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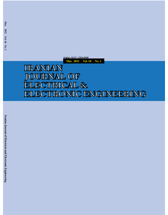

Adaptive Z_2 Protection Scheme Based on Setting Groups for Distance Relaying of Wind Farms Integrated Power Systems

Y. Fattahyan*, N. Ramezani*(C.A.), and I. Ahmadi*

Abstract: Using doubly-fed induction generator (DFIG) based onshore wind farms in power systems may lead to mal-operation of the second zone (Z_2) of distance protection due to the uncertain number of available wind turbines on the one hand and the function of DFIGs control system to maintain the bus voltage on the other hand. In such cases, variable injected current by the wind farm causes distance relay fall in trouble to distinguish whether the fault point is in the Z_2 operating area or not. In the current study, an adaptive settings scheme is proposed to determine the Z_2 setting value of distance relays for such cases. The proposed method is based on the adaptive approach and the settings group facility of the commercial relays. The proposed method applies the k-means clustering approach to decrease the number of setting values calculated by the adaptive approach to the number of applicable settings group in the distance relay and uses the Particle Swarm Optimization (PSO) algorithms to achieve the optimum setting values. The high accuracy of the proposed method in comparison with other methods, suggested in the literatures, is shown by applying them to the IEEE 14-bus grid.

Keywords: DFIG, Distance Relay, K-Means Algorithm, PSO, Setting Groups.

1 Introduction

IN power system with high penetration level (PL) of wind power plants, paying attention to the protective relays' setting is of more essential. Wind farms, based on doubly-fed induction generator (DFIG), are dramatically increasing in power grid at different voltage levels. The main problem with the inclusion of wind farms in power systems is the variations of injected power resulting from the number of available wind turbines. The generated power of these generators has a non-linear relationship with the wind speed in the interval between cut-in and rated speed. Moreover, when the wind speed is out of the range between cut in and cut out wind speed the generators have to be disconnected. Clearly, the transmission system connected to the wind farm is always exposed to environmental changes [1, 2]. Distance relays are commonly used in transmission lines, whether as primary or backup protection. General principles of distance protection is the measurement of apparent impedance using the voltage and current seen by the relay, which determines the distance between the relay location and the short circuit point. During a fault, the measured apparent impedance is compared to a pre-set area in the relay performance characteristic, named the trip zone. If the presence of the apparent impedance inside the trip zone lasts more than a pre-defined time the relay operates and sends the trip signal to the related circuit breakers. Appropriate time delays are considered for the operation of the backup zones in distance relays. The second zone (Z_2) of the relay acts as backup protection and usually protects a part of the lines emanating from the remote bus of the line protected by the relay.

Presence of a power source in the remote bus can lead the Z_2 of distance relay to under reach depends on the ratio of the source rated power to the short circuit level of the bus in MVA. In the case of fixed Z_2 setting value, alteration of injected power will change the reach point of the relay's second zone. If the source were a wind

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farm, the problem would be more severe because of the unpredicted changes in injected power of the source. In the case of failing the main protection system, changing the reach point of the backup protection (i.e. Z_2 of distance relay) will cause some faults not be cleared in a specified time delay.

If the fault clearing time exceeds the critical clearing time, the system is exposed to instability. Studies performed in [3] show the effect of wind farms on the operating and polarized signals of the first zone (Z_1) of a Mho distance relay. A method has been developed to eliminate the effect of wind farm fluctuations on the Z_1. Due to the rapid changes in wind speed, it is not possible to set the relay instantly and the method presented in this article cannot be implemented in practice. In addition, the effect of wind farms on the Z_2 has not been investigated. In [4], using AC, DC, and frequency rotation of stator fault current, an adaptive method is presented for over-current protection of power systems consisting of DFIG-based wind farms.

According to [5], in the presence of large-scale distributed generation (DG), the distance relays are more adaptable in comparison with over-current relays and are inherently directional. An adaptive method for distance relaying of the collector line (low voltage) of wind farms is proposed in [6], where the performance of the proposed method has not been evaluated at different PL and wind speeds. In [7], using wind farm impedance and fault resistance as variables of an artificial neural network (ANN), an adaptive protection has been proposed for Z_1 of distance relay [7]. In the study, only single-phase to ground fault has been investigated and the various operating modes of the wind farm have not been considered. Jain *et al.* described the effect of wind farms on supervisory elements of distance relays [8]. They evaluated the combined protection solution including distance and differential relays. In this study only combined protection, which increases costs, is suggested and no adaptive method for line protection in the presence of a wind farm is proposed. In [9] impacts of offshore wind farms on the Z_2 seen impedance of the distance relay have been investigated where the impact the control system of voltage source converter (VSC) is included in the study, but no setting approach for distance relay has been proposed. Dubey *et al.* have focused on the simultaneous effect of wind farms and FACTs devices, including static synchronous series compensator and static var compensator, on distance relays [10]. The various operating modes of the wind farm and their impacts on distance relay have not been considered in this study. Zolfaghari *et al.* studied the effect of wind farm VSC parameters on the Z_2 seen impedance [11]. They developed a control system that decreases the injected reactive power of DFIG during fault conditions to reduce the wind farm impacts on the power system. This reduction can put the power system in risk of instability if the protection relay does not operate. Biswas *et al.* to protect the TCSC compensated transmission lines connected to DFIG-based wind farms proposed a new algorithm based on sign of the half-cycle superimposed positive-sequence current signal at two ends of the line [12]. The Z_2 settings approach was not considered in the study.

