A WSN Clustering Algorithm for Micro-grid

Bin Cai, Bin Wang, Yi Shi, Xiao-Hui Li

***Abstract*—**Considering the practical situation when applying the wireless sensor network to the micro-grid, the unbalanced energy consumption among the nodes will lead to the problem of blind areas, poor monitoring quality and the short lifetime of the monitoring network, an uneven clustering algorithm based on the real-time energy of the nodes for the state and information monitoring network of micro-grid was proposed. In the proposed algorithm, the flag bit and the real time node energy factor were introduced to the calculation of the cluster head competition radius, and the clustering judgment factor was applied to realizing dynamic and unequal clustering of the network. The algorithm balanced the energy consumption by choosing the node with sufficient real-time energy and low communication cost as cluster head. Simulation results show that the proposed algorithm can more efficiently balance the energy consumption, make the death nodes distribute evenly, improve the quality of network monitoring and prolong the network lifetime.

***Keywords*—**wireless sensor network, uneven clustering, micro-grid, real-time energy, energy balance.

I. INTRODUCTION

AS an important part of smart grid, micro-grid is an effective way to realize active power distribution [1]. The micro-grid can control and manage the grid intelligently and automatically. It can also optimize system operation, detect the fault condition automatically and manage the power quality. Moreover, the micro-grid can dynamically connect to the external power grid or operate alone depending on the actual demand. Considering the large amount of distributed power supply [2] and the requirement of bidirectional, real-time and efficient communication [3], a large number of monitoring devices are used in the network to improve the efficiency and stability of the power grid. Micro-grid communication system includes control center layer, centralized control layer and local control layer [4-5], where the local control layer is responsible for data collection, protection and control of local equipment. In view of the complex network conditions including multi-nodes and decentralized node location in the local control layer of micro-grid [6-7], it is an appropriate way to build the local control layer data monitoring network by using wireless sensor network(Wireless Sensor Networks, WSN) technology.

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Considering the actual characteristics of the micro-grid, a clustering structure with high-energy efficiency and high scalability is selected as the monitoring network [8]. Traditional clustering algorithms, such as LEACH algorithm, use uniform clustering. As the inter-cluster route is single-hop, there is a problem that the cluster-head nodes, which are far away from the sink node, die prematurely because of the high communication cost [9-10]. Another algorithm, the EEUC algorithm has introduced a concept called non-uniform clustering. In the cluster-head selection phase, the communication cost is high and in the cluster head selection and clustering phase, there is a lack of consideration for the node's residual energy, leading to premature death of cluster head nodes near the sink node [11-14]due to insufficient energy to finish data forwarding, thus affecting the overall life cycle of the network.

Taking the deficiencies of LEACH and EEUC algorithms and the distributed power distribution in micro-grid into account, this paper presents a non-uniform clustering algorithm based on real-time energy of nodes in wireless sensor networks.(Node Real-time Energy based Uneven Clustering algorithm for WSN in micro-grid, NREUC). NREUC algorithm introduces the node real-time energy as the partial weight in the cluster head competition radius. In the clustering stage, the common node chooses the cluster according to the clustering judgment factor, thus achieving the purpose of non-uniform clustering. In the whole cluster process, NREUC algorithm can guarantee that the cluster head nodes in the network always have high real-time energy, especially the cluster head that is close to the aggregation point and needs to forward a lot of other information. At the same time, the concept of rotation is introduced in the clustering stage, so that the nodes with low energy will not participate in the cluster head election in the current cycle, thus raising the efficiency of cluster head election and reducing the communication cost in the clustering stage. Experimental results show that, compared with LEACH and EEUC, the NREUC algorithm significantly delays the dead time of the first node in the network, balances the energy consumption of each node, and prolongs the network lifetime. The death nodes are evenly distributed, which avoids the occurrence of blind spots and improves the quality of network monitoring.

II. MICRO-GRID MONITORING NETWORK

The distributed power-monitoring network in the micro-grid operation control is shown in Figure 1. Due to the complex structure and various information of the micro-grid, the real-time performance and accuracy of the acquired data are required. Thus, the communication network of the micro-grid adopts layer structure to optimize data collection of the devices, reduce the engineering quantity and the cost of devices installation and operation and increase the flexibility of monitoring the distributed generation during the operation of the micro-grid. The terminal power supply unit sends its own state information to the monitoring unit of the data aggregation layer through the wireless sensor network, and then the information is transferred from the data aggregation layer to the control center layer via optical fiber transmission [15]. In this paper, it is supposed that all the monitoring nodes and regional sink nodes in the network are fixed. Each monitoring node is isomorphic and can be a cluster head, a candidate cluster head or a common node. At the same time, the link in the network is symmetrical, and when the transmission power of the other party is known, the node can calculate the distance according to the received signal intensity.

