods		
	Metaheuristic-based [15, 18, 19]	Mathematics-based [4–6, 10, 11, 14, 17, 21–23, 25, 26, 28]	Proposed method
No need to training data	✗	✓	✓
No complexity in analyzing data	✓	✗	✓
Less-computation burden	✓	✗	✓

✓: Compatible with the characteristic ✗: Incompatible with the characteristic.

Table 3. Comparison of the detection time between the proposed method and the other island detection methods

Reference	Detection time (ms)
Pai and Huang, 2001 [23]	83.33–100
Merino et al., 2014 [21]	308
Bekhradian et al., 2018 [25]	201
Chen et al., 2018 [26]	176.8
Laaksonen, 2013 [28]	30
Reigosa et al., 2012 [4]	200
Ganivada and Jena, 2020 [5]	170
Sun et al., 2015 [10]	252
Hernandez-Gonzalez and Iravani, 2006 [11]	33.3
Huang and Pai, 2000 [22]	233
Mohanty et al., 2014 [18]	22–26
Kim et al., 2020 [15]	100
Proposed method	20

all the three phases are with the same amplitude by the difference in the phase angle, the parameter for islanding detection (i.e., I_{RMS}) can be obtained by the sampling of one phase (i.e., phase a) that oscillated within 0.02 seconds. Therefore, according to the test results given in Table 3, the proposed method improved the detection time in island detection in comparison to the other methods. It is to be noted that the ranges used in the detection time column in some references in Table 3 refer to different scenarios or parameters.

With the abovementioned details, the proposed island detection scheme concludes a faster detection time using the PMU technology, and the fault current amplitude as the detection criterion. Moreover, the proposed scheme obtains this approach utilizing the following advantages:

1. It is based on real-time data sampling and there is no need for training data.
2. It is a less-computation burden and easy to analyzing method to detect the islanded mode.

6. CONCLUSIONS

In this paper, an effective scheme for island detection is proposed. In the proposed scheme, sampled data from the fault current waveform which are obtained from the PMUs are used for the island detection procedure. The FCM is used for finding the center of the samples. Consequently, the final decision-making to determine the MG operation mode is made by comparing the center of data to the value of RMS corresponding to the fault current waveform in the islanded mode which is obtained in an offline manner. The advantage of the proposed scheme is the faster detection utilizing the PMU technology, removing the complex mathematics computations and time-consuming procedure of training data in the existing methods, and more importantly, the island detection criterion (fault current amplitude), which can be obtained directly with the measuring devices. To validate the proposed detection scheme, a sample MG is simulated using MATLAB software. The simulation results show that the proposed island detection scheme is capable of finding the mode of operation in the MG in a shorter time.

REFERENCES

[1] M. Abdulhamid and K. Benard, “Study of stability analysis of power system with increasing wind power,” *Int. Rev. Appl. Sci. Eng.*, vol. 11, pp. 1–3, 2020.

[2] L. Che, M. E. Khodayar, and M. Shahidehpour, “Adaptive protection system for microgrids: protection practices of a functional microgrid system,” *IEEE Electrification Mag.*, vol. 2, pp. 66–80, 2014.

[3] R. Bakhshi-Jafarabadi, J. Sadeh, and M. Popov, “Maximum power point tracking injection method for islanding detection of grid-connected photovoltaic systems in microgrid,” *IEEE Trans. Power Deliv.*, vol. 36, pp. 168–79, 2020.

[4] D. Reigosa, F. Briz, C. B. Charro, P. Garcia, and J. M. Guerrero, “Active islanding detection using high-frequency signal injection,” *IEEE Trans. Industry Appl.*, vol. 48, pp. 1588–97, 2012.

[5] P. K. Ganivada and P. Jena, “Frequency disturbance triggered d-axis current injection scheme for islanding detection,” *IEEE Trans. Smart Grid*, vol. 11, pp. 4587–603, 2020.