According to the literature survey, no practical solution has been presented for distance relays Z_2 setting in transmission lines connected to wind farms. In the current work, an adaptive setting approach for the Z_2 of the distance relay has been introduced. Under-reach of the Z_2 has been presented as a function of the number of available wind turbines. Considering the different modes caused by the variation in the number of available wind turbines, separate Z_2 settings values have been calculated. Setting groups facility of commercial distance relays has been used for implementation of the calculated settings values. Due to the limited number of applicable setting groups of commercial protective relays, the best representatives of the calculated settings values should be selected. To do this, a clustering approach is used. Clustering has been performed in MATLAB software environment by combining the K-means and PSO algorithms. The proposed method has been implemented on the IEEE 14-bus grid in DigSilent software environment. The effect of changing in the wind farms PL and the control system of DFIG on the performance of the distance relay has been studied. Finally, the results of the proposed method have been compared with previous methods [16].

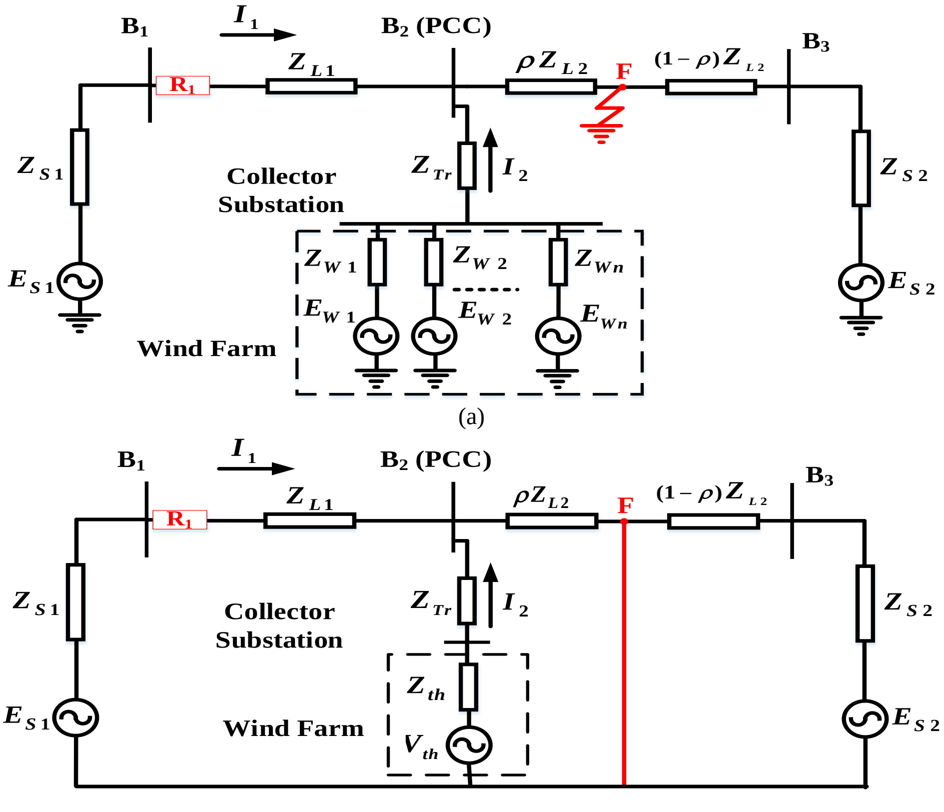
2 Impact of DFIG-Based Wind Farms on the Z_2 Seen Impedance of Distance Relay

Nowadays, variable speed wind turbines based on DFIGs are widely used in power systems. While the number of wind turbines connected to the network increases, new codes would be issued to support the grid instead of disconnecting during power system disruption [13].

2.1 Impact of Wind Farm PL

A 4-bus power system, consisting of a DFIG-based wind farm, is depicted in Fig. 1. Distance relay R_{01} is the main protective device of the transmission line between buses B_1 and B_2 (i.e. the line L_1). The Z_2 of the relay R_{01} is the backup protection for the transmission line between buses B_2 and B_3 (i.e. the line L_2). A three-phase fault occurred at ρ per unit distance of the transmission line L_2. The equivalent circuit of the system during the fault is shown in Fig. 1(b) to study the Z_2 performance of the relay R_{01}.

In Fig. 1(a), Z_{wi} and E_{wi} represent the positive sequence impedance and equivalent voltage of each wind generator, respectively. Z_{tr} denotes the positive sequence impedance of the power transformer that connects the collector substation of the wind farm to the transmission grid. Z_{L1} and Z_{L2} are the positive sequence impedance of the transmission lines L_1 and L_2



(a)

(b)

Fig. 1 4-bus system consisting of a DFIG based wind farm; a) System configuration and b) Equivalent circuit during three-phase fault at point F on the line L_2.

respectively. I_1 and I_2 are the portion of fault current passing through the L_1 transmission line and the power transformer toward the fault point, respectively.

In Fig. 1(b) the wind farm is modeled using the Thevenin equivalent which its parameters (i.e. Z-th and V-th) are expressed in (1) and (2), respectively.

$$Z_{th} = \left[\sum_{i=1}^{n} \frac{1}{Z_{Wi}} \right]^{-1} \tag{1}$$

$$V_{th} = Z_{th} \times \left[\sum_{i=1}^{n} \frac{E_{Wi}}{Z_{Wi}} \right] \tag{2}$$

The apparent impedance seen by the relay R_{01}, when a short circuit occurred at point F, is depicted in (3).

$$\begin{aligned} Z_{R_1} &= \frac{V}{I_1} = \frac{Z_{L1} I_1 + \rho Z_{L2} \left(I_1 + I_2 \right)}{I_1} \\ &= Z_{L1} + \rho Z_{L2} \left(1 + \frac{I_2}{I_1} \right) = Z_{L1} + K \rho Z_{L2} \end{aligned} \tag{3}$$

where V and I_1 are measured at relaying point and the factor K is a function of the ratio of I_2 to I_1.