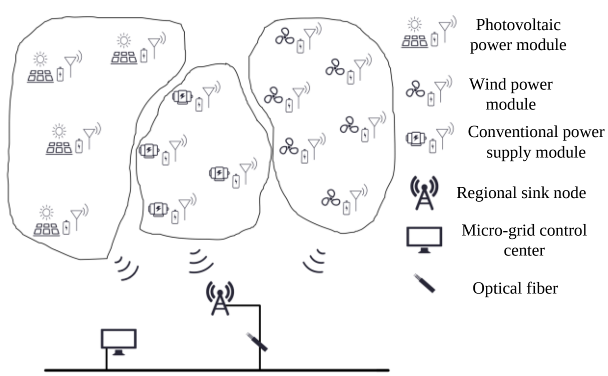


Fig.1. Distributed power module-monitoring network in micro-grid

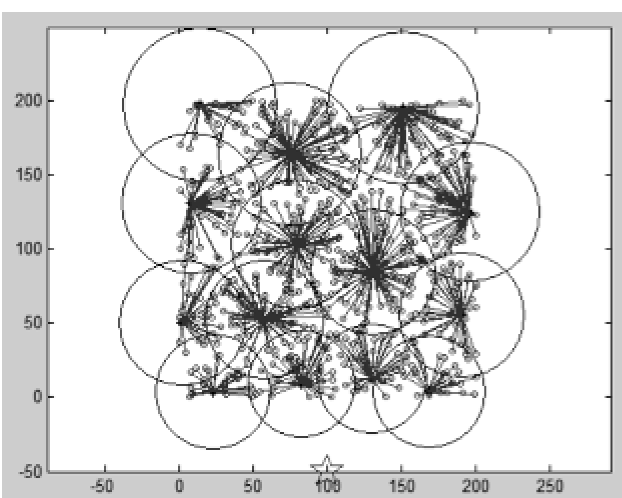


Fig.2. Simulation scene of the monitoring network

According to Fig. 1, the simulation scene of the monitoring network (Fig. 2) is drawn out, in which the small circle is the monitoring node and the five-pointed star is the sink node. In the distributed power supply module monitoring network of micro-grid, the overall trend is that the cluster near the sink node is with small scale and large number and the cluster far away from the sink node is with large scale and small number, which makes the cluster head close to the sink node have more energy to forward message, and will not die prematurely to form "hot zone."

III. Clustering Algorithm

A. Cluster head election

When clustering is performed, the cluster head is elected firstly in the wireless sensor network. In the cluster head election process, NREUC algorithm uses the cluster head competition radius to realize the non-uniform distribution of cluster head node, and distance and energy are introduced into the calculation formula of rival radius R_i.

$$\mathrm{R}_i = (1 - \mathrm{c}\frac{d_{\max} - d(s_i, s_0)}{d_{\max} - d_{\min}}(1 - \frac{\cos(\pi E_{ip}/2)}{10}))\mathrm{R}_0 \quad (1)$$

In Equation (1) , dmax and dmin represent the maximum and minimum distances of the nodes in the network to the sink node. d(si,s0) is the distance between the node i and the sink node. R0 is the maximum value of the cluster head competition radius, Ep is the ratio of the average energy of the surviving nodes in the network to the real energy of the node i, c is the parameter used to control the range of values.

Considering the communication energy consumption of nodes, the distance between nodes and sink node is still the main factor in the cluster head radius calculation of NREUC algorithm. The farther the distance is, the bigger the competition radius is. The nodes' own real-time energy is a secondary factor, which plays a role in fine-tuning the competition radius of the cluster head. The node with large energy has a larger competition radius, but will not affect the overall structure of cluster distribution.

