A novel power management strategy based on combination of 3D droop control and EKF in DC microgrids

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Abstract
Voltage regulation and power management are necessary to maintain balance of supply and demand in DC microgrids. In such systems, power sharing is normally done through parallel operation of distributed energy resources equipped with droop controllers. However, low power sharing accuracy and not allowing the microgrid to maximise the available power from the renewable sources are two main problems associated with conventional droop control methods. In addition, the 2D droop method is a parameter-dependent method for extracting maximum available energy from renewable sources. In this paper, a novel power management strategy based on the optimal 3D droop coefficients is developed for a DC microgrid. Optimal state estimation is attained using a combination of extended Kalman filter and adaptive recursive least square method. Reference currents of renewable energy sources (wind and solar) and battery energy storage system are estimated using the proposed prediction based model. The proposed strategy not only increases the power sharing accuracy but also remains the bus voltage around a nominal value. The performance of the proposed method is evaluated for the considered DC microgrid in two different scenarios. Results show the high effectiveness and robustness of the proposed method. It has been concluded that precise estimation of the sources reference currents and 3D droop coefficients are critical for optimal power management and bus voltage regulation in DC microgrids.

1 INTRODUCTION

In recent years, the continued increase in demand, the energy crisis and environmental pollution issues have led to more attention toward renewable energies [1]. Considering these problems and consequently the increasing penetration of renewable energy sources (RESs) into modern electric grids, the concept of microgrid has emerged [2]. A microgrid is a localised grid that consists of loads and distributed energy resources and can play a role as a controllable entity. Microgrids have AC, DC and hybrid types. The AC microgrid faces challenges such as power quality, losses, synchronisation etc. Considering the challenges in the AC microgrid and the ever-increasing rise of DC consumers, DC microgrids have received attention in recent years. Advantages of DC microgrids can include reducing air pollution by increasing renewable energy resources penetration level, reducing losses by eliminating the skin effect in cables, simplicity due to not required to the synchronisation and increasing stability, reliability, and system controllability [3].

Control and operation of the microgrid have challenges such as power management, energy management, protection, power quality and stability. Voltage regulation improvement and accurate power sharing among energy resources are the most important power management goals in DC microgrids. Power management schemes in DC microgrids determine output powers or voltages (or both of them) of each source in the microgrid. Output signals of power management schemes are fed to the control system of interfacing converters to control energy sources output power. Power management schemes in microgrids are classified into two general categories, which are called communication-based and communication-less schemes. In the literature, three types of centralised, distributed, and decen-
tralised control methods are used for implementing power management strategies in DC microgrids [4, 5]. In the centralised control, the controller unit communicates with all energy resources using communication links, which especially in large systems might not be economical and practical [6–8]. The distributed control method however benefits from a low-bandwidth communication established among local controllers for each microgrid component. In this structure, each control node shares knowledge with the neighbouring ones eliminating the need for a mesh networking [9–12]. The decentralised control based on droop characteristics offers a cost-effective and efficient solution by combining the advantages of the previously mentioned topologies. It uses local information for lower-level control purposes while meeting coordination needs among upper-level controllers which in turn increases system reliability and stability [13]. A lot of researches have been performed about the droop control method in DC microgrids. In the literature, the droop control strategies have been implemented in four main categories including conventional and variants of the droop control [14–16], virtual framework structure-based method [17], constructed and compensated based method [18, 19], and the hybrid droop/signal injection method [20]. All of these strategies are implemented using conventional (2D) droop control. One of the main problems of conventional droop control (2D) is low accuracy power sharing [14], [21–24]. In [21], the optimal power management and the voltage regulation are considered simultaneously. However, the proposed method is designed for a small-scale microgrid and reveals the lack of focus on the optimal operation of the available power of the renewable sources in the DC microgrid. Also, the performance of the method has not been analysed as a DC multi-microgrid (MMG). In [25], a droop based control strategy has been proposed in order to improve the energy efficiency of wind resources in microgrids. The proposed method in [25] utilises a droop surface (3D droop) to maximise extracted power from available wind energy and to maintain the system bus voltage within the permissible range. Also, the authors have extended the same control strategy in the next research [26] and have represented a mathematical optimisation to obtain optimal reference currents for microgrid resources. The control strategy does not have predictive capability and is not able to provide optimal performance in different load profiles, so it can lead to instability of the system.

Estimation based methods such as model predictive control (MPC) and extended Kalman filter (EKF) can be used to improve the droop control operation. Shadmand [27] proposed MPC-MPPT and MPC-droop scheme for current regulation of PV DC–DC interface converter in DC smart distribution system, however, the scheme decreases efficiency and increases system complexity because of using two-stage back to back DC–DC converters. Also, the method is designed only for the PV sources in a small-scale microgrid. In [28], the MPC algorithm has been used for power control in DC microgrid. Energy management system (EMS) is required for power management in AC and DC microgrids in order to achieve optimal operation of sources and optimal charging/discharging scheduling of battery energy storage system (BESS). In [29], a coordinated and multivariable energy management strategy is proposed using a nonlinear MPC (NMPC) algorithm for the regulation of DC bus voltage and proper power sharing in a DC microgrid. Accurate power sharing among generators in proportion to their ratings for variable load demands is the main objective of the proposed method in [29]. Although, the strategy includes both the power management and the voltage regulation, it is designed for standalone applications. In addition, it does not have the capability to expand into MMG, as well as it is dependent on the extracted power instead of the available power.