As seen in (1) and (2), Z_{th} and V_{th} depend on the number of available wind turbines, so changes in these parameters will also change the wind farm portion of fault current (i.e. I_2). As a result, the apparent impedance seen by the Z_2 of the relay R_{01} would be affected by the factor K. Therefore, the impedance setting of the Z_2 should change accordingly, to prevent mal-operation.

2.2 Impact of DFIG Control System

A typical DFIG system, shown in Fig. 2, includes a wound rotor induction generator with slip rings and a back-to-back converter between the rotor slip rings and grid. The rotor side VSC directly controls the active and reactive output power of the stator. The grid-side VSC keeps the DC voltage constant and also transmits reactive power to the grid during short circuits to restore the voltage [14, 15].

This control system can make rapid changes (in the order of milliseconds) in voltage and current. Therefore, the function of the control system can lead the Z_2 of the distance relay to under reach and detects short circuit in the third zone (Z_3) instead of the Z_2, resulting in protective relays miscoordination and probable instability of the power network.

3 Proposed Z2 Setting Approach

In literatures, several setting approaches have been

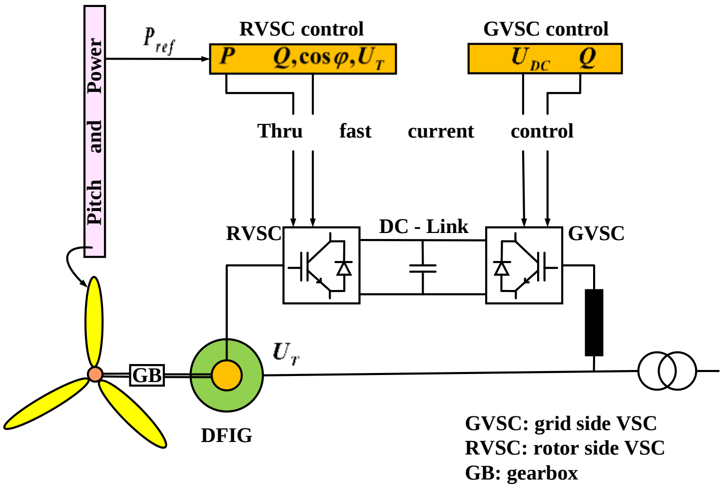


Fig. 2 4Wind farm structure based on DFIG [14].

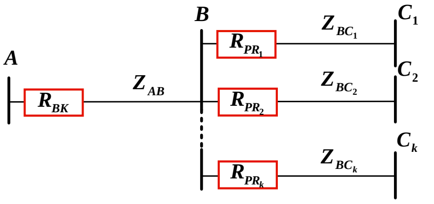


Fig. 3 A typical radial transmission network protected by distance relay [14].

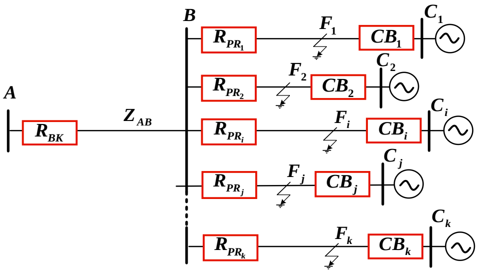


Fig. 4 A typical transmission network used to explain the Z_2 setting approaches [14].

suggested for Z_2 setting. In this section, the most important ones are explained. Then the proposed Z_2 setting method based on the setting groups facility of commercial distance relays is presented.

3.1 Conventional Method

In the conventional method, the Z_1 setting value is 80-90% of the positive sequence impedance of the line and Z_2 is set to protect 40-50% of the length of the outgoing line from the remote bus of the relay with the lowest positive sequence impedance. According to the power system depicted in Fig. 3, the setting impedance of the distance relay's Z_2 is calculated as follows:

$$Z_{set2}\left(R_{BK}\right) = Z_{AB} + 0.5 \times \text{Minimum}\left\{Z_{BCi}\right\} \qquad (4)$$

where BK stands for the back-up, Z_{AB} and Z_{BCi} are the positive sequence impedances of the lines A–B and $–C_i$, respectively. R_{PR_i} and R_{BK} are the main distance relay of the lines BC_i and AB, respectively. Evidently, the Z_2 of the relay R_{BK} plays the role of backup protection for all BC_i ($i = 1, 2, \ldots, k$) lines.

3.2 Non-Adaptive Method

In the non-adaptive method, the apparent impedances seen by the Z_2 are analyzed during occurring a three-phase short-circuit at the end of the Z_1 of the lines outgoing from the remote bus. The Z_2 seen impedance is calculated for the minimum and maximum generators outputs. The minimum value of the calculated impedances in these scenarios is used as the relay's Z_2 setting value. This setting method increases the reach of the Z_2 of the relay, without any interference with the primary relays. Regarding Fig. 4, the following steps are required to set the Z_2 of the relay R_{BK} using the non-adaptive setting method [16]:

1) Set the system in its minimum generation capacity.
2) Eliminated the line B–C_j from the system.
3) Simulate a three-phase short circuit (F_i) at the Z_1 reach limit of the relay R_{PRi} when the remote end circuit breaker, CB_i, is open.
4) Calculate the Z_2 settings value for the relay R_{BK} using (5).

