Decentralised DC voltage control and flexible power regulation for multi-port converter-based energy router

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Abstract: The idea of ‘energy router’ (ER) is put forward as a critical application of the energy Internet (EI), especially in the new generation of electric power system to fulfill the power management and to deal with the integration of massive distributed generations. Furthermore, AC/DC hybrid network becomes a kind of development trend since it can improve the power quality and efficiency compared with adding converters for DC loads. This article proposes a decentralised control method for multi-port converter (MPC)-based ERs to achieve flexible power regulation and ‘plug and play’ operation. With the proposed schemes, DC bus voltage can be maintained together by multi-ER through appropriately adjusting their transmitted power according to the pre-set power-sharing ratio. Furthermore, the sharing ratio can be online changed for flexible power regulation. The stability of the system is ensured by Lyapunov method, detailed simulation results are presented to validate the feasibility of the proposed scheme under different operating conditions.

1 Introduction

With the depletion of the fossil energy and the deterioration of the natural environment, considerable attentions have been paid to the research of applying renewable energy generation, improving energy efficiency and high-quality power regulation in the recent years. A new power distribution infrastructure called ‘energy internet’ (EI) has been developed as a promising way to solve these problems, and the energy router (ER) will serve as the crucial component [1, 2], which is responsible for integrating multi-type sources and loads, forming different voltage-level links and effectively managing the power in the future EI framework-based grid [3].

The ER originates from the solid-state transformer (SST) in the distributed networks [4]. However, with the increasing connection of various distributed generators to the power grid, the traditional distributed network is changing from a radial structure, AC voltage type, and central management system to a gridding structure, AC/DC hybrid type and multi-autonomous agents system [5]. Consequently, a variety of ER technologies are further introduced in the medium-/low-voltage hybrid distributed network or micro-grid to build future EI. According to the different types of technology implementations, the ER can be typically divided into three categories as: SST-based ER, multi-port converter (MPC)-based ER and power line communication (PLC)-based ER [2]. Among which, MPC-based is widely applied in the medium-/low-voltage distribution networks or micro-grid to build future EI. According to the different types of technology implementations, the ER can be typically divided into three categories as: SST-based ER, multi-port converter (MPC)-based ER and power line communication (PLC)-based ER [2].

As most distributed energy resources (DERs) and loads are DC inherent, and the DC power supply has many advantages such as the number of inverters can be effectively reduced, moreover, less transmission loss and higher power supply quality can be ensured, which conform well with the objective of an EI for effectively providing high-quality electric power to users in an environmentally friendly and sustainable way [7–9]. The MPC-based ER can play an important role to construct an AC/DC hybrid network as a new form in the medium-/low-voltage distributed network for compatibility with existing AC network. For a single ER, a multi-infeed structure is adopted to reduce the stress of each converter and improve the power supply reliability, furthermore, the energy exchanged between the distributed network and the utility grid can be shared among more than one ERs [10, 11].

Despite the advantage of better power supply reliability by using this control structure, there are still several control issues that need further development. For the multi-ER, although their AC-sides are connected to different points of the AC bus, the common control objective is to maintain the DC-voltage stability, which is related to the power balance [12]. What’s more, since there are multi-parallel connected converters in an individual ER, proportional power-sharing among each converter should also be concerned according to their capacities or power management requirements [13]. Various control strategies have been proposed to realise these control objectives, of which droop control is commonly used since it is a main forms of the decentralised control, the DC voltage is formed under the cooperative action of all controllers in the operation process [14, 15]. However, it has some significant drawbacks, such as voltage deviation, inaccurate power sharing due to line, and limited transient performance.

This paper proposes a decentralised control scheme based on back-stepping design for the converters in a multi-infeed ER system. The advantages of the proposed method can be summarised as:

i. DC-link voltage can be maintained together by the ERs connected to the multiple AC power terminals even from different distribution feeder lines, each ER consists of multi-parallel connected converters. Meanwhile, a proper power-sharing among these DC voltage forming units can be achieved in a decentralised manner.

ii. Flexible power regulation and automatic power balance can be realised without affecting the DC-link voltage, thus the ‘plug and play’ characteristic can be ensured for the MPC-based ERs.

iii. The DC-link voltage can be maintained stable in both normal operation and unplanned operation such as a sudden outage of the converter, which ensures the reliable performances.

