Dynamic power allocation of the hybrid energy storage system in islanded AC microgrid based on virtual impedance

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Abstract: To realise the distributed control of the hybrid energy storage system (HESS) in an islanded AC microgrid, a dynamic HESS power allocation strategy based on the virtual impedance (VI) for supercapacitor (SC) and the battery is proposed. Dynamic power-sharing of two kinds of energy storage devices can be achieved without real-time measuring of load power. The state of charge (SOC) recovery of SC is achieved with a SOC loop integrated into the VI loop. The principle of dynamic power-sharing of HESS is derived based on the establishment of HESS equivalent circuit model. By analysing the influence of the voltage and current double loop controller parameters on the output impedance and the VI of the DC/AC converter, the method of setting the controller parameters for power distribution is presented. A simulation model is established with the designed equivalent power fluctuation conditions. The simulation results show that under various working conditions, the SC loop can compensate for the high-frequency part of the equivalent power fluctuation and the battery loop absorbs the low-frequency part of the power fluctuation. The dynamic power-sharing of HESS with the SC SOC recovery is realised effectively.

1 Introduction

Energy crisis and environmental pollution problems cause human beings to seek clean alternative energy resources. Distributed generation (DG), as one of the effective ways to utilise clean energy such as wind and solar energy, has been greatly explored [1]. Microgrid (MG) is an improved DG system, in which the renewable energy sources (RESs), loads and energy storage systems (ESSs) are integrated [2].

Due to the fluctuation and randomness of RES, the power balance and reliability are two major issues that need to be addressed in MG. One solution is using the control of RES and demand response. In [3], with a stochastic programming method considering risk constraint, an optimal scheduling approach is proposed to maximise the MG profit expectation. The other solution is using the ESS to improve the stability, reliability and the power quality of the MG [4]. Different ESSs have different energy densities, power density and response time, and their prices and service life are also different. However, single energy storage is generally difficult to meet various requirements of practical application. For example, the supercapacitor (SC) has higher power density and faster response speed, but lower energy density, which means it cannot give sustainable energy in a long time. The battery, on the other hand, has relatively lower power density, slower response speed and higher energy density [5]. By integrating different types of energy storage into the same system and forming hybrid ESS (HESS), the advantages of different types of energy storage equipment can be explored [6].

In HESS, it is necessary to allocate proper power to different types of energy storage device. An effective way is to make the energy storage equipment respond to the steady part of the power fluctuation of the system, while the power storage equipment compensates the transient part of the power imbalance. Centralised control based on filter algorithm is widely used for HESS [7]. In [8], the power fluctuation signal of the system passes through a high-pass filter and low-pass filter as the given power of different types of energy storage devices. In [9], a battery-SC HESS for islanded photovoltaic (PV) power system in the rural area is investigated, in which the SC can effectively mitigate the power fluctuation of the battery caused by load change. Besides the traditional control strategies, the advanced control theory like the model predictive control and the sliding mode control, are also applied in the control of HESS [10, 11]. Researchers in [12] use the stochastic mode predictive control strategy in operating management of MG considering the probabilistic constraints, making the decision process for the control action of MG more predictable in a relatively long time. All the above control strategies have to accurately measure the power of the system and provide a power reference value for the local controller of the HESS through the communication signals. Once the communication delay is large or the communication link failure occurs, the system will not work properly.

Considering the distribution of RES in MG, exploring the decentralised control strategy without communication connection and the central controller is necessary to further improve the reliability of the MG system [13]. The decentralised control is a method of independent control on l0 y based on local information [14]. This control method has low dependence on the communication bandwidth of the central controller, and can effectively improve the reliability and scalability of the MG operation. Droop control is a widely used decentralised control method in MG [15]. However, traditional droop control can only achieve the effect of power proportional distribution when the system reaches a steady-state [16]. As different types of energy storage equipment have different dynamic characteristics in the time domain, the power allocation effect of different energy storage equipment in the different frequency domain is also different. In order to make different characteristics of energy storage response to power fluctuation in HESS, it is necessary for energy storage equipment to show different response characteristics to different frequency bands of load power fluctuation. The virtual impedance (VI) strategy, which is similar to the droop control method is widely applied in the uninterruptible power system (UPS), MG and electrical vehicle [17]. Authors in [18] employ a virtual complex impedance for the active and reactive power sharing of low- and medium-voltage MG, improving the voltage stability of the system. VI can be designed as resistive, inductive and capacitive [19–21]. In [19], a virtual capacitor and virtual resistor are applied in the SC ESS to mitigate the power fluctuation caused by load changing in DC MG. The VI is also used for instantaneous power sharing and circulation current suppressing in paralleled UPS in [20]. In [21], the reactive power sharing performance is improved.
with the virtual capacitor strategy. In [22], a novel large-signal black box analysis approach is developed for the DC MG of electric ships, by which the non-linear characteristics of the whole system are properly assessed and the performance is improved. In [23], a decentralised control strategy based on VI for power sharing in HESS, and the state of charge (SOC) recovery of SC is considered in DC MG.