$$Z_{set2}\left(R_{BK}, R_{PRi}\right) = Z_{AB} + K_2 \times \left[Z_A\left(R_{BK}, F_i\right) - Z_{AB}\right] \qquad (5)$$

where $Z_{set2}(R_{BK}, R_{PRi})$ is the impedance setting value obtained for Z_2 of the relay R_{BK} when the three-phase fault is in line BC_i. $Z_A(R_{BK}, F_i)$ is the apparent impedance seen by the relay R_{BK} during short circuit at the point F_i and K_2 is a constant coefficient for Z_2 setting (usually 5% less than the percentage reach limit of the Z_1)
5) Repeat steps (3) and (4) for all lines emanating from the remote bus.
6) Return the removed section B–C_j to the grid.
7) Repeat steps (3) to (6) while removing the remaining lines and elements (such as transformers, generators, etc.).
8) Selected the minimum value of Z_2 settings in steps (1) to (7) and save the settings value along with the related removed line.
9) Remove the specified line in step (8) and close all remote end circuit breakers. Simulate a three-phase short circuit (F_i) at the Z_1 reach limit of all other lines.
10) Compare the apparent impedance seen by the relay R_{BK} in each simulation of step (9) with the impedance setting value selected in step (8) and evaluate the performance of the relay R_{BK}.
11) If the relay R_{BK} has operated for some cases in step (10), the Z_2 settings value is reduced by 90% of the smallest short circuit impedance seen by it.
12) Repeat steps (1) to (11) when the generation

capacity has its maximum value. The final Z_2 settings value is the minimum value between the specified values for maximum and minimum system generation capacity.

3.3 Adaptive Method

In the adaptive relay setting method, all operating status of the power system (including load flow, generation rate and topology) is identified and a specific Z_2 setting value is calculated for each operating status that should be uploaded into the relay when the related operating status has occurred.

Regarding Fig. 4, for each operating status the adaptive setting method contains the following steps to specify the Z_2 setting value of the relay R_{BK} [16]:

1) Simulate a three-phase short circuit (F_i) at the Z_1 reach limit of the relay R_{PRi} when the remote end circuit breaker, CB_i, is open.

2) Calculate the Z_2 settings value for the relay R_{BK} using (6).

$$Z_{set2}\left(R_{BK},R_{PRi}\right)=Z_{AB}+K_2\times\left[Z_A\left(R_{BK},F_i\right)-Z_{AB}\right] \tag{6}$$

3) Repeat steps (1) and (2) for all lines emanating from the remote bus.

4) Select the minimum value of Z_2 settings in steps (1) to (3) and save the settings value.

5) Close all remote end circuit breakers. Simulate a three-phase short circuit (F_i) at the Z_1 reach limit of all lines.

6) Compare the apparent impedance seen by the relay R_{BK} in each simulation of step (5) with the impedance setting value selected in step (4) and evaluate the performance of the relay R_{BK}.

7) If the relay R_{BK} has operated for some cases in step (5), the Z_2 settings value is reduced by 90% of the smallest short circuit impedance seen by it.

3.4 Setting Groups Facility in Commercial Distance Relays

Commercial distance relays can accept several groups of setting values. At a specific time, only one group is active. In normal conditions of the power system, changing the setting groups is permitted using binary address inputs. The main advantage of having several setting groups is the better performance of the protection system when the configuration of the power grid would change [17, 18].

3.5 The Proposed Method

In a wind farm, changes in the number of operating turbines create different Thevenin impedances and different generation levels. In addition, the control strategy of DFIGs leads to different operating situations. Therefore, wind farms operation includes numerous operating statuses that make it impossible to use an adaptive approach for distance relays' Z_2 setting.

Although the adaptive setting approach cannot be used for Z_2 setting in presence of wind farm, using setting groups facility can return a big portion of its benefits. Regarding the large number of wind farm operating statuses resulting in many Z_2 setting values, from one side and the limited number of setting groups from another side, the clustering approach should be used to select the several representatives of the Z_2 setting values. Since the number of representatives (i.e. cluster center) is equal to the number of applicable setting groups of the relay and therefore is predefined, the K-means clustering approach used in this paper. The particle swarm optimization (PSO) algorithm is employed to ensure the selection of the optimum setting values, with maximum closeness to the adaptive approach.

Each PSO particle contains several representatives of the Z_2 setting values as the cluster center. Equation (7) depicts the rule of assigning each Z_2 setting value to a cluster in the t-th iteration of the PSO.

$$S_r^{(t)}=\left\{Z_{set}\mid\left\|Z_{set}-C_r^{(t)}\right\|^2\le\left\|Z_{set}-C_j^{(t)}\right\|^2\right\}$$
$$1\le r\ \&\ j\le N^{SG}\quad \&\ r\ne j \tag{7}$$

where, Z_{set} is a Z_2 setting value belonging to an operating condition of the wind farm that is calculated using the adaptive approach. N^{SG} is the number of applicable setting groups of the relay. $S_r^{(t)}$ is the r-th cluster in the t-th iteration of the PSO algorithm.

Based on (7), in each iteration of the PSO, a Z_2 setting value is assigned to the r-th cluster when the Euclidean distance between the setting value and the cluster center (i.e. $C_r^{(t)}$) is less than the Euclidean distance between the setting value and other cluster centers. In (8) and (9) the cost function of the PSO optimization process is presented.

$$CED_r=\sum_{Z_{set}\in S_r}\left\|Z_{set}-C_r^{(t)}\right\|^2 \tag{8}$$

$$PSO\Rightarrow \text{Minimize}\left\{OF=\sum_{r=1}^{N^{SG}}CED_r\right\} \tag{9}$$

In (8), the sum of all Euclidean distances between the members of the r-th cluster and their own cluster center (i.e. $C_r^{(t)}$) is defined as cluster Euclidean distance (CED). These Euclidean distances are shown in Fig. 5. The objective function of the PSO algorithm is presented in (9) that implies in the reached optimum representatives of the setting values, the sum of all CED is minimum. This ensures us that the selected setting values as the cluster centers have the maximum closeness to the other members of their own clusters and therefore are the optimum representative of them. These three steps are alternately repeated until the stopping criterion is achieved. In this paper, the number of iterations is the stopping criteria of the PSO algorithm.