B. Clustering stage

After the cluster head node is determined, it enters the clustering stage. In the NREUC algorithm of this paper, the normal node decides which cluster to join according to the clustering judgment factor.

$$\mathrm{C}(i, j, k) = \frac{Re(i,k)}{E_k}\frac{1}{d^2(s_i, s_j)} \qquad (2)$$

In Equation (2), the kth round, C(i,j,k) is the cluster judging factor from node j to cluster head i, Re(i,k) is the real energy of cluster head I, Ek is the average energy of nodes in current network, d(si,sj) is the distance from node j to cluster head i. In this way, nearest clustering can reduce the communication cost and meanwhile cluster heads with large residual energy are able to receive more nodes to achieve energy balance. The nodes losing the election become the common nodes and participate in the stage of clustering.

C. NREUC algorithm

When a network is initialized, the sink node broadcasts the message to all nodes so that the nodes can compute the distance from the sink node for later non-uniform clustering and the choice of transmitting power when the node transmits information to the base station. NREUC algorithm uses a circular mechanism; each round includes the election of cluster heads and cluster formation, inter-cluster routing and data transmission. There are four states of nodes in the network: normal node state, candidate cluster head state, cluster head state, and dead state. Each node has the cluster head flag G, the initial state of the flag G is set to 0, and the flag G is set to 1 if the node is elected as cluster head. The state of the node changes dynamically in each round. The cluster head is generated in the candidate cluster head. The competition radius of the candidate cluster head node is Ri, which is got through Equation 1. Different competition radius form clusters of different sizes. Finally, the distribution of the cluster in the network has the feature that the cluster close to the sink node is smaller and has more nodes comparing with the cluster far from the sink node.

The specific steps of NREUC algorithm are as follows:

Step1. Initialize the flag G

Set the cluster head flag bit G to 0 for all nodes.

Step2. Election of candidate cluster head

First, judge the value of the cluster head flag G, and the nodes with flag 0 are allowed to perform candidate cluster head election. Otherwise, the node will sleep until the cluster head election ends. Then select some nodes as candidate cluster heads according to probability, and other nodes will sleep until the cluster head election ends.

Step3. Cluster head election

According to Equation (1), the competition radius can be used to realize the cluster head election. In each round of cluster head election, candidate cluster head node i has a cluster header information table of adjacent candidate nodes, and any node j in the table satisfies the condition that the distance between node j and node i is less than the maximum competition radius of the two nodes. The candidate cluster head with the largest real-time energy is selected as the cluster head firstly, and the adjacent nodes in the candidate cluster head information table are deselected as common nodes. Among the remaining candidate cluster heads, the node with the highest real-time energy is chosen as the cluster head. The other candidate cluster heads in the candidate cluster head information table are selected as ordinary nodes. This cycle lasts until there is no candidate cluster head. After the node is selected as cluster head, its node flag G is set to 1.

Step4. Clustering stage

The common nodes in the network choose the cluster heads according to the clustering judgment factor of Equation (2) and form clusters of different sizes.

Step5. Information transmission stage

In this network, the cluster uses single-hop mode for information transmission, and cluster head with multi-hop approach. Cluster header node compresses and integrates the data transmitted from the cluster members to reduce the data amount and energy consumption of the communication.

Step6. Re-judgment of the cluster head mark G

After the information transmission is compl- eted, the remaining energy of each node at the end of the current round is calculated, and the flag G of the cluster head node whose residual energy is greater than or equal to the average residual energy is set to 0 so that it can participate in the following cluster head election.

Step7. Judgment of death node number

If the number of death nodes in the network exceeds the preset maximum value, the network declares death, otherwise it enters a new round of network clustering and information transmission.