This paper presents an alternative method based on a combination of the 3D droop and EKF which is very useful specially in isolated microgrid where “power limiting” mode [30, 31] can be activated to dispatch renewable sources more efficiently and economically as compared to conventional maximum power point tracking (MPPT) methods. The underlying motivation for this study is to develop EKF with the combination of multidimensional droop to estimate the true state of a DC microgrid to improve power management in the microgrid. An optimal power management and voltage regulation are done simultaneously. The optimal operation is based on the available power of the renewable sources in the DC microgrid. Besides, a novel droop based control strategy is presented using a combination of the 3D droop principle and the EKF algorithm. EKF is used for state estimation in the system in order to reduce the system and measurement noises. In the proposed strategy, 3D droop control for wind sources [25] is generalised for PV sources and BESS.

The comparison between the proposed method in this paper and the existing control methods for DC microgrid is shown in Table 1. As a whole, the main contributions of this paper are as follows:

1. The proposed method is based on the combination of EKF as a predictive control and 3D droop which leads to extracting maximum available energy of renewable sources and BESS, improves the DC bus voltage and reference currents of power sources to obtain optimal power management.
2. Because of the EKF capabilities, the proposed method provides significant advantages such as high precision estimation, robustness against parameter variation and measurement noises.
3. Unlike conventional methods, the proposed scheme, in this work, is a parameter-independent method for extracting the maximum available power of the renewable sources.

This paper is organised as follows: Section 2 describes model of different elements in the considered DC microgrid. In Section 3, controller design and optimisation problem are discussed. The process of combining the EKF and the 3D optimal droop in the proposed method is discussed in this section. In Section 4, Simulation results on the considered DC microgrid under two different scenarios are presented. Finally Section 5 concludes the paper.
### Table 1: Comparison of control strategies

| Power management methods | Strategies type | Optimal voltage regulation | Power management accuracy | Expandability to multi-microgrid | Prediction capability | Optimal |
|--------------------------|----------------|---------------------------|--------------------------|---------------------------------|-----------------------|---------|
| Ref.[14]                 | Decentralised  | ✓                         | Medium                   | No                              | ✓                     | ✓       |
| Ref.[16]                 | Decentralised  | ✓                         | Low                      | No                              | ✓                     | ✓       |
| Ref.[9]                  | Distributed    | ✓                         | High                     | Yes                             | ✓                     | ✓       |
| Ref.[10]                 | Distributed    | ✓                         | Low                      | No                              | ✓                     | ✓       |
| Ref.[20]                 | Distributed & decentralised | ✓             | Low                      | No                              | ✓                     | ✓       |
| Ref.[21]                 | Decentralised  | ✓                         | High                     | No                              | ✓                     | ✓       |
| Ref.[24]                 | Decentralised  | ✓                         | High                     | No                              | ✓                     | ✓       |
| Ref.[6]                  | Centralised    | ✓                         | High                     | No                              | ✓                     | ✓       |
| Ref.[11]                 | Distributed    | ✓                         | Medium                   | No                              | ✓                     | ✓       |
| Ref.[7]                  | Centralised    | ✓                         | High                     | No                              | ✓                     | ✓       |
| Ref.[12]                 | Distributed    | ✓                         | High                     | No                              | ✓                     | ✓       |
| Ref.[8]                  | Centralised    | ✓                         | High                     | No                              | ✓                     | ✓       |
| Ref.[25]                 | Decentralised  | ✓                         | Medium                   | No                              | ✓                     | ✓       |
| Ref.[1]                  | Decentralised  | ✓                         | High                     | Yes                             | ✓                     | ✓       |
| The proposed method      | Decentralised  | ✓                         | High                     | Yes                             | ✓                     | ✓       |

**FIGURE 1** Generic structure of the considered microgrid

### 2.1 Wind energy conversion system

In this paper, wind source is modelled using a three-phase AC source according to Figure 2 and presented in [32]. Wind turbine aerodynamics is neglected in equations of wind source. Similar to many other applications, the wind energy conversion system (WECS) consists of a permanent magnet synchronous generator (PMSG), a three-phase diode bridge rectifier and a unidirectional DC–DC buck converter [33]. In order to track the wind profile, the buck converter duty cycle control is performed using output signals of the proposed control strategy. The numerical values of the source model parameters are shown in Table 2. State equations of wind source are as follows:

\[
\frac{dI_a}{dt} = V_ga - (V_{ca} + R_{a}I_a) \tag{1}
\]

\[
\frac{dI_b}{dt} = V_gb - (V_{cb} + R_{b}I_b) \tag{2}
\]

\[
\frac{dI_c}{dt} = V_gc - (V_{cc} + R_{c}I_c) \tag{3}
\]

\[
C \frac{dV_{dc}}{dt} = I_{dc} - I_{lh}; V_{dc} = \frac{3\sqrt{3}}{\pi} V_{ga} \tag{4}
\]

\[
\frac{dI_h}{dt} = V_{dh} - R_hI_{lh} - V_{ch} \tag{5}
\]
TABLE 2  The microgrid specifications