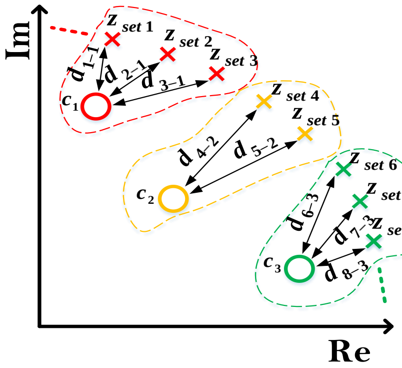


Fig. 5 Euclidean distances between cluster members and their own cluster center.

Table 1 The PSO parameters.

Setting parameters	Value
Number of population	50
Number of iteration	200
c_1, c_2	1.4
$\omega^{\max}$	0.9
$\omega^{\min}$	0.4

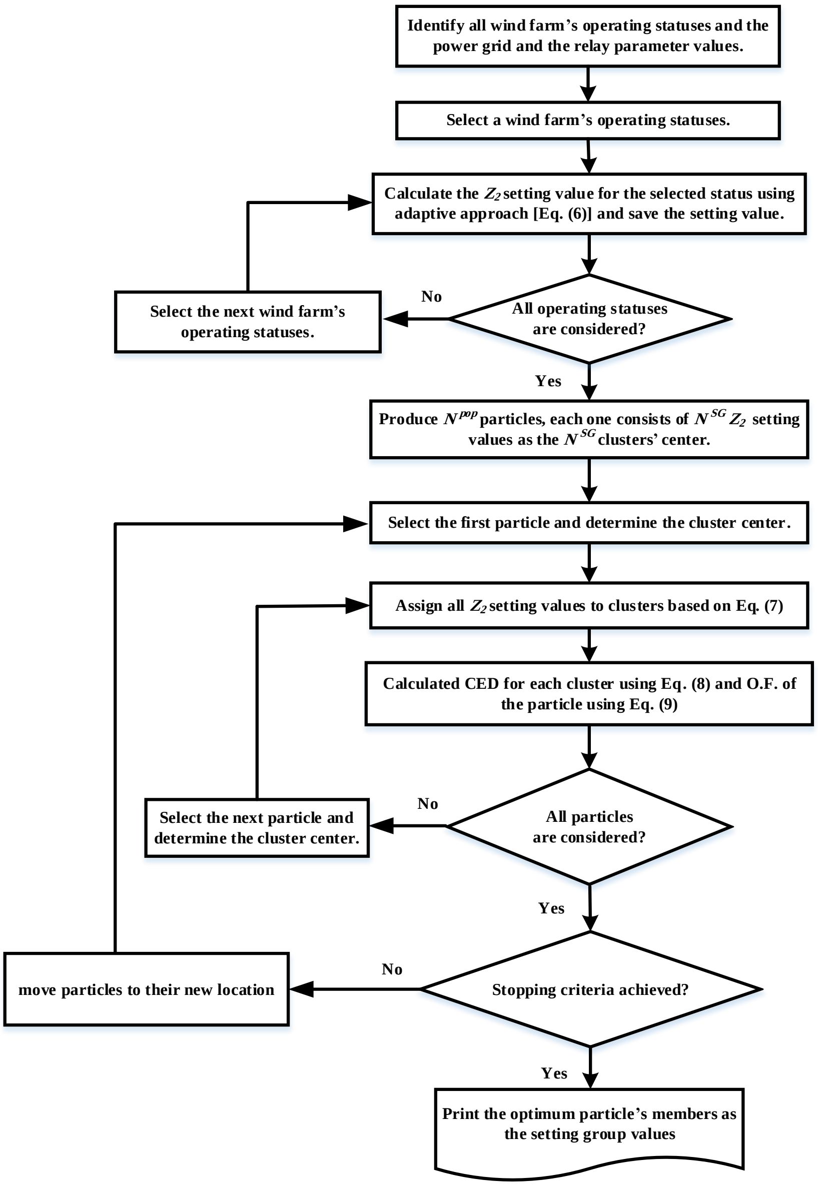


Fig. 6 Flowchart of the proposed method.

The parameters of the PSO algorithm are presented in Table 1.

The flowchart of the proposed algorithm is presented in Fig. 6.

4 Case Study

The IEEE 14-bus grid, shown in Fig. 7, is used to assess the performance of the proposed method. This grid includes 16 transmission lines (32 distance relays), 2 synchronous generators, 3 synchronous condensers, and 19 loads at voltage levels of 33 and 132 kV. The grid frequency is 60 Hz. The synchronous generator connected to bus 2 is replaced with a wind farm consisting of 100 DFIGs each rated at 1 MW. The wind farm control system kept the voltage and active power constant (i.e. bus 2 is a PV bus).

In this study, the network simulation has been performed in DigSilent software (version 2016) and the combination of the K-means clustering approach and the PSO optimization algorithms have been executed in MATLAB (version 2019) environment.

The effect of changing the number of available wind turbines on the performance of the Z_2 of the relay R_{01}, in the form of the reach limit of Z_2, is investigated. For the sake of comparison in addition to the proposed method, the performance of three other setting approaches (i.e. conventional, non-adaptive, and adaptive) are investigated. It should be mentioned that although employing the adaptive setting approach is not possible as discussed in section 3.5, it is studied as the highest borderline of the relay's Z_2 setting performance. The closer the coverage of Z_2 in a setting approach to the Z_2 coverage in the adaptive approach, the better performance of the setting approach.