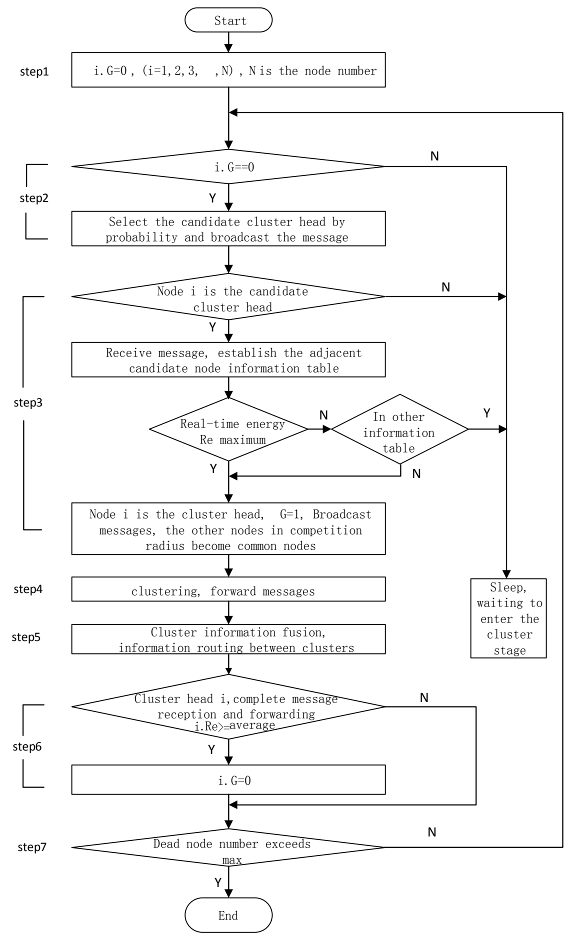


Fig.3. NREUC algorithm

IV. Algorithm Simulation

A. Simulation parameter setting

In this paper, LEACH algorithm, EEUC algorithm and NREUC algorithm are respectively coded in MATLAB, and the simulation perfor-mance is analyzed. In the experiment, 800 nodes are randomly distributed in the 200m square area. The energy of the network is mainly consumed by the transmitting circuit and the power amplify-cation circuit. When the node's transmitting number of bits is k and the distance between the bit and the convergence position is d, the calculation formula[5] of communication energy consumption is as follows:

$$E_{TX}(k,d)=\begin{cases} kE_{elec}+k\varepsilon_{fs}d^2, d<d_0 \\ kE_{elec}+k\varepsilon_{mp}d^4, d\ge d_0 \end{cases} \quad (3)$$

E_{elec} is the energy consumed by the transmitting circuit, ε_{fs} and ε_{mp} are the maximum energy consumed by the power amplification circuit in the two channel models. The parameters of the relevant simulation scene are shown in Table 1.

Table.1. Simulation parameters

Parameter name	Value
Node range	(0,0)~(200,200)m
Sensor node number	800
Convergence point coordinate	(100,-50)m
Initial energy of sensor node	0.3J
Radio frequency energy consumption coefficient	50nJ/bit
Power amplification circuit energy consumption coefficient ε_{fs}	10pJ/(bit·m2)
Power amplification circuit energy consumption coefficient ε_{mp}	0.0013 pJ/(bit·m4)
Threshold d_0	87m
Data packet size	4000bit
Control packet size	100bit

In the calculation of the cluster head competition radius Ri in Equation (1), the values of the coefficient c and the maximum competition radius R0 need to be set in advance. For the convenience of comparison with the EEUC algorithm, the value of the coefficient c follows the original EEUC value of 0.5. The maximum competition radius R0 of candidate cluster heads affects the final number of clusters generated. When the maximum competition radius is large, the number of clusters generated is small, which affects the cluster distribution in the final network.

In the simulation, based on the given area of network, different maximum competition radius is taken to carry on the experiment. As the micro-grid monitoring network has high requirements on the accuracy of information collection, the death time of the first node in the network is an important index to evaluate the network performance. Otherwise, the emergency of blind areas and fault will generate great economic loss. In Figure 4, R0 is 70m, death of the first node has the largest round. At the same time, simulation has defined when the dead node number is more than 80, the network fails and the network life ends. In Figure 5, when R0 is 70m, the network lifetime is the longest. The maximum competition radius R0 in Eq. 2 is 70 m.

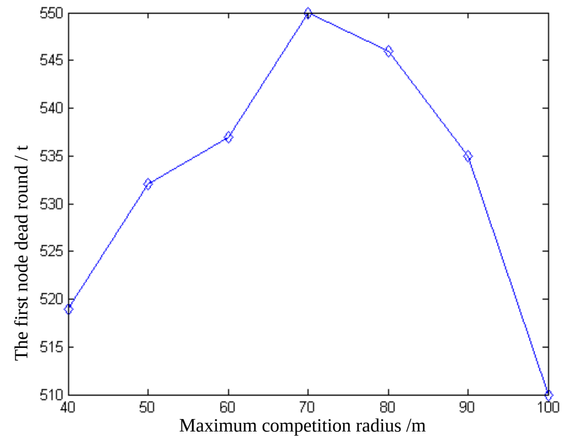


Fig.4. The relationship between the maximum competition radius and the death cycle of the first node