Furthermore, the non-linear control laws are designed based on Lyapunov theory, which guarantees the system stability in a large operating range with fast dynamic performances.
2 Energy router-based AC/DC network

2.1 Structure of the AC/DC hybrid network

The configuration of the three-phase MPC-based ER is shown in Fig. 1. Multi-ER is used to maintain the DC voltage and properly transform, the control inputs of the system are fluctuation of the AC power grid, the proposed MPC-based ER can according to the Kirchhoff current law, we have

\[
\begin{bmatrix}
\dot{i}_{d}\ni \\
\dot{i}_{q}\ni \\
\end{bmatrix} = \begin{bmatrix}
a_1i_{d}\ni + a_2i_{q}\ni - b_1V_{d}\ni \\
a_1i_{q}\ni - a_2i_{d}\ni - b_2V_{q}\ni \\
\end{bmatrix} + \begin{bmatrix}
b_1V_{d}\ni \\
b_2V_{q}\ni \\
\end{bmatrix} \begin{bmatrix} u_{d}\ni \\
u_{q}\ni \\
\end{bmatrix}
\]

(1)

Since there are \( n \) paralleled converters connected to the common DC bus, the above model with \( n \) modules can be expressed as

\[
V_{dc} = \frac{\sum_{i=1}^{n} P_{dc}\ni - P_{load}}{C_{eq} V_{dc}}
\]

(2)

where \( \omega \) is the system angular frequency, \( a_i = -R_i/L_i \), \( b_i = -1/L_i \), \( V_{d}\ni \) and \( V_{q}\ni \) are, respectively, the \( d \)-axis and \( q \)-axis components of the respective AC feeder voltage \( V_{\text{f}}\ni \). \( P_{dc}\ni \) is the active power at the DC side of converter, and \( P_{load} = V_{dc}I_{load} \) is the equivalent load power of the DC network, and \( I_{load} \) is the total feeding current to the DC bus.

Since the \( d \)-axis is set to be in phase with \( V_{\text{f}}\ni \), \( V_{d}\ni \) is equal to the magnitude of \( V_{\text{f}}\ni \), which gives the active and reactive power at the AC feeder side of the converter as

\[
P_{\text{a}} = 1.5V_{d}\ni I_{\text{a}} \quad Q_{\text{a}} = -1.5V_{d}\ni I_{\text{q}}
\]

(3)

Ignoring the power losses of the converter, \( P_{dc}\ni \) in (2) can be replaced with \( P_{\text{a}} \) then we have

\[
V_{dc} = \frac{\sum_{i=1}^{n} V_{d}\ni I_{\text{a}}}{V_{dc}} + d
\]

(4)

where \( C_{eq} = 3/(2C_{dc}) \), \( d = -I_{load}/C_{dc} \).

3 Decentralised controller design

First, the tracking error of the DC bus voltage is defined as

\[
e = V_{dc} - V_{dc}
\]

(5)

where the DC voltage reference \( V_{dc}^* \) is constant control reference. Since the derivative of a constant is zero \( (V_{dc} = 0) \), combined with (4), the time derivative of the tracking error in (5) can be represented as

\[
\dot{e} = -C_{eq} \sum_{i=1}^{n} V_{d}\ni I_{\text{a}} - d
\]

(6)

Considering the following Lyapunov function candidate

\[
V_1 = \frac{1}{2} e^2
\]

(7)

Taking the time derivative of (7) and submitting (6), it becomes

\[
V_1 = e\dot{e} = -e\left[ C_{eq} \sum_{i=1}^{n} V_{d}\ni I_{\text{a}} + d \right]
\]

(8)

Define the desired virtual control signal for \( i_{\text{a}} \) as

\[
\xi_{\text{a}} = -\lambda_{i} \times \frac{V_{dc}}{C_{eq} V_{d}\ni} (d - \alpha e)
\]

(9)

where \( \alpha \) is a positive constant, and \( \lambda_{i} \) is user defined constant which satisfies \( \sum_{i=1}^{n} \lambda_{i} = 1 \). We can see from (8) that if \( I_{\text{a}} = \xi_{\text{a}} \), then \( V_1 = -\alpha e^2 \) can be obtained.

Thus, the tracking error can be further defined as \( r_{\text{a}} = \xi_{\text{a}} - I_{\text{a}} \), (9) can be rewritten as

\[
V_1 = -\alpha e^2 + C_{eq} e \sum_{i=1}^{n} V_{d}\ni I_{\text{a}}
\]

(10)

Meanwhile, the \( q \)-axis current tracking error can be defined as \( r_{\text{q}} = \xi_{\text{q}} - I_{\text{q}} \), where \( \xi_{\text{q}} \) is the control reference which can be easily
3

In steady state, which means \( P_i = 0 \) and \( r_{di} = 0 \), the voltage tracking error can be derived.