| Item            | Parameter | Value | Parameter | Value |
|-----------------|-----------|-------|-----------|-------|
| Windsource      | $R_a$     | 0.2 Ω | $L_h$     | 1.5 mH |
|                 | $R_b$     | 0.2 Ω | $C_h$     | 0.2 mF |
|                 | $R_c$     | 0.2 Ω | $L_i$     | 5 mH   |
|                 | $L_a$     | 15 mH | $C_i$     | 0.08 F |
|                 | $L_b$     | 15 mH | $R_B$     | 0.23 Ω |
|                 | $L_c$     | 15 mH | $L_B$     | 0.8 mH |
|                 | $C$       | 3 mF  | $V_{dc}$  | 380 V  |
|                 | $R_h$     | 0.2 Ω | $V_{ref}$ | 300 V  |
| PVsource        | $R_P$     | 0.2 Ω | $C_{po}$  | 0.08 F |
|                 | $L_{pi}$  | 1.5 mH| $R_{pl}$  | 0.28 Ω |
|                 | $C_{pi}$  | 0.2 mF| $L_{pl}$  | 0.5 mH |
|                 | $L_{po}$  | 5 mH  | $V_{cp}$  | 360 V  |
|                 | $V_{ref}$ | 300 V |
| Conventional source | $R_c$     | 0.2 Ω | $C_{co}$  | 0.08 F |
|                 | $L_{ci}$  | 1.5 mH| $R_{cl}$  | 0.1 Ω  |
|                 | $C_{ci}$  | 0.2 mF| $L_{cl}$  | 1.2 mH |
|                 | $L_{co}$  | 5 mH  | $V_{e}$   | 400 V  |
|                 | $V_{ref}$ | 300 V |
| BESS            | $C_B$     | 1 mF  | $L_{Bo}$  | 1 mH   |
|                 | $R_B$     | 1 mΩ  | $C_{Bo}$  | 0.08 F |
|                 | $R_{Bo}$  | 0.1 Ω | $R_{Bl}$  | 1 Ω    |
|                 | $L_{Bl}$  | 0.2 mH| $L_{gg}$  | 1.2 mH |
|                 | $C_{Bi}$  | 1 mF  | $V_{0}$   | 296 V  |
|                 | $V_{ref}$ | 300 V |
| Variable load   | $R_d$     | 0.23 Ω| $L_v$     | 9.5 mH |
|                 | $L_{cl}$  | 0.1 mH| $C_{co}$  | 0.9 mF |
|                 | $C_{ci}$  | 25 μF |            |        |
| Constant load   | $R_{load}$| 30 Ω  | $C_{load}$| 0.1 F  |

\[
C_h \frac{dV_{Ch}}{dt} = i_h - Di_i \quad \text{(6)}
\]

\[
L_d \frac{di_h}{dt} = DV_{Ch} - V_{cl} \quad \text{(7)}
\]

\[
C_i \frac{dV_{cl}}{dt} = i_h - i_W \quad \text{(8)}
\]

\[
L_B \frac{di_E}{dt} = V_{cl} - R_B i_W - V_{Bus} \quad \text{(9)}
\]

where $D$ is the buck converter duty cycle. Equations (1)–(3) are the diode bridge rectifier state equations, where $R$ and $L$ include the resistance and inductance of the PMSG, the line and the possible transformer. $V_{ga}$, $V_{gb}$ and $V_{gc}$ are the induced emf. $i_a$, $i_b$ and $i_c$ are the phase currents, $i_{dc}$ is the bridge rectifier output current, $V_{dc}$ is the bridge rectifier output voltage, and $C$ is the filter capacitor. Equations (5)–(8) are related to the buck converter. The equivalent circuit of the DC–DC buck converter is shown in Figure 2 [25, 33].

2.2 Conventional and PV sources

Similar to the WECS modelling approach, conventional and PV sources could be considered as DC sources connected to a unidirectional DC–DC buck converter as shown in Figures 3 and 4, respectively. The irradiance profile is tracked using the buck converter duty cycle control in the proposed algorithm, which results in a variable voltage in the converter output. The conventional source is a gas turbine [25]. The model of the conventional and PV sources are presented in Figures 3 and 4, respectively. The numerical values of the two sources model parameters are shown in Table 2 [25, 34].
State equations of the conventional source are expressed as follows:

\[
L_{ci} \frac{d}{dt} i_{ci} = V_S - R_c i_{ci} - V_{cci} 
\]

\[
C_{ci} \frac{d}{dt} V_{cci} = i_{ci} - D i_{co}
\]

\[
L_{co} \frac{d}{dt} i_{co} = D V_{cci} - V_{cco}
\]

\[
C_{co} \frac{d}{dt} V_{cco} = i_{co} - i_{Conv}
\]

\[
L_{cl} \frac{d}{dt} i_{Conv} = V_{cco} - R_{cl} i_{Conv} - V_{Bus}
\]

As can be seen in Figure 3, the buck converter of the conventional source is defined by Equations (10)–(13), and the output current of the source is defined by Equation (14). The conventional source equations are based on [25].

State equations of the PV source are expressed as follows:

\[
L_{pi} \frac{d}{dt} i_{pi} = V_S - R_p i_{pi} - V_{cpi}
\]

\[
C_{pi} \frac{d}{dt} V_{cpi} = i_{pi} - D i_{po}
\]

\[
L_{po} \frac{d}{dt} i_{po} = D V_{cpi} - V_{cpo}
\]

\[
C_{po} \frac{d}{dt} V_{cpo} = i_{po} - i_{PV}
\]

\[
L_{pl} \frac{d}{dt} i_{PV} = V_{cpo} - R_p i_{PV} - V_{Bus}
\]

The buck converter of the PV source is described in Equations (15) to (18), and the output current of the source is defined as Equation (19).