[6] A. Pigazo, M. Liserre, R. A. Mastromauro, V. M. Moreno, and A. Dell'Aquila, “Wavelet-based islanding detection in grid-connected PV systems,” *IEEE Trans. Ind. Electron.*, vol. 56, pp. 4445–55, 2008.

[7] H. H. Zeineldin and S. Kennedy, “Sandia frequency-shift parameter selection to eliminate nondetection zones,” *IEEE Trans. Power Deliv.*, vol. 24, pp. 486–7, 2008.

[8] M. E. Ropp, M. Begovic, and A. Rohatgi, “Analysis and performance assessment of the active frequency drift method of islanding prevention,” *IEEE Trans. Energ. Convers.*, vol. 14, pp. 810–6, 1999.

[9] M. E. Ropp, M. Begovic, A. Rohatgi, G. A. Kern, R. H. Bonn, and S. Gonzalez, "Determining the relative effectiveness of islanding detection methods using phase criteria and nondetection zones," *IEEE Trans. Energ. Convers.*, vol. 15, pp. 290–6, 2000.

[10] Q. Sun, J. M. Guerrero, T. Jing, J. C. Vasquez, and R. Yang, "An islanding detection method by using frequency positive feedback based on FLL for single-phase microgrid," *IEEE Trans. Smart Grid*, vol. 8, pp. 1821–30, 2015.

[11] G. Hernandez-Gonzalez and R. Iravani, "Current injection for active islanding detection of electronically-interfaced distributed resources," *IEEE Trans. Power Deliv.*, vol. 21, pp. 1698–705, 2006.

[12] B. Bahrani, H. Karimi, and R. Iravani, "Nondetection zone assessment of an active islanding detection method and its experimental evaluation," *IEEE Trans. Power Deliv.*, vol. 26, pp. 517–25, 2009.

[13] G. K. Hung, C. C. Chang, and C. L. Chen, "Automatic phase-shift method for islanding detection of grid-connected photovoltaic inverters," *IEEE Trans. Energ. Convers.*, vol. 18, pp. 169–73, 2003.

[14] R. Nale, M. Biswal, and N. Kishor, "A transient component based approach for islanding detection in distributed generation," *IEEE Trans. Sustain. Energ.*, vol. 10, pp. 1129–38, 2018.

[15] J. S. Kim, C. H. Kim, Y. S. Oh, G. J. Cho, and J. S. Song, "An islanding detection method for multi-RES systems using the graph search method," *IEEE Trans. Sustain. Energ.*, vol. 11, pp. 2722–31, 2020.

[16] E. J. Estebanez, V. M. Moreno, A. Pigazo, M. Liserre, and A. Dell'Aquila, "Performance evaluation of active islanding-detection algorithms in distributed-generation photovoltaic systems: two inverters case," *IEEE Trans. Ind. Electron.*, vol. 58, pp. 1185–93, 2010.

[17] C. N. Papadimitriou, V. A. Kleftakis, and N. D. Hatziargyriou, "A novel method for islanding detection in DC networks," *IEEE Trans. Sustain. Energ.*, vol. 8, pp. 441–8, 2016.

[18] S. R. Mohanty, N. Kishor, P. K. Ray, and J. P. Catalo, "Comparative study of advanced signal processing techniques for islanding detection in a hybrid distributed generation system," *IEEE Trans. Sustain. Energ.*, vol. 6, pp. 122–31, 2014.

[19] A. Kamis, Y. Xu, Z. Y. Dong, and R. Zhang, "Faster detection of microgrid islanding events using an adaptive ensemble classifier," *IEEE Trans. Smart Grid*, vol. 9, pp. 1889–99, 2016.

[20] A. Samui and S. R. Samantaray, "Wavelet singular entropy-based islanding detection in distributed generation," *IEEE Trans. Power Deliv.*, vol. 28, pp. 411–8, 2012.