However, these references are mainly about DC MG, in which the key variables are direct. Very few researches have been conducted for the same function in AC MG. The currents and voltages are alternating variables in AC MG. Therefore, the effective splitting of alternating current is an issue need to be addressed. Besides, the output impedance of converter is affected by controller parameters, thus the proper design of controller parameters is necessary for developing VI. Hence, the detailed design of parameters in the HESS is also a problem to be solved.

In this paper, a power allocation method for HESS in AC MG is proposed, considering the SOC recovery of SC in the HESS. The influence of parameters in double-loop to the VI is analysed and the output impedance of converter is affected virtual resistance for the power allocation of HESS in AC MG is influence of parameters in double-loop to the VI is analysed and the output impedance of converter is affected virtual resistance for the power allocation of HESS in AC MG is.

The main contributions of this paper are as follows:

(i) A method based on VI consisting of a virtual capacitor and virtual resistance for the power allocation of HESS in AC MG is designed for mitigating the power fluctuation.

(ii) The dynamic power splitting, which means the SC connected by virtual capacitor only adjusts the fast dynamic part of power fluctuation, while the battery connected with virtual resistance only providing power support in steady-state, is achieved.

(iii) The parameters of the PI controller are analysed using the bode diagram and properly selected to ensure the stable operation of the system and improve the performance of power allocation with VI.

The rest of this paper is organised as follows. Section 2 gives the structure of a typical islanded AC MG. The proposed VI-based control of HESS is depicted in Section 3 with the detailed controller parameters and VI design in Section 4. The simulation study is conducted in Section 5 to verify the effectiveness of the proposed control strategy. Conclusions of the study are drawn in Section 6.

2 Topology of islanded AC MG

The typical structure of an islanded AC MG is shown in Fig. 1. The RES include wind turbine and PV array, where AC/AC and DC/AC converters are connected to the AC bus, respectively, to realise load support. The HESS consisting of battery and SC is connected to AC bus by bidirectional DC/AC converters, responsible for maintaining the power balance of the system and the voltage stability of the AC bus.

3 Control strategy of HESS based on VI

3.1 VI principle

By controlling the output voltage, the converter presents a certain characteristic of voltage variation after series VI, thus showing the feature of impedance to the outer circuit. As shown in Fig. 2, the output voltage of the converter satisfies (1) by applying VI control.

\[ v_{oi} = v_{oref} - Z_i i_o \]

where \( v_{oi} \) is the output voltage of the converter, \( v_{oref} \) is the rated output voltage of the converter, \( i_o \) is the output current and \( Z_i \) is the VI. Here, \( Z_i \) may be resistance, inductance and capacitance, or their series connection.

3.2 Dynamic power distribution of HESS based on VI

The decoupling control of active power and reactive power can be realised by constant power Park transformation and voltage vector orientation control. With the output impedance and line impedance of the converter are ignored, the HESS in Fig. 1 can be equivalent to the system in Fig. 3.

From Fig. 3, it can be seen that the HESS connected to the AC bus, where the virtual equivalent load constituted with the RES and loads is also linked. The power of the equivalent load is the power difference between the RES and the actual load. The output voltage of battery and SC satisfies

\[ \begin{align*}
    v_{obat} &= v_{obatref} - R_v i_{obat} \\
    v_{osc} &= v_{oscref} - \frac{1}{C_v} i_{osc}
\end{align*} \]

where \( v_{obatref} \) and \( v_{oscref} \) are the no-load output voltage of SC and battery; \( v_{obat}, v_{osc}, i_{obat}, i_{osc} \) and \( i_{obat} \) are the actual output voltage and current of SC and battery; \( R_v \) and \( C_v \) are the virtual resistance and virtual capacitance, respectively.