2.3 | BESS

In remote areas, natural gas-fired distributed generations are not cost-efficient choices. For this reason, power producers should use renewable energy sources to produce electricity in those areas [35]. Due to the uncertainty of renewable energy sources, BESS can also be used to balance power between demand and supply [36]. Considered model for BESS is such as Figure 5 with technical characteristics adopted from [25] and shown in Table 2. Differential equations of the BESS model are defined as:

\[
C_b \frac{d}{dt} V_{cb} = i_{Bo}
\]

\[
L_{Bi} \frac{d}{dt} i_{Bi} = V_{Batt} - R_{Ba} i_{Bi} - V_{cBi}
\]

\[
C_{Bi} \frac{d}{dt} V_{cBi} = i_{Bi} - D i_{Bo}
\]

\[
L_{Bo} \frac{d}{dt} i_{Bo} = D V_{cBi} - V_{cBo}
\]

\[
C_{Bo} \frac{d}{dt} V_{cBo} = i_{Bo} - i_{Batt}
\]

\[
L_{Bl} \frac{d}{dt} i_{Batt} = V_{cBo} - R_{Bl} i_{Batt} - V_{Bus}
\]

Equations (21)–(24) are related to bidirectional buck converter of the BESS. The battery model and the output currents of the BESS are defined with Equations (20) and (25), respectively. The equations are based on [25].

2.4 | Loads

Considered microgrid includes a constant impedance load and a variable load, which is shown in Figure 6. The variable load is connected to the DC bus through a DC–DC buck converter. Load models in this paper are based on the models used in [25].

The constant impedance load has only one state. Equation (26) is the state equation for constant impedance load and Equations (27)–(30) are differential equations for the variable load. In Equation (26), total of the sources and the battery storage currents are collected (total of the injected currents on the DC bus), and then the variable load current and the passing current from \( R_{load} \) are subtracted it, so the current flows through capacitor \( C_{load} \) is obtained.

\[
C_{load} \frac{d}{dt} V_{Bus} = (i_W + i_{Conv} + i_{PV}) - (i_{L,2}) + i_{Batt} - \frac{V_{Bus}}{R_{load}}
\]
where $i_{L2}$ is variable load current. The numerical values of the loads model parameters are shown in Table 2.

### 3 | CONTROLLER DESIGN

The proposed control strategy will optimise power flows in the microgrid using combination of surface droop control strategy and EKF algorithm. The multidimensional droop control strategy is used as an open-loop control scheme in [25]. The open-loop control is modified into closed-loop control in the presented scheme. Also, the proposed multidimensional droop control for wind sources in [25] is generalised for PV sources and energy storage. In the proposed algorithm, the droop coefficients and the duty cycles of the converters are obtained from output variables of Figure 10. The considered objective function is defined in Section 3.2. By solving the objective function, the optimised droop coefficients and the duty cycles can be obtained. Optimisation of these parameters leads to maximising extracted energy from available in the renewable energy sources and the BESS.

Reference currents of the energy sources and the energy storage are defined as

\[
i_{\text{ref}} = \frac{V_{\text{ref}} - V_{\text{Bus}}}{R_{\text{d}1}} + \frac{V_{W}}{R_{\text{d}2}} \tag{31}
\]

\[
i_{\text{refPV}} = \frac{V_{\text{ref}} - V_{\text{Bus}}}{R_{\text{d}3}} + \frac{\text{Irradiance}}{R_{\text{d}4}} \tag{32}
\]

\[
i_{\text{refBatt}} = \frac{V_{\text{ref}} - V_{\text{Bus}}}{R_{\text{d}5}} + \frac{\text{SOC}}{R_{\text{d}6}} \tag{33}
\]

where $V_{W}$, irradiance and SOC are wind speed, solar irradiance and state of charge of the BESS, respectively. $R_{\text{d}1}$ to $R_{\text{d}6}$ are the droop coefficients (droop setting), which the calculation method is discussed in Section 3.1.

Generally, the output voltage and current errors of the sources and battery converter are as follows

\[
\frac{d(\text{error}_1)}{dt} = i_{\text{ref}} - i_{\text{out}} \tag{34}
\]

\[
\frac{d(\text{error}_2)}{dt} = V_{\text{out,ref}} - V_{\text{out}} \tag{35}
\]

where $V_{\text{out}}$, $i_{\text{out}}$, are the output voltage and current of the converters. $V_{\text{out,ref}}$ and $i_{\text{ref}}$ are the voltage and current reference of the converters.

Two proportional–integral (PI) controllers are considered to compensate for these errors that one of them is used to compensate for the voltage error and the other to for the current error. Therefore, we have:

\[
V_{\text{out,ref}} = k_{\text{pi}} (i_{\text{ref}} - i_{\text{out}}) + k_{\text{ii}} \text{error}_1 \tag{36}
\]

\[
D = k_{\text{pi}} (V_{\text{out,ref}} - V_{\text{out}}) + k_{\text{ii}} \text{error}_2 \tag{37}
\]

where $k_{\text{pi}}$ and $k_{\text{ii}}$ are the proportional and integral gains of the PI current controller. $k_{\text{pi}}$ and $k_{\text{ii}}$ are the proportional and integral gains of the PI voltage controller.