4.1 Performance of the Conventional Z_2 Setting Approach

First, the Z_2 of the distance relay R_{01} was set by the conventional method. The setting value is $Z_{set} = 32.546\measuredangle 70°$ (Ω). With this setting value, the reach limit of the Z_2 of the relay R_{01} in different lines emanating from bus 2 is 20.7% of line (1-2(2)), 11.2% of line (2-3), 12.4% of line (2-4) and 12.6% of line (2-5) length.

A three-phase short circuit was simulated on line (1-2(2)) at 18.5% of the line length from bus 2, to assess the impact of the number of the available wind turbines on the performance of the conventional Z_2 setting approach. The performance of the relay R_{01}, while 20 wind turbines were in service and the output power of each one was 1 MW, is shown in Fig. 8(a). As depicted, the relay detected the short circuit in the Z_2 area and issued the trip signal at t = 0.3s. Then the number of available wind turbines increased to 100. As shown in Fig. 8(b), in this case, the relay R_{01} encountered under reach and detected the short circuit in the Z_3 and issued the trip signal at the time t = 0.6 s. Therefore, changing the PL of the wind farm will affect the performance of the conventional Z_2 setting approach.

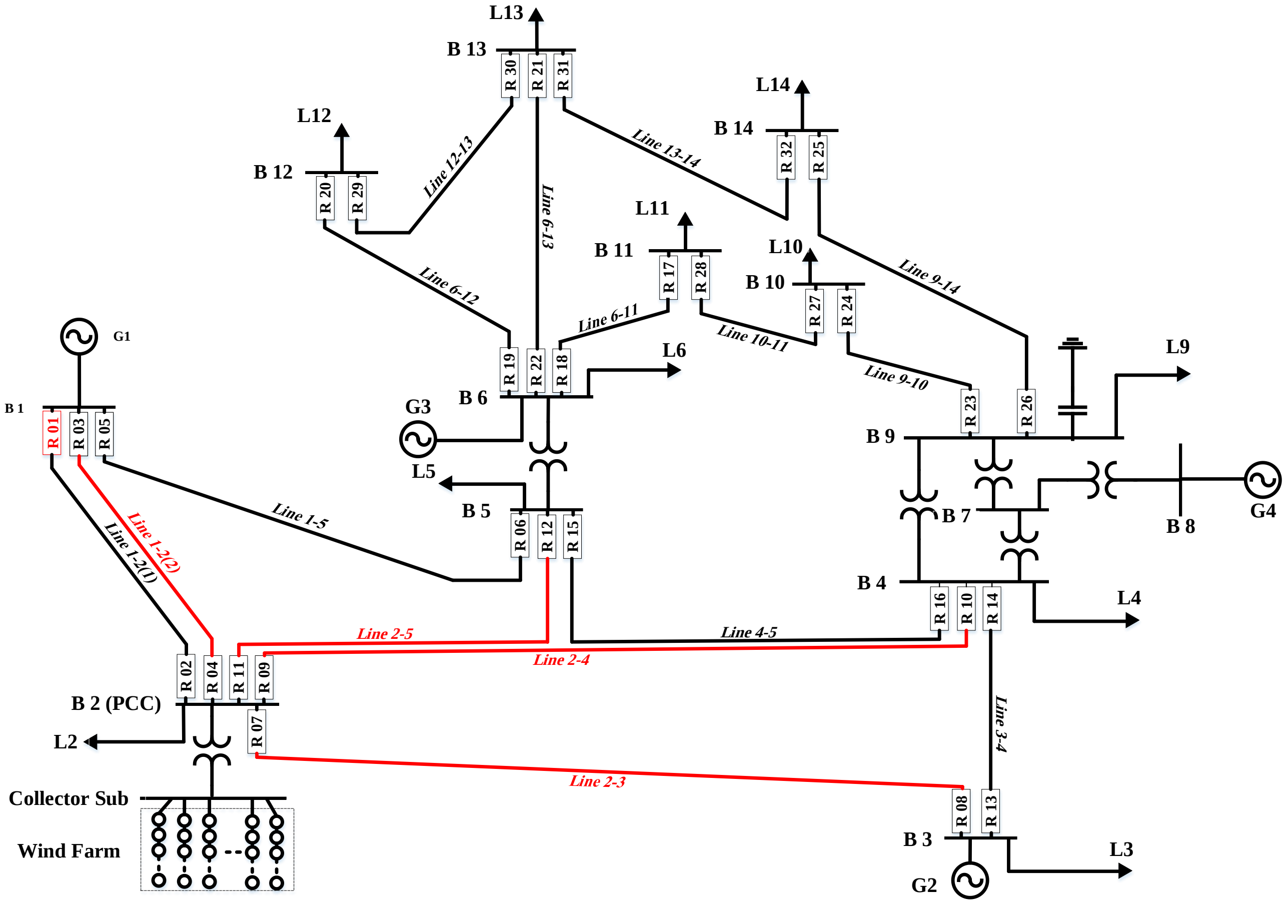


Fig. 7 IEEE 14-bus power grid configuration [19].