Ignoring the line impedance, the output voltage of SC and battery is equal to that of the AC bus, which is

\[ v_{obat} = v_{osc} = v_{ac} \]

As the output voltage is equal, only the output current can be controlled to adjust the output power of the energy storage unit. According to the energy flow relationship in Figs. 1 and 3, it is obvious that the current satisfying

\[ \begin{align*}
    i_{eq} &= i_{es} - i_l \\
    i_{eq} &= i_{obat} + i_{osc}
\end{align*} \]
In order to realize VI, it is necessary to transform the related variables of energy storage converter into corresponding variables in two-phase dq synchronous reference frame (SRF) by Park transformation. This makes the alternating variables into direct and maintain the AC bus voltage. Battery and SC share the same compensation voltage

\[ v_{comp} = G_v v_{ref} - Z_d o \]  

where \( i_{res} \) is the output current of the RES, \( i_l \) is the load current and \( i_{eq} \) is the equivalent load current provided by HESS.

By combining (2)–(4), the relationship between the output current of the battery and the SC and the equivalent load current can be obtained as

\[
\begin{align*}
    i_{hat} &= \frac{1}{R_i C_s} i_{eq} \\
    i_{hat} &= \frac{R_i C_s}{R_i C_s + 1} i_{eq}
\end{align*}
\]  

Fig. 5  Control loops of energy storage converter with VI

It can be seen from (5) that the current transfer function of the battery and the SC have the characteristics of the low-pass filter and the high-pass filter, respectively, and the time constant is

\[ T_i = R_i C_i \]  

3.3 Control strategy of HESS based on VI

In order to realize VI, it is necessary to transform the related variables of energy storage converter into corresponding variables in two-phase dq synchronous reference frame (SRF) by Park transformation. This makes the alternating variables into direct variables, facilitating the control strategy design. Fig. 4 shows the control structure of the HESS system using the VI control strategy in SRF. For the symmetric characteristic of \( d \) and \( q \)-axis variables, the subscripts of SRF variables are omitted.

In Fig. 4, the SC and battery are connected to the AC bus through DC–AC converter, \( v_{AC} \) is the rated voltage of the AC bus. The double-loop control structure of the voltage outer loop and the current inner loop is employed, where \( v_{obatref} \) and \( v_{in} \) are the reference output voltage of DC–AC converters of battery and SC, respectively. When the given voltage of the voltage control loop is generated, the VI control is realized by subtracting the rated voltage of the battery and the SC with the voltage drop caused by \( C_v \) and \( R_v \), respectively. After applying the VI control strategy, it is obvious that the bus voltage will be lower than its rated value. To maintain the bus voltage constant, it is necessary to compensate and maintain the AC bus voltage. Battery and SC share the same compensation voltage \( \Delta V_i \). After VI control strategy is realized in SRF, the final modulation output voltage of the converter is calculated by Park inverse transformation to control the DC/AC converter. For SC, its SOC is signified by its terminal voltage \( v_{SC} \). After a transient power response, the SOC of SC will deviate from its initial value revealed by the voltage \( v_{SC} \). In this system, a SOC recovery loop realized by a PI controller is integrated into the voltage control loop of SC to maintain the SOC of SC at a certain scale and keep it endurable working.

4  Parameter design of HESS controllers and VI

4.1 Control schema of HESS

In this paper, a voltage and current double-loop control combined with the VI control strategy is adopted by the bidirectional DC/AC converters of battery and SC in HESS. The basic control diagram is presented in Fig. 5.