Taking into consideration Equations (6), (7), (31), (36) and (37), we have:

\[
\frac{d(\text{error}_1)}{dt} = \left( \frac{V_{\text{ref}} - V_{\text{Bus}}}{R_{\text{d}1}} + \frac{V_{W}}{R_{\text{d}2}} \right) - i_{W} \tag{38}
\]

\[
\frac{d(\text{error}_2)}{dt} = k_{\text{pi}} \left( \frac{V_{\text{ref}} - V_{\text{Bus}}}{R_{\text{d}1}} + \frac{1}{R_{\text{d}2}} \right) + k_{\text{ii}} \text{error}_1 - V_{\text{d}} \tag{39}
\]

Taking into consideration Equations (16), (17), (32), (36) and (37), we have:

\[
\frac{d(\text{error}_1)}{dt} = \left( \frac{V_{\text{ref}} - V_{\text{Bus}}}{R_{\text{d}3}} + \frac{\text{Irradiance}}{R_{\text{d}4}} \right) - i_{\text{PV}} \tag{40}
\]
Section 2, the state vector variables is represented by

\[ \mathbf{X} = \begin{bmatrix} i_W \\ i_{PV} \\ i_{Batt} \\ i_{Conv} \\ V_{Bus} \end{bmatrix} \]

Taking into account Equations (22), (23), (33), (36) and (37), we have:

\[ \frac{d}{dt} (\text{error}_1) = k_p \left( \frac{V_{ref} - V_{Bus}}{R_{ds}} + \text{Irradiance} - i_{PV} \right) + k_e \text{error}_1 - V_{cpu} \]

(41)

\[ \frac{d}{dt} (\text{error}_2) = k_e \left( \frac{V_{ref} - V_{Bus}}{R_{ds}} + \frac{\text{SOC}}{R_{ds}} - i_{Batt} \right) + k_e \text{error}_1 - V_{cpu} \]

(42)

\[ \frac{d}{dt} (\text{error}_3) = k_e \left( \frac{V_{ref} - V_{Bus}}{R_{ds}} + \frac{\text{SOC}}{R_{ds}} - i_{Batt} \right) + k_e \text{error}_1 - V_{cpu} \]

(43)

3.1 | EKF

A nonlinear system can be linearised around the Kalman filter estimate; the Kalman filter estimate is based on the linearised system. The EKF idea was presented by Stanley Schmidt that can be used for linearised nonlinear systems [37]. In this paper, EKF is used for estimation of the wind and PV sources reference currents, energy storage current and the DC bus voltage. The objective function will optimise using the estimated values. The optimal values of the 3D droop coefficients and age. The objective function will optimise using the estimated

\[ X(k) = X(k-1) + T_s f \left( X(k-1), u(k-1) \right) \]

(50)

\[ P(k) = F(k-1) P(k-1) F^T(k-1) + Q(k-1) \]

(51)

2. Update measurement

\[ G(k) = P(k) H^T(k) \left[ (H(k) P(k) H^T(k) + R(k))^{-1} \right] \]

(52)

\[ \dot{X}(k) = X^-(k) + G(k) (y(k) - H \dot{X}^-(k)) \]

(53)

\[ P(k) = (I - G(k) H(k)) P(k) \]

(54)

where \( \dot{X}(k) \) and \( \dot{P}(k) \) are the posteriori estimated states vector and the covariance matrix of the states at time step \( k \), respectively. \( \dot{X}(k) \) and \( \dot{P}(k) \) are the priori estimated states vector and the covariance matrix of the states, respectively. \( F(k) \) is transition matrix which is the linearised dynamic in Equation (51), \( G(k) \) is the Kalman filter gain and \( I \) is the identity matrix.

For estimation using nonlinear differential equations, first, they have to be linearised. Then estimation variables are obtained based on the expressed discrete state space model in Equation (48). The linearization process is accomplished after-wards by calculating transition matrix \( F \). Considering the expressed model in Section 2 and Equation (48), the system equations are organised as Equations (55)–(59).

\[ i_W(k + 1) = f_1 = i_W(k) + \frac{1}{L_{pl}} \left( V_{cl}(k) - R_{dl} i_W(k) - V_{Bus}(k) \right) \]

(55)

\[ i_{PV}(k + 1) = f_2 = i_{PV}(k) + \frac{1}{L_{pl}} \left( V_{cpu}(k) - R_{pl} i_{PV}(k) - V_{Bus}(k) \right) \]

(56)
\[ \dot{i}_{\text{Batt}}(k+1) = f_3 = \frac{i_{\text{Batt}}(k)}{L_{\text{Bl}}} \times \left( V_{\text{cBo}}(k) - R_{\text{Bl}}i_{\text{Batt}}(k) - V_{\text{Bus}}(k) \right) \]  
(57)

\[ \dot{i}_{\text{Conv}}(k+1) = f_4 = \frac{i_{\text{Conv}}(k)}{L_{\text{cl}}} \times \left( V_{\text{cCo}}(k) - R_{\text{cl}}i_{\text{Conv}}(k) - V_{\text{Bus}}(k) \right) \]  
(58)

\[ V_{\text{Bus}}(k+1) = f_5 = V_{\text{Bus}}(k) + \frac{1}{C_{\text{load}}}[\left( i_{\text{W}}(k) + i_{\text{PV}}(k) + i_{\text{Batt}}(k) \right) + i_{\text{Conv}}(k) - \left( i_{\text{2}}(k) + \frac{V_{\text{Bus}}(k)}{R_{\text{load}}(k)} \right)] \]  
(59)