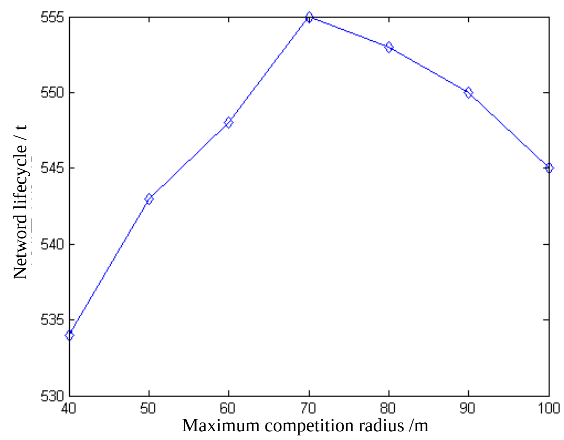


Fig.5. The relationship between the maximum competition radius and the network life cycle

In the NREUC algorithm, when the maximum competition radius is 70m, the number of clusters in each round is as shown in Figure 6. The network is divided into 10 to 13 clusters, and the number of clusters per round is stable.

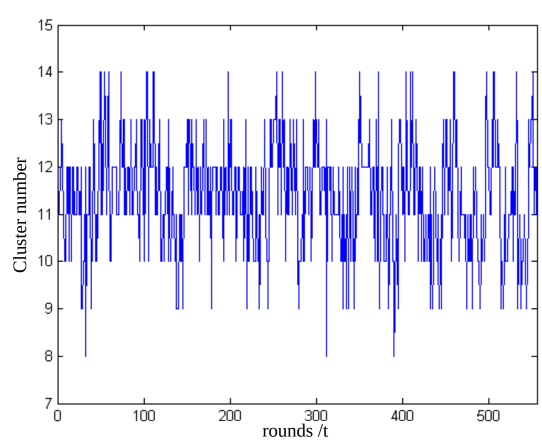


Fig.6. Number of clusters in each round in NREUC algorithm（

R_0=70m)

B. Simulation results analysis

In the network simulation, this paper mainly compares and analyzes the network life cycle and the death nodes distribution of the network. The longer the network life cycle is, especially the death time of the first node in the network, the more balanced the energy is in the network and the node will not die prematurely. The distribution of death nodes affects the monitoring quality of the whole network. The more uniform the distribution of death nodes is, the better the quality of monitoring is.

Network life cycle

The initial dead time of a node determines the life cycle of the whole network for networks with high accuracy of information collection. Taking micro-grid as an example, the unit-level equipment state data acquisition needs to achieve full coverage and high-precision requirements, and the emergence of blind spots will affect the entire network security. The death of the nodes will lead to the early emergence of blind spots. As the result, the quality of the monitoring network will reduce sharply.

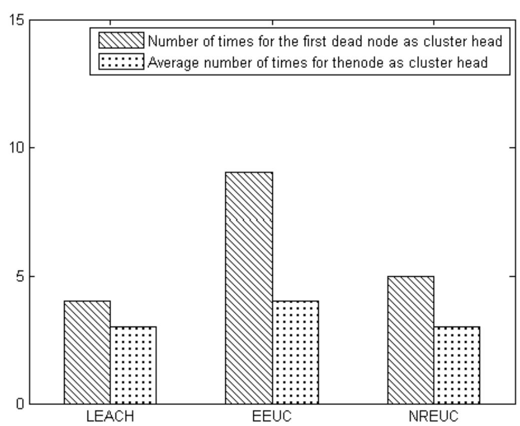


Fig.7. Number of times for the nodes as cluster head in LEACH, EEUC, NREUC algorithm

The practical micro-grid requires the high quality of the monitoring, the death time of the nodes must be considered because the death of the node means the emergence of blind spots. Among all nodes, the cluster head nodes consumes more energy than usual nodes every turn because the cluster head nodes need to gather the information of each node, integrate and transmit the information. Thus, the first dead node must be the nodes who have acted as cluster head.

In Figure 7, the first dead node have acted as cluster head four times in LEACH algorithm, which is nearly the average times of all nodes as cluster head. The probability of the nodes chosen as cluster head is the same because the cluster heads are selected averagely and periodically to balance the energy consumption topically regardless of the energy consumption of the communication related to the distance. As a result, the nodes far away from sink nodes are dead early because their excessive energy consumption of communication. The first dead node have acted as cluster head nine times in EEUC algorithm while the average times of all nodes as cluster head is nearly four. The difference indicates that the first dead node is dead because the times of the node acted as cluster head is above the average times of all nodes as cluster head, which results in the more energy consumption of the first dead node. The selection of the cluster heads in EEUC algorithm has two stages. The selection of candidate cluster head in first stage is based on a fixed threshold considered limited control factor resulted in partial nodes acted as cluster heads frequently and dead early.