Considering the tracking characteristics of the voltage loop and the rapidity of the current loop, the PI-P controller is adopted in the voltage and current double loop. Ignoring the time delay of the switching devices, the main circuit of the converter is approximately equivalent to a voltage proportional amplifier with a coefficient of \( K_{PWM} \). In Fig. 5, \( K_v, K_{ip}, K_{vp} \) and \( K_{ip} \) are the proportional, integral coefficient of the voltage controller and the proportional coefficient of the current controller. \( V_{ref} \) and \( V_i \) are defined as the reference and output voltage of the converter, respectively. \( L, r \) and \( C \) are the LC filter inductance, the parasitic resistance and filter capacitance of the converter, respectively. For the battery subsystem, the VI \( Z_d \) is \( R_v \), for SC subsystem it is \( C_v \). Suppose the VI control is not used in the system, that is, when the VI is zero, the equivalent circuit model of the energy storage converter can be expressed as

\[
\begin{align*}
    v_i &= G_v v_{ref} - Z_d o
\end{align*}
\]  

The transfer functions of the output voltage gain \( G_v \) and the equivalent output impedance of the converter \( Z_o \) are

\[
\begin{align*}
    G_v &= \frac{K_{PWM} K_{ip} K_{vp} + K_{PWM} K_{ip} K_{vi}}{[LC] s^3 + (r C + K_{PWM} K_{ip} C) s^2 + (1 + K_{PWM} K_{vp} K_{ip} + K_{PWM} K_{ip} K_{vi})} \\
    Z_o &= \frac{[L s^2 + (r + K_{PWM} K_{ip})] [LC s^3 + (r C + K_{PWM} K_{ip} C) s^2 + (1 + K_{PWM} K_{vp} K_{ip}) s + K_{PWM} K_{ip} K_{vi}]}{[LC] s^3 + (r C + K_{PWM} K_{ip} C) s^2 + (1 + K_{PWM} K_{vp} K_{ip} s + K_{PWM} K_{ip} K_{vi})}
\end{align*}
\]
4.2 Design of parameters for controller and VI

In the equivalent circuit of the converter, it is obvious that the output impedance is not zero. Equation (9) shows that several factors determine the output impedance, among which the gain of the converter and the parameters of the filter are determined by the circuit structure and system performance. Nevertheless, the parameters of voltage and current controllers also influence the output impedance. In order to analyse the influence of controller parameters on output impedance, the method of frequency domain analysis is adopted.

Fig. 6a shows the bode diagram of controller output impedance with the parameters of the current loop with (10). It reveals that the changing of $K_{ip}$ will not affect the output impedance of the converter. Considering the bandwidth of the current loop, and the dynamic characteristics of the system as well as the other factors affecting the output impedance, the controller parameter of the current loop are determined

$$\mathcal{G}_i = \frac{K_{ip}K_{pwm}}{L_s + r + K_{ip}K_{pwm}}$$  \hspace{1cm} (10)

where $K_{pwm} = 400$, $r = 0.1 \, \Omega$ is the equal resistance of the LC filter.

The switching frequency of converter $f_s = 20 \, \text{kHz}$. The cut-off frequency of the current loop is

$$f_{ic} \leq \frac{1}{2\pi f_s} = 4 \, \text{kHz}$$  \hspace{1cm} (11)

In view of the faster inner current loop responses, the proportional coefficient can be selected relatively larger on the premise of appropriate bandwidth. In this paper, the proportional coefficient of the current loop $K_{ip}$ is 0.126.

Fig. 6b is the bode diagram of controller output impedance when the proportional coefficient $K_{vp}$ of the voltage controller changes. It can be seen from the figure that the system damping increases with the increase of the proportional coefficient of the controller.
After the implementation of VI control, the voltage output leads the output impedance of converter to be inductive, which is a trade-off for the virtual capacitor of SC loop. Hence, the parallel impedance of converts with VI is

\[ Z_{ovc} = Z_{ov} - Z_{ovc} \]

By choosing the virtual resistance and the virtual capacitance, both SC power and loads change with the system oscillation. Therefore, the battery voltage loop proportional coefficient \[ K_{vbat} \] is selected as 2.4, the SC circuit voltage loop proportional coefficient \[ K_{vpasc} \] is equal to \[ K_{vbat} \].

Fig. 6c is the bode diagram of output impedance when the voltage controller integral coefficient \[ K_{vi} \] changes. From Fig. 6c, it can be seen that the output impedance characteristics are significantly changed by modifying \[ K_{vi} \]. When \[ K_{vi} = 0 \], the output impedance is pure resistance. Therefore, the voltage control loop of the virtual resistance loop using the \[ P \] controller to make its output impedance pure resistance, so that the virtual resistance integrated on it will still show pure resistance characteristic. The bigger \[ K_{vi} \] makes the voltage quickly tracking the reference value. However, too big \[ K_{vi} \] leads the output impedance of converter to be inductive, which is a trade-off for the virtual capacitor of SC loop. Hence, the voltage loop integral coefficient \[ K_{vc} \] of SC is set as 53.