Output power of the wind, the PV, the battery energy storage and the conventional sources can be obtained from Equations (60)–(63).

\[ R_W(k+1) = V_{\text{Bus}}(k)i_{\text{W}}(k) - R_{\text{pW}}i_{\text{W}}^2(k) \]  
(60)

\[ P_{\text{PV}}(k+1) = V_{\text{Bus}}(k)i_{\text{PV}}(k) - R_{\text{pPV}}i_{\text{PV}}^2(k) \]  
(61)

\[ P_{\text{Conv}}(k+1) = V_{\text{Bus}}(k)i_{\text{Conv}}(k) - R_{\text{pConv}}i_{\text{Conv}}^2(k) \]  
(62)

\[ P_{\text{Batt}}(k+1) = V_{\text{Bus}}(k)i_{\text{Batt}}(k) - R_{\text{pBatt}}i_{\text{Batt}}^2(k) \]  
(63)

The optimisation method searches for an optimum solution in which the value of the 3D droop coefficients of wind, PV and energy storage sources are placed within their feasible regions.

According to Equation (64), the optimisation problem attempts to minimise the discrepancy between extracted power (from wind and PV sources) and available power in these sources. Extracted powers from these sources are obtained from Equations (60) and (61) while available powers of these sources are determined using the wind speed and the irradiance profiles according to the wind turbine [32] and the photovoltaic system [34] power curves.

Recursive least square (RLS) method is one of the best methods of online identification. Classic RLS algorithm with time-varying parameters, such as droop coefficients in this paper may lack enough precision during the identification process. Therefore, the adaptive recursive least square (ARLS) is used to perform the recursive estimation of 3D droop coefficients of wind, PV and energy storage sources. The ARLS algorithm using Equation (66) is considered.

\[ y(k) = [\varphi(k)]^T \Theta(k) + \xi(k) \]  
(66)

where \( \xi(k) \) is a stochastic noise with normal distribution and zero mean, \( \varphi(k) \) is the regressor vector which defines the evolution of the reference currents of wind, PV and energy storage sources. \( y(k) \) is the discrepancy between extracted and available power of sources, \( \Theta(k) \) is the system parameter vector (3D droop coefficients) and \( k \) is the time step. The ARLS implementation is based on the formulation in [38].

The 3D Compliance convergence curve for the unused energy of wind and PV sources (prediction error for the simulated day) with respect to droop coefficients of wind source is shown in Figure 7. The 3D convergence curve shows the convergence of the unused energy of the renewable sources with respect to the \( R_{\text{dW}} \) and \( R_{\text{dPV}} \) as the variables of the Equations (31) and (55). The unused energy is the sum of \( \varepsilon \) in Equation (64) for 24 h of the simulation timeframe. It is a tangible indicator for understanding the performance of the proposed power management strategy. This function indicates how much of the total available energy from the renewable sources has not been used.
during the study period. This curve also shows the effectiveness of changing the slope in bus voltage direction $\frac{1}{R_{d1}}$ and wind speed direction $\frac{1}{R_{d2}}$ on the objective function. There are similar figures for changes in the objective function relative to the droop variables of the PV source and the energy storage system in Equations (32) and (33). The droop variables $R_{d1}$ and $R_{d2}$ are the output of the optimisation problem in Equation (64), which is restricted by constraint (65). The optimum droop coefficients are shown in Table 4 of the paper. The mean squared error curve has adequate results for ARLS even, for operating parameter variation as shown in Figure 8. According to Figure 8, the steady-state average squared error of the objective function (64) is about 5%, and the convergence time is about 20 iterations. The optimisation was performed in Matlab software.

### 3.3 Stability analysis

In order to evaluate the robustness of the proposed method, we are focused on the 3D droop coefficients. Since the 3D droop coefficients play a key role in the system stability [39], analysing the effects of the 3D droop coefficients is useful to determine the stability of the system. Based on the proposed algorithm, in this paper, the most important determinative factors of the 3D droop coefficients are some of the EKF parameters. The disturbing noise terms and the Kalman gain are selected as the EKF parameters [41]. Also, the filter component parameters of the sources, the BESS, and the variable load are selected as some parameters [41]. The line impedances are selected as the other parameters also [41].

In order to determine the most injurious parameter on the stability of the closed-loop system, we carry out a sensitivity analysis. Finally, the effect of the selected parameters on the dominant poles (the closest one to the imaginary axis), are investigated. In the sensitivity analysis, one of the acceptable operating points is analysed, in which the bus voltage, wind speed, solar irradiance, and SOC are 295(v), 13(m/s), 600(w/m²), and 50%, respectively. Note that the results of the sensitivity analysis with respect to the selected parameters of the wind source are outlined in Table 3. The parameters are perturbed by 10%, and then the real part of the most critical dominant pole ($\lambda_C$) is observed. As shown in Table 3, the Kalman gain $G_k$ has the largest effect on the most critical dominant pole compared to other selected parameters (0.79 against $-0.18$, $-0.039$ and $-0.01$).