In NREUC algorithm, the difference between the times of first dead node as cluster head and the average times of all nodes as cluster head is small, which is between LEACH algorithm and EEUC algorithm. The EREUC algorithm uses cluster heads flags to optimal the selection of candidate cluster heads, which reduces the probability of the nodes acted as cluster heads repeatedly. Compared with the EEUC algorithm, the NREUC algorithm has balanced the times of nodes as cluster heads in the network. In the selection of cluster heads, the NREUC algorithm considers the real-time energy of the nodes and chooses multiple hops routing policy in adjacent clusters routing, which reduces the energy consumption of communication of the nodes far away from sink node to avoid the early death of the nodes far away from sink node in LEACH algorithm. Generally, the NREUC algorithm considers the different energy consumption of all nodes and balances the times of nodes as cluster head to achieve high quality of monitoring.

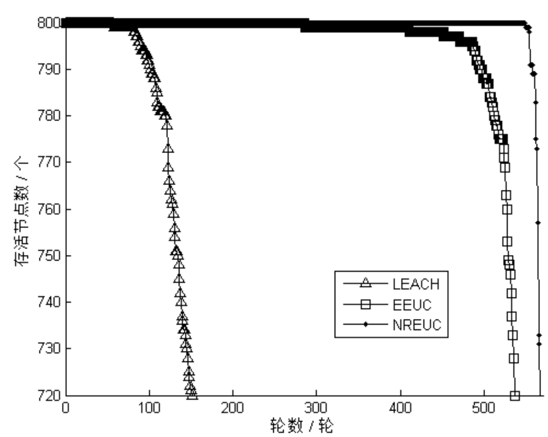
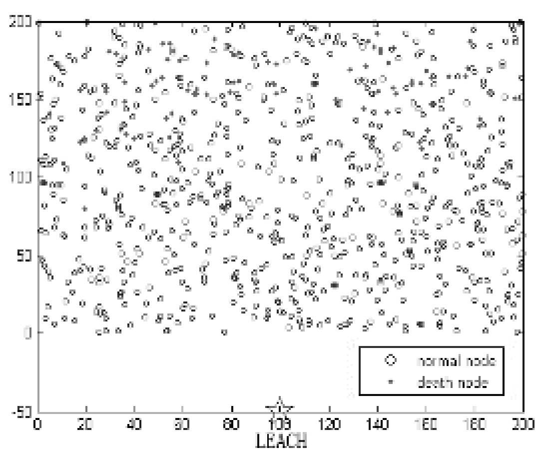


Fig.8. Network life cycle of three clustering algorithms

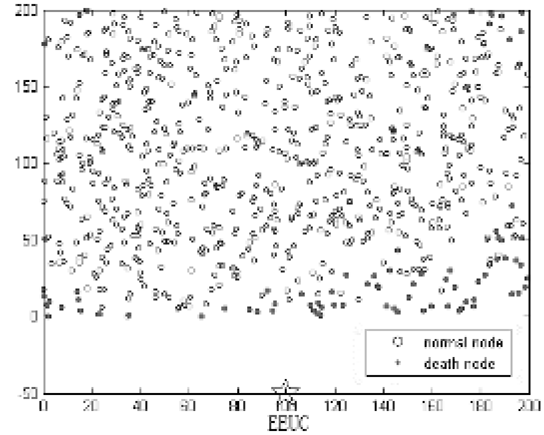
In Figure 8, the network lifecycle of the three clustering algorithms is given. Compared with the LEACH algorithm and the EEUC algorithm, the death time of the first node in the network using the NREUC algorithm is greatly extended, and the life time of the whole network also increased. Consequently, the lifetime of the monitoring network is ensured, the replacement cost of the devices is reduced and the goal of economic and efficiency is achieved. In NREUC algorithm, the election mechanism is adopted in the selection of the cluster head, which solves the problem that the LEACH algorithm randomly chooses the cluster head to cause the energy imbalance of the network nodes. The algorithm chooses the cluster heads through two stages, the first stage is candidate cluster heads generated from common nodes and the second stage is the non-uniform distribution of cluster heads generated from the candidate cluster heads based on the cluster completion radius. In the selection of candidate cluster heads, the judgment of the cluster head flag in NREUC algorithm excludes the cluster head in the previous round with large energy consumption from participating in the later cluster head election. This improves the quality of candidate cluster heads, avoids unnecessary energy consumption, and alleviates the large energy cost of cluster head selection in EEUC algorithm. In the calculation of cluster head radius, the energy of the node itself and its distance to the sink node have been taken into consideration in the NREUC algorithm, which makes the cluster size more reasonable than that in the EEUC possibility that nodes with less energy have larger cluster and avoids the death of those nodes due to their excessive energy consumption. From the attenuation curve of the NREUC algorithm in Figure 8, it can be seen that under the same energy consumption condition, the NREUC algorithm improves the energy balance degree in the network. Because the energy consumption of the nodes are balanced. In the latter part of the network, the proportion of surviving nodes in each round is higher than that in LEACH algorithm and EEUC algorithm and the death nodes are almost the cluster head in the previous round. During the end lifetime of the network, NREUC algorithm still can ensure the quality of monitoring network. The feature of wide coverage and small blind areas is more suitable for micro-grid to satisfy the requirement of high precision monitoring.