After the implementation of VI control, the voltage output transfer function of the system is written as

\[ V_o = G_v V_{ref} - (G_c Z_o + Z_v) i_0 \]

where \( Z_v \) is the VI.

In HESS, the final output impedance of converter is determined as

\[ Z_{ov} = G_v Z_o + Z_v \]

It can be seen that the final output impedance is not the direct summation of the VI and the equivalent output impedance of the converter. Substituting the parameters of the control loops into (13), the final output impedance of the converter with VI control strategy is expressed as the following equations. For battery, it is (14), and for SC, it is (15)

\[ Z_{ov} = \left[ Ls^2 + (r + K_p \omega_n R_s) s + K_p \omega_n R_s \right] + \left[ Ls^2 + (rC + K_p \omega_n C_s) s \right] + \left[ (1 + K_p \omega_n R_s)s + K_p \omega_n R_s \right] \]

and for SC, it is

\[ Z_{ovc} = \left[ L C s^3 + (r C_s + K_p \omega_n C_s) s \right] + \left[ L C s^3 + (r C_s + K_p \omega_n C_s) s \right] + \left[ (C_s + K_p \omega_n R_s C_s) s + K_p \omega_n R_s C_s \right] \]

Then, the parallel impedance of converts with VI is

\[ Z_{ovc} = Z_{ov} - Z_{ovc} \]

By choosing the virtual resistance and the virtual capacitance, both SC power and loads change with the system oscillation. Therefore, the battery voltage loop proportional coefficient \[ K_{vbat} \] is selected as 2.4, the SC circuit voltage loop proportional coefficient \[ K_{vpasc} \] is equal to \[ K_{vbat} \].

Fig. 6c is the bode diagram of output impedance when the voltage controller integral coefficient \[ K_{vi} \] changes. From Fig. 6c, it can be seen that the output impedance characteristics are significantly changed by modifying \[ K_{vi} \]. When \[ K_{vi} = 0 \], the output impedance is pure resistance. Therefore, the voltage control loop of the virtual resistance loop using the \[ P \] controller to make its output impedance pure resistance, so that the virtual resistance integrated on it will still show pure resistance characteristic. The bigger \[ K_{vi} \] makes the voltage quickly tracking the reference value. However, too big \[ K_{vi} \] leads the output impedance of converter to be inductive, which is a trade-off for the virtual capacitor of SC loop. Hence, the voltage loop integral coefficient \[ K_{vc} \] of SC is set as 53.

After the implementation of VI control, the voltage output transfer function of the system is written as

\[ V_o = G_v V_{ref} - (G_c Z_o + Z_v) i_0 \]

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\[ Z_{ovc} = \left[ Ls^2 + (r + K_p \omega_n R_s) s + K_p \omega_n R_s \right] + \left[ Ls^2 + (rC + K_p \omega_n C_s) s \right] + \left[ (1 + K_p \omega_n R_s)s + K_p \omega_n R_s \right] \]

and for SC, it is

\[ Z_{ovc} = \left[ L C s^3 + (r C_s + K_p \omega_n C_s) s \right] + \left[ L C s^3 + (r C_s + K_p \omega_n C_s) s \right] + \left[ (C_s + K_p \omega_n R_s C_s) s + K_p \omega_n R_s C_s \right] \]

Then, the parallel impedance of converts with VI is

\[ Z_{ovc} = Z_{ov} - Z_{ovc} \]

By choosing the virtual resistance and the virtual capacitance, both SC power and loads change with the system oscillation. Therefore, the battery voltage loop proportional coefficient \[ K_{vbat} \] is selected as 2.4, the SC circuit voltage loop proportional coefficient \[ K_{vpasc} \] is equal to \[ K_{vbat} \].