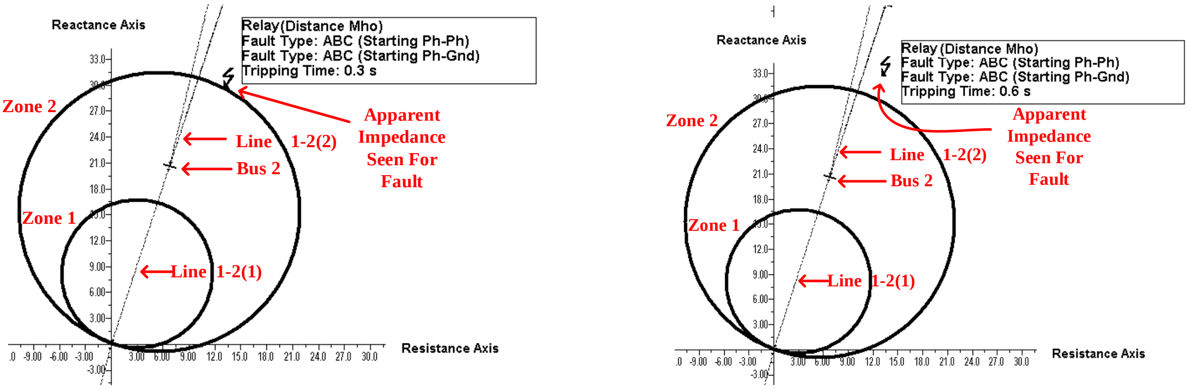
4.2 The Effect of DFIG Control System on Z_2 of Relay R_{01}

The function of the DFIG control system put the backup relay into maloperation. The dynamic response of the wind farm during a three-phase fault is shown in Fig. 9. The wind farm consists of 40 DFIGs each one with 1 MW output power and with constant voltage control strategy. The fault occurred at 10% of the line (2-3) at time 5s and lasted for 300 ms. When the short circuit occurred, the voltage of the point of common coupling (PCC) decreased (Fig. 9(a)). Regarding the control strategy, DFIGs injected reactive power into the PCC (Fig. 9(b)). Therefore, the bus voltage at the PCC increased and the current passing through the relay R_{01} decreased, consequently caused the relay R_{01} under reach.

4.3 The Z_2 Setting of relay R_{01} Using the Proposed Method

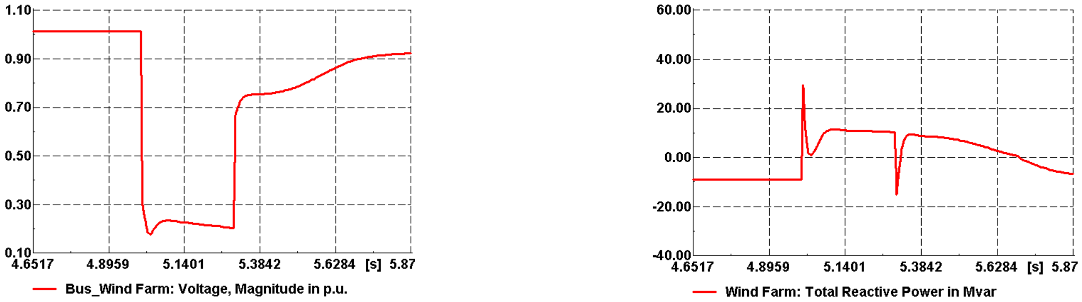
The Z_2 impedance setting of the relay R_{01}, in different operating states (i.e. different numbers of in-service turbines), was obtained by the adaptive approach. It was assumed that the number of available turbines varied from 0 to 100. For 101 operating statuses, the obtained Z_2 impedance settings are shown in Fig. 10(a).

According to the setting groups of the relay R_{01}, which are assumed to be 4, the clustering was performed based on (7) to (9) and the results were shown in Fig. 10(b). The convergence curve of the PSO algorithm is presented in Fig. 11. As it is observed, the PSO algorithm converged rapidly.



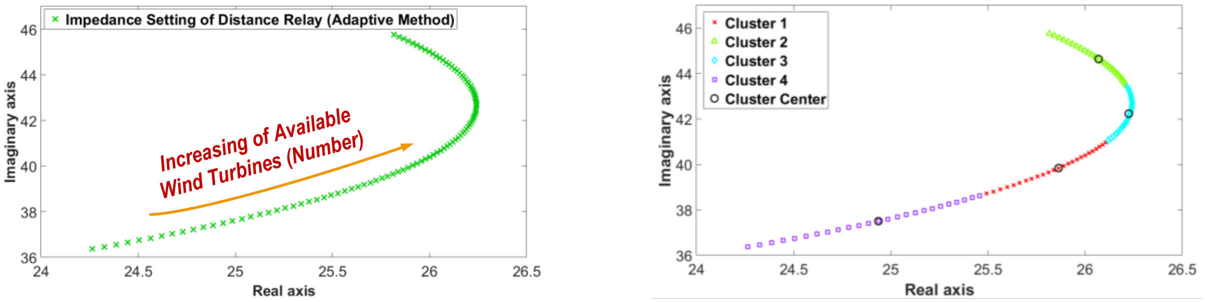
(a) (b)

Fig. 8 Performance of the Z_2 of the relay R_{01} when it was set using the conventional setting approach (three-phase fault at 18.5% of the line (1-2(2)) length from the bus 2); a) 20 wind turbines each one with 1 MW output power are in service and b) 100 wind turbines each one with 1 MW output power are in service.



(a) (b)

Fig. 9 Dynamic response of DFIG during short circuit; a) Bus 2 rms voltage (p.u) and b) Wind farm injected reactive power (MVar).



(a) (b)

Fig. 10 The obtained Z_2 impedance settings and the setting groups values of the relay R_{01}; a) Obtained Z_2 impedance settings for 101 operating states of the wind farm and b) Members and centers of 4 clusters of Z_2 impedance settings.