![Diagram of the decentralised controller](image)

**Theorem:** Consider the multi-ER system characterised by (1)–(5). The decentralised control laws are proposed as in (16) and (17). Then, the following facts hold during the normal operation of the system:

1. The DC voltage and converter current tracking errors \( e, r_{di} \) and \( r_{qi} \) all go to zeros asymptotically;
2. The power-sharing ratio of any two converter \( i \) and converter \( j \) is \( (\lambda_i: \lambda_j) \) in steady state, which leads to the power sharing error goes to zero as

\[
(1/\lambda_i) P_{di} - (1/\lambda_j) P_{dq} = 0
\]

**Proof:** By submitting (15) and (16) into (14) yields

\[
V_j = -ae - \sum_{i=1}^{n} q_{di} r_{di} - \sum_{i=1}^{n} q_{qi} r_{qi} \leq 0
\]

According to the Lyapunov function, the tracking errors \( e, r_{di} \) and \( r_{qi} \) will go to zero asymptotically, the first fact holds.

Based on these, the referential active power of the \( i \)th converter \( P_{si} \) can be expressed as

\[
P_{si} = \frac{3}{2} V_{dc} e_{di} = -\lambda_i V_{dc} \frac{C_{dc}}{V_{dc}} d
\]

Since the value of term \( (V_{dc}/C_{dc}) \) is same for each converter, then we can obtain that

\[
\frac{P_{sa}}{P_{sb}} = \frac{\lambda_i}{\lambda_j}
\]

Thus, the second fact holds.

According to the above analysis, the multi-ER power management can be realised by setting the appropriate power-sharing coefficients through the superior control layer. Since the coordinated control only regulates the steady-state performance, it does not need to be very fast, which reduces the communication requirements. The coordination control is illustrated as Fig. 4.

![Diagram of the ER-based coordination control](image)

5 Simulation results

The simulation model set up for verifying the features of the proposed control method, two ERs are connected to the end of two different distribution feeder lines, ER #1 includes two parallel connected converters and ER #2 includes only one converter, and together they support the operation of the DC network. Three cases are designed in the simulation to verify the features of the proposed ER-controller, Fig. 5 shows the simulation results with the proposed control method using the MATLAB/Simulink software. The top subfigures shows the DC bus voltage regulation, the middle subfigure shows the output power of each converter and the bottom subfigure shows the AC current of each converter, respectively. The simulation parameters are listed in Table 1, and the details of the tested cases are illustrated as follows.

![Simulation results](image)

5.1 Case 1 – plug and play

In this case, the plug and play capacity of the proposed control algorithm has been tested. The settings for the ERs are as follows: ER #1 remains connected to the DC bus for all the time, ER #2 is connected to the DC bus at the very beginning and disconnected at 0.4 s. The total load is 120 kW, and the power-sharing ratio is set as 1:1.1.
It can be seen from the top subfigure of Fig. 5a that some fluctuation occurs when the ER #2 is disconnected to the system, which lasts for a very short time (within 1 cycle), then the voltage is maintained at around referential value. Before the outage of ER #2, the total 120 kW load can be shared equally by the three converters, after 0.4 s, the output power of ER #2 drops to zero and the load is shared by the two parallel-connected converters in ER #1 with the output power of 60 kW, respectively, as shown in the middle subfigure of Fig. 5a.

The AC current of each converter changes with fast dynamic responses as shown in the bottom subfigure of Fig. 5a.

5.2 Case 2 – loads variation

In this case, the load makes a step change from 120 to 240 kW at 0.4 s, whereas the simulation results of the proposed approach (with the ratio 3:2:1) are shown in Fig. 5b. Unlike the droop-based control method that has the inherent voltage deviation after the transient, which degrades the power supply reliability of the system, especially for the sensitive load. It can be observed in Fig. 5b that the DC voltage can always be maintained stable before and after the loads variation. Meanwhile, the power-sharing performance can also be ensured during the simulation with the fast dynamics as shown in the middle and bottom subfigures of Fig. 5b.

5.3 Case 3 – flexible power sharing

This case investigated the flexible power-sharing performance by online changing the power-sharing ratio $\lambda_i$. At the beginning, the power-sharing ratio is set equally (1:1:1) for each converter, then the ratio is online changed as 3:2:1, simulation results are shown in Fig. 5c. It can be seen that there is no impact on voltage regulation and all three converters adjust their output power accordingly, which means the proportional and flexible power-sharing performance can be realised only by adjusting the power-sharing ratios.

6 Conclusion

This paper proposes a decentralised control scheme based on backstepping design for the converters in a multi-infeed ER system, which helps to improve the power supply reliability, maintain the DC voltage stability, and flexibly share the load power among converters with different capabilities or based on the optimal operating consideration. Compared with the existing droop-based control method, there is no voltage deviation during the load change, ER outage and sharing ratio variation, and fast dynamic can be ensured. The stability of the system controlled by the proposed method can be guaranteed by using Lyapunov theory. An outstanding performance in both steady state and transient state are tested through simulations, which verified the effectiveness of the proposed control strategy. Furthermore, this decentralised control method can be well combined with the existing hierarchical control to provide useful characteristics.

7 References

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