The trace of the eigenvalues for both the proposed method and the 3D droop method are depicted in Figure 9. As shown in Figure 9, the effect of the perturbation (10%) of the selected parameters on the dominant pole is well-cleared. In the 3D droop method, the system gain is rather than it in the proposed method, which leads to instability of the system quickly. In other words, the stability margin of the 3D droop method is smaller compared to the proposed method and the dominant pole is moved faster toward the imaginary axis. Consequently, the 3D droop method is more prone to the instability; on the other side, the stability of the system is more susceptible to perturb of 3D droop coefficients in the 3D droop method.

According to Table 3 the proposed method is more robust than the 3D droop method, and it is less sensitive to the selected parameters (0.79 against 1.35 and 4.21).

Flowchart of the proposed algorithm in this paper is shown in Figure 10. As can be seen in the algorithm, the optimisation process and state estimation using EKF are combined to yield optimal power management in the considered DC microgrid. The obtained droop coefficients by the proposed algorithm are outlined in Table 4.

### 4 Simulation results

Figure 1 shows the understudy DC microgrid in this paper. Two scenarios have been studied for validation of the proposed method performance. In the first scenario, the proposed algorithm is simulated on the understudy microgrid. The main purpose of this scenario is to optimise power management in the microgrid while keeping DC bus voltage in the acceptable range. In the second scenario, the understudy microgrid is connected to a similar microgrid but with a different load profile and nominal voltage level (which is 600 V in this case) via a bidirectional DC–DC converter. Irradiance and wind speed profiles of renewable sources in these scenarios are shown in Figure 11(a,b).

The profiles have belonged to June 1, 2019, and are estimated from the national renewable energy laboratory (NREL) database at the aforementioned date [42]. The load profiles of
TABLE 3  Sensitivity of the most critical pole with respect to the selected parameters

| Control method         | $\Delta \alpha$ | $\Delta \beta$ | $\Delta \gamma$ | $\Delta \omega$ | $\Delta \xi$ | $\Delta \zeta$ | $\Delta \eta$ | $\Delta \xi$ |
|------------------------|-----------------|----------------|-----------------|-----------------|--------------|--------------|--------------|--------------|
| The proposed method    | 0.79            | 0.18           | 0.039           | 0.01            |             |              |              |              |
| 3D droop method        |                | 0.32           | 0.07            | 0.03            | 1.35         | 4.21         |              |              |

FIGURE 9 Trace eigenvalues for the closed-loop system as a function of increasing (a) the Kalman gain in the proposed methods and (b) 3D droop coefficients in the 3D droop method

FIGURE 10 Flowchart of the proposed method

the microgrids in scenarios 1 and 2 are shown in Figure 12(a–c), respectively. The load profiles include constant and variable loads. Based on the assumption of this paper the constant load is a base load for the microgrid and variable load is caused by the consumer’s demand changes. In scenario 1, the maximum load is 16.88 kW occurred at 20 o’clock. The simulation is performed for 24 h time horizon of the considered day. In scenario 2, LV and HV are defined for the low voltage side of the micro-
TABLE 4  Optimal 3D droop coefficients values

| Values | Droop coefficients |
|--------|--------------------|
| $R_{d1}$ | 1.4286 |
| $R_{d2}$ | 0.3849 |
| $R_{d3}$ | 1.2987 |
| $R_{d4}$ | 133.513 |
| $R_{d5}$ | 0.9009 |
| $R_{d6}$ | 15.3006 |

FIGURE 11  (a) Irradiance- and (b) wind speed- profiles for renewable sources

FIGURE 12  (a) Load profiles for scenario 1, (b) the LV side and (c) the HV side- load profiles for scenario 2

FIGURE 13  Output power of (a) conventional source (b) Wind source (c) PV source (d) BESS- for scenario 1

grid (300 V) and the high voltage side of the microgrid (600 V), respectively. As can be seen in Figure 12 the load profiles in scenario 2 consist of the LV side and the HV side microgrids load profile. It is assumed that the HV side microgrid has higher electricity demand than the LV side. It is worth noting that these load profiles are hypothetical.

4.1  |  Results of the first scenario

In this scenario, conventional, wind, PV sources and battery energy storage nominal powers are considered 2, 12, 2.5 and 9 kW, respectively. The simulation output results of the first scenario are shown in Figure 13. The output power of conventional, wind and PV sources are shown in Figure 13(a–c), respectively. According to Figure 13 the output powers of the wind and solar sources track the wind speed and solar irradiance profiles, respectively. Between 1 and 4 a.m. conventional and wind sources supply the total load of the microgrid and PV output power is zero because there is no irradiance in this time interval. From 5 to 12 a.m. PV output power is increased and wind source output power is decreased. In this time interval, the proposed control raise conventional source output power to
supply the load. Between 12 and 8 p.m. the wind source output power is increased and the PV output power is decreased. Actually the proposed control is properly maximised the output power of wind and PV sources by tracking wind speed and solar irradiance profiles. The conventional source output power is set to the minimum value (500 W) whenever renewable sources output powers are enough to supply the microgrid load. Based on the proposed control BESS is in the charge mode when excess energy exists in the system (i.e. the total produced power of renewable sources is more than the total load of the system). When the microgrid load is relatively higher than available power in the microgrid sources, the BESS could be in discharge mode to supply part of the system load. Charge/discharge profile of the BESS for 24 h is shown in Figure 13(d). Figure 14(a) shows the common DC bus voltage profile in the first scenario. With the operation of the proposed control strategy, the bus voltage is in the allowable range and voltage variations are low (i.e. in the range of 297.5 to 302 V).