Network Death Node Distribution

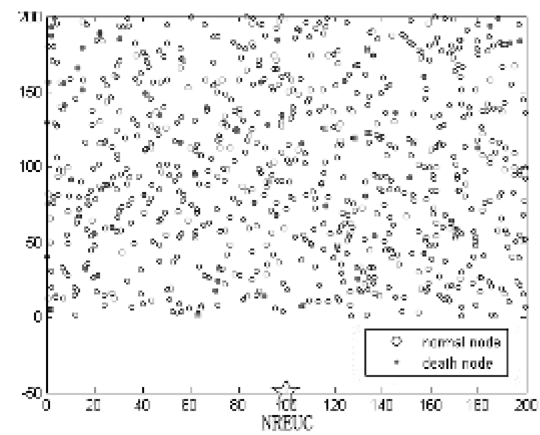
Figure 9 shows the death node distribution of the network. It can be seen from subgraph a. that the death nodes in the LEACH algorithm are mainly distributed in areas far from the convergence point. In subgraph b., the death nodes in the EEUC algorithm are mostly concentrated near the sink node. In subgraph c., the death nodes of NREUC are evenly distributed.



(a)



(b)



(c)

Fig.9. Distribution of death nodes in three clustering algorithms

For NREUC algorithm, cluster heads use multi-hop routing communication. The residual energy of each node is considered in the cluster- head election stage of each round to reduce the possibility that the low-energy nodes become cluster heads. In the calculation of the cluster head competition radius, the cluster head's own energy is taken into account, and the cluster head's competition radius is used to achieve the no-uniform distribution of the cluster head nodes in the network. In clustering stage, the NREUC algorithm takes the cluster head energy into account. The common nodes no longer choose the nearest cluster head but make judgments according to the residual energy of cluster head and the distance between node and cluster head. Finally, the distribution of death nodes in the network is uniform. The algorithm optimizes the structure of the cluster to balance the energy consumption among the nodes and avoid the polarization of the nodes' residual energy on the condition that the cost of communication is minimum. It solves the problem that the cluster head nodes far away from the sink node in the LEACH algorithm die prematurely due to the high communication cost, and the cluster head nodes near the sink node in the EEUC algorithm die prematurely due to transmitting too much data. NREUC algorithm achieves the purpose of improving the quality of network monitoring.

V. CONCLUSION

This paper presents a non-uniform WSN clustering algorithm for Micro-grid. The core idea of the algorithm is to consider the real-time energy of the nodes in the cluster-selection phase and the clustering stage to balance the energy consumption in the network and prolong the network lifetime. Micro-grid monitoring network has the characteristics of wide distribution of nodes and high monitoring precision. Compared with the traditional clustering algorithm, the algorithm proposed in this paper can achieve higher energy balance in the network, later initial death time of the nodes, and longer lifetime of the network.

Although the NREUC algorithm has a good effect on the energy balance in wireless sensor networks, it needs some message cost when clustering, which may influence the network lifetime. In the following study, it will be taken into consideration how to reduce the energy consumption of each round in the network, and verify the feasibility of the NREUC algorithm in the actual micro-grid environment.

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