[21] J. Merino, P. Mendoza-Araya, G. Venkataramanan, and M. Baysal, "Islanding detection in microgrids using harmonic signatures," *IEEE Trans. Power Deliv.*, vol. 30, pp. 2102–9, 2014.

[22] S. J. Huang and F. S. Pai, "A new approach to islanding detection of dispersed generators with self-commutated static power converters," *IEEE Trans. Power Deliv.*, vol. 15, pp. 500–7, 2000.

[23] F. S. Pai and S. J. Huang, "A detection algorithm for islanding-prevention of dispersed consumer-owned storage and generating units," *IEEE Trans. Energ. Convers.*, vol. 16, pp. 346–51, 2001.

[24] Z. Ye, A. Kolwalkar, Y. Zhang, P. Du, and R. Walling, "Evaluation of anti-islanding schemes based on nondetection zone concept," *IEEE Trans. Power Electron.*, vol. 19, pp. 1171–6, 2004.

[25] R. Bekhradian, M. Davarpanah, and M. Sanaye-Pasand, "Novel approach for secure islanding detection in synchronous generator based microgrids," *IEEE Trans. Power Deliv.*, vol. 34, pp. 457–66, 2018.

[26] X. Chen, Y. Li, and P. Crossley, "A novel hybrid islanding detection method for grid-connected microgrids with multiple inverter-based distributed generators based on adaptive reactive power disturbance and passive criteria," *IEEE Trans. Power Electron.*, vol. 34, pp. 9342–56, 2018.

[27] N. W. Lidula and A. D. Rajapakse, "A pattern recognition approach for detecting power islands using transient signals-Part I: design and implementation," *IEEE Trans. Power Deliv.*, vol. 25, pp. 3070–7, 2010.

[28] H. Laaksonen, "Advanced islanding detection functionality for future electricity distribution networks," *IEEE Trans. Power Deliv.*, vol. 28, pp. 2056–64, 2013.

[29] S. K. Salman, D. J. King, and G. Weller, "New loss of mains detection algorithm for embedded generation using rate of change of voltage and changes in power factors," in *The 7th International Conference on Developments in Power Systems Protection (DPSP)*, 2001, pp. 82–5.

[30] D. Dua, S. Dambhare, R. K. Gajbhiye, and S. A. Soman, "Optimal multistage scheduling of PMU placement: an ILP approach," *IEEE Trans. Power Deliv.*, vol. 23, pp. 1812–20, 2008.

[31] S. Mousavian, J. Valenzuela, and J. Wang, "A probabilistic risk mitigation model for cyber-attacks to PMU networks," *IEEE Trans. Power Syst.*, vol. 30, pp. 156–65, 2014.

[32] J. Luque, I. Gomez, and J. I. Escudero, "Determining the channel capacity in SCADA systems using polling protocols [power system telecontrol]," *IEEE Trans. Power Syst.*, vol. 11, pp. 917–22, 1996.

[33] A. Kaur, J. Kaushal, and P. Basak, "A review on microgrid central controller," *Renew. Sustain. Energ. Rev.*, vol. 55, pp. 338–45, 2016.

[34] A. Derviskadic, P. Romano, M. Pignati, and M. Paolone, "Architecture and experimental validation of a low-latency phasor data concentrator," *IEEE Trans. Smart Grid*, vol. 9, pp. 2885–93, 2016.

[35] D. M. Laverty, J. Hastings, and X. Zhao, "An open source analogue to digital converter for power system measurements with time synchronisation," in *2017 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, 2017, pp. 1–5.

[36] J. C. Bezdek, *Pattern Recognition with Fuzzy Objective Algorithms*. Plenum, 1981.

[37] J. L. Fan, W. Z. Zhen, and W. X. Xie, "Suppressed fuzzy c-means clustering algorithm," *Pattern Recognition Letters*, vol. 24, pp. 1607–12, 2003.

[38] https://www.mathworks.com/matlabcentral/fileexchange/46410-hybrid-photovoltaic-and-wind-power-system.