4.4 Comparison of Coverage Percentage of the Presented Methods

The Z_2 impedance setting values of the relay R_{01} using the four aforementioned setting approaches (i.e. conventional, non-adaptive, adaptive, and the proposed approaches) are calculated and presented in Table 2. For the sake of simplicity in the adaptive method calculations, the 101 states of PLs of wind farm decreased to 11 states with the constant difference of 10 available turbines. The Z_2 coverage percentage of the relay R_{01} versus different PL of wind farms in the lines emanating from the remote bus of the relay for all four setting approaches are studied and depicted in Figs. 12(a)-(d). It can be clearly seen that the amount of protective coverage with the proposed approach is close to the adaptive approach, as the approach with the highest performance, and covered a higher percentage of the line in comparison with the conventional and non-adaptive methods. Moreover, the proposed approach would not cause miscoordination and interference with the Z_2 of other relays.

It should be noticed that regarding the numerous operating statuses of the wind farm (here 101 statuses) raised by changes in the number of available wind turbines and the limited number of setting groups (here four groups) employing the adaptive setting approach is not possible. Therefore, although the adaptive approach seems better than the proposed one, since it is not applicable, the proposed method is the best applicable method to overcome the Z_2 problem raised by integrating wind farms into the grid.

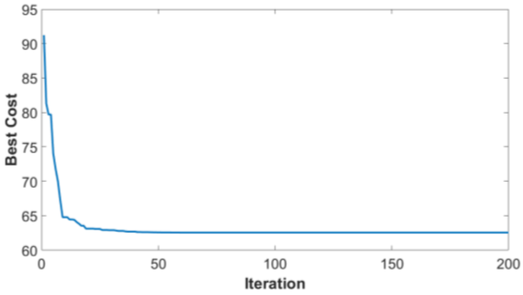
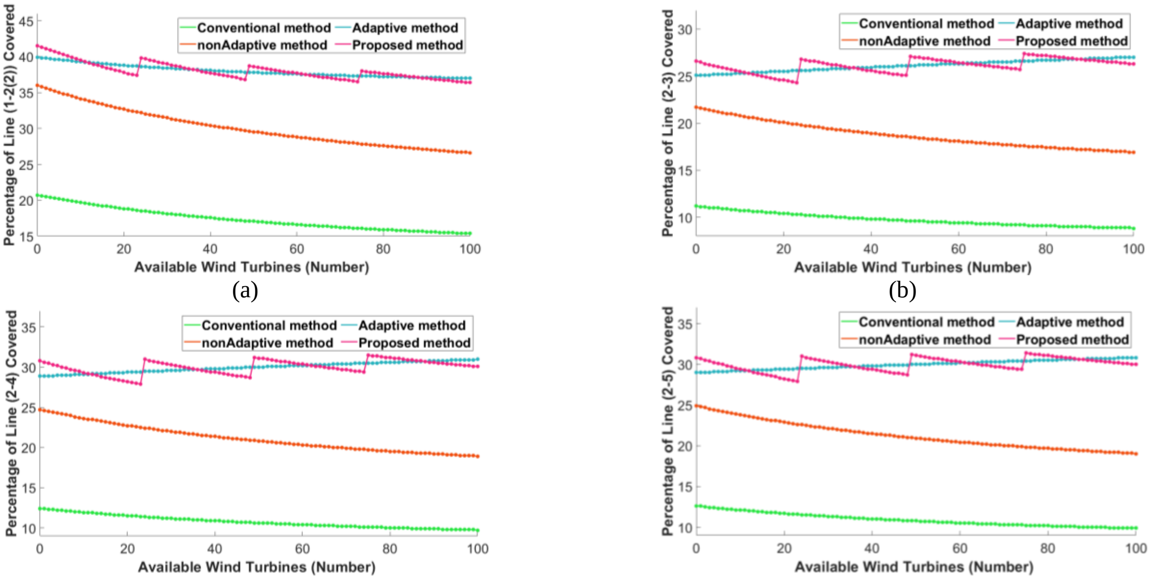


Fig. 11 Convergence of the PSO algorithm.

Table 2 Impedance setting values of the Z_2 of the relay R_{01}.

PL of wind farm [%]	Setting value [Ω]*			
	Conventional method	Non-adaptive method (setting with minimum generation power)	Adaptive method	Proposed method
0	32.546	42.096	44.998	46.281
10			46.123	
20			47.157	
30			48.115	48.657
40			49.006	
50			49.837	50.721
60			50.614	
70			51.342	
80			52.024	52.501
90			52.662	
100			53.259	

* All impedance angles are set in 70°



(a) (b)

(c) (d)

Fig. 12 Z_2 coverage percentage of different setting approaches versus wind farm PL in different lines; a) Line (1-2(2)), b) Line (2-3), c) Line (2-4), and d) Line (2-5).

5 Conclusion

An adaptive method based on setting groups has been proposed to determine the setting values of the Z_2 of distance relays in transmission lines connected to wind farms. K-means clustering approach is employed to decrease the large number of Z_2 setting values computed by the adaptive setting approach to the number of applicable setting groups in the relay. Also, the PSO optimization algorithm is used to select the optimum setting values. The performance of the proposed method and three other famous methods in the area are compared by applying them to the IEEE 14-bus grid. Since the large number of calculated Z_2 setting values by the adaptive approach makes it impossible to apply the approach to this problem, it is simulated as the highest borderline of the setting approaches performance. The percentage of the covered area by the Z_2 of the backup distance relay in different protected lines is introduced as the comparison criteria. Numerical results indicate that the proposed method offers better performance than other applicable methods.

Intellectual Property

The authors confirm that they have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

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Y. Fattahyan: Research & investigation, Software and simulation, Methodology, Analysis. **N. Ramezani:** Supervision, Idea & conceptualization, Methodology, Analysis, Verification, Original draft preparation, Revise & editing. **I. Ahmadi:** Idea & conceptualization, Analysis, Methodology, Analysis.

Declaration of Competing Interest

The authors hereby confirm that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to “Iranian Journal of Electrical and Electronic Engineering”.

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