Fig. 6c is the bode diagram of output impedance when the voltage controller integral coefficient \[ K_{vi} \] changes. From Fig. 6c, it can be seen that the output impedance characteristics are significantly changed by modifying \[ K_{vi} \]. When \[ K_{vi} = 0 \], the output impedance is pure resistance. Therefore, the voltage control loop of the virtual resistance loop using the \[ P \] controller to make its output impedance pure resistance, so that the virtual resistance integrated on it will still show pure resistance characteristic. The bigger \[ K_{vi} \] makes the voltage quickly tracking the reference value. However, too big \[ K_{vi} \] leads the output impedance of converter to be inductive, which is a trade-off for the virtual capacitor of SC loop. Hence, the voltage loop integral coefficient \[ K_{vc} \] of SC is set as 53.

After the implementation of VI control, the voltage output transfer function of the system is written as

\[ V_o = G_v V_{ref} - (G_c Z_o + Z_v) i_0 \]

where \( Z_v \) is the VI.

In HESS, the final output impedance of converter is determined as

\[ Z_{ov} = G_v Z_o + Z_v \]

It can be seen that the final output impedance is not the direct summation of the VI and the equivalent output impedance of the converter. Substituting the parameters of the control loops into (13), the final output impedance of the converter with VI control strategy is expressed as the following equations. For battery, it is (14), and for SC, it is (15)
of SC output power. The SC voltage drops to 735 V with the discharging process. At \( t = 0.3 \text{ s} \), the power of SC soon changes to \( -50 \text{ kW} \) and then gradually returns to zero. In the same process, the battery power varies from 100 to 50 kW which is the same value as the load. The SC voltage increases to 743 V with the charging process. From the simulation results, it can be seen that the SC responds quickly and provides all the power support when the power of the equivalent load is fluctuating. The power of the battery varies slowly. With the increase of the power of the battery, the power of SC decreases gradually to zero. In steady state, the battery provides all equivalent load power. During this process, the AC bus voltage remains constant. Hence, the dynamic power allocation of SC and battery is achieved.

From the simulation results, it also can be seen that the voltage of SC changes with the varying of equivalent power and cannot return to the initial value in steady-state. The reason is that the power response causes the charging and discharging of the SC, and there is no SOC recovery control strategy employed.

5.3 Case C: power allocation of HESS with SC SOC recovery

In HESS, the SC, as its low energy density that cannot provide continuous power supporting function, should be viewed as a short-term power device and its SOC recovery should be considered properly. In this case, the SOC recovery loop is employed to realise the terminal voltage adjustment of SC so that its SOC can recover to the initial value after a transient adjustment.

The simulation results are depicted in Fig. 9. The same equivalent load condition with Case B is implemented in this case. Comparing the waveforms of Case C with Case B, similar powersharing dynamics can be observed. The difference is that at the end of the power-sharing process the SOC recovery loop begins to adjust the voltage of SC by the battery current, making the power of battery a little overshoot. Nevertheless, at steady state, the battery supplies the total load power and the output power of SC smoothly towards zero. Besides, the voltage of SC reaches its initial value at the end of the adjusting process, which means the recovery of SOC is realised.

5.4 Case D: power allocation of HESS in the ramp equivalent load condition

In this case, the equivalent power set to has two slope periods in which the power is changing in a linear increase and decrease mode \( (t = 0.1–0.3 \text{ and } 0.6–0.8 \text{ s}) \). The responses of HESS are depicted in Fig. 10. As shown in Fig. 10 the battery power is changing according to the equivalent power, while the SC power also returns to zero when the equivalent power does not change. However, during the periods when the equivalent power is changing in a ramp mode, the SC power has the trend to compensate it and gives a power of 25 kW gradually until the end of power changing. This is not the expected feature for the SC. The simulation results reflect that the proposed VI scheme is not suitable for the ramp changing load power situation.

### 6 Conclusion

In this paper, a dynamic power allocation control strategy for HESS is proposed considering the SOC recovery of SC. The proposed control strategy, which is based on the VI, is essentially a decentralised control without high band communication link and centre controller. With the virtual capacitance method for the SC control loop and the virtual resistance strategy for battery control loop applied, the transient and steady components of power fluctuation can be allocated automatically to SC and battery. The influence of voltage and current cascaded loop PI parameters on the output impedance of HESS controller is analysed and a PI parameter design guideline is obtained. A SOC recovery loop is integrated into the SC control loop, eliminating the SOC deviation of SC and ensuring the continuous working ability of it. The simulation study is conducted to validate the effectiveness of the proposed method which improves the robustness and scalability of the system by its decentralised characteristics.

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