According to Figure 14(a) voltage is become slightly lower than 300 V, when the wind power output has a significant increase. Between 5 a.m. and 3 p.m. which wind speed is decreased, the controller lets the bus voltage decrease in the acceptable range in order to compensate for the shortage of wind and PV sources to track the load profiles. Figure 14(b) shows the common DC bus voltage in the LV side of the system. Figure 14(c) shows the HV side common bus voltage which is on its reference value (600 V) during the 24 h of the simulated day.

DC bus voltage and supplied power from wind and solar sources are compared to their available powers in Figure 15. Figure 15(a) shows the comparison of the available power with the extracted power from the wind source for both of the proposed and the 3D droop methods. As can be seen, the extracted power from the wind source using the proposed method is greater than the one by the 3D droop method. In Figure 15(b), the extracted power from the PV source is compared to its available power for both of the proposed and the 3D droop methods. As shown in Figure 15(b), a large amount of power is extracted from the available power of the PV source in the proposed method compared to the 3D droop method. According to Figure 15(a,b), the proposed method offers a better power management capability compared to the 3D droop method due to efficient use of available wind or solar energy sources. The comparison of the numerical values for Figure 15(a–c) are illustrated in Table 5. As can be seen, the percentage of the unused energy for both of the wind and the PV sources in the proposed method are less than it in the 3D droop method (4.12% against 6.88% for the PV source and 5.65% against 12.5% for the wind source). Consequently, the effectiveness of the proposed method on the power management is cleared. Figure 15(c) shows DC bus voltage for two strategies. As can be seen in Table 5, the volt-
TABLE 5  The comparison of the unused energy and the voltage variation between the two methods

| Source  | Control method          | PV Available (Wh) | PV Unused energy (Wh) | PV Unused energy (%) | Wind Available (Wh) | Wind Unused energy (Wh) | Wind Unused energy (%) | DC bus voltage Variations (%) |
|---------|-------------------------|-------------------|-----------------------|----------------------|---------------------|-------------------------|------------------------|-----------------------------|
|         | The proposed method     | 22150             | 913.68                | 4.12                 | 240500              | 15389.83                | 5.65                   | 4.5                         |
|         | The 3D droop method     | 22150             | 1524.72               | 6.88                 | 240500              | 30087.89                | 12.50                  | 6                           |

The age variation of the proposed method respect to its reference value (300V) is less than the 3D droop method in [25] (1.5% against 2%).

4.2 Results of the second scenario

Simulation results of the second scenario for the low voltage (LV) side of the understudy DC microgrid are shown in Figure 16. The load profile of the LV side of the microgrid is similar to the load profile of the first scenario. It is assumed that wind speed and solar irradiance profiles are exactly the same as scenario 1. In this scenario, another microgrid is connected to the understudy microgrid of scenario 1. This microgrid has the same structure as the microgrid in scenario 1 but with a higher voltage level. Power transaction is possible between interconnected microgrids via a bidirectional interlink buck-boost converter where the controller tries to compensate power shortage by transferring power from the HV to the LV side, and thus the voltage is regulated when the system load is increased. As shown in Figure 16(a) the conventional source output power is increased just between 3 and 5 p.m. compared to its minimum allowable power output limit to meet the peak load. According to Figure 16(b,c) the wind and solar sources output power profiles closely track the wind speed and solar irradiance profiles which shows the proper performance of the proposed control. Due to the power transfer capability between the LV and the HV sides of the system, BESS in the LV side switches to discharge mode when the HV side microgrid faces the power shortage. Figure 14(b) shows the common DC bus voltage in the LV side of the system, considering power exchange between two microgrids. The load profiles of each side are supplied and the bus voltage is maintained approximately on the reference value of 300 V during the whole study duration.

Figure 17 shows the transmitted power between the LV and the HV side. According to Figure 17 in most hours of the day power is transmitted from the HV to the LV side since the nominal capacities of the sources are significantly greater in the HV side. Figure 18 shows similar results to Figure 16 for the HV side of the understudy microgrid in scenario 2. The HV side BESS transmits power to the LV side to maintain bus voltage on its reference value. Conventional source has a greater share of load supply on the HV side.

FIGURE 16  Output power of (a) conventional source (b) wind source (c) PV source and (d) BESS- for the LV side of the understudy microgrid in scenario 2

FIGURE 17  Exchanged power with the interlink converter
In this paper, an effective model for optimal power management in DC microgrid was proposed. Optimal droop coefficients were used in the proposed algorithm. The combination of EKF and the adaptive recursive least square optimisation method was used in the proposed algorithm to maximise extracted power from wind and PV sources. The proposed model coordinated the optimal power management, DC voltage bus control, BESS charge and discharge management and optimal power exchange between the LV and the HV side of the tested microgrid. By connecting two microgrids, the proposed algorithm was validated for multi-microgrid structure as well. Simulation results validated the effectiveness and robustness of the model. The proposed studies also highlighted the importance of optimising 3D droop coefficients. The proposed power management method reduced unused energy of the renewable energy sources and resulted in better use of available power in the microgrid. Additionally, it maintained the DC bus voltage close to the nominal voltage throughout the study. Compared to the 3D method the proposed method reduced the unused energy of PV and wind sources by 2.7% and 6.85% (9.7% in total), respectively. Also, the variation of DC bus voltage was reduced by 0.5%. For future works, the effectiveness of the proposed method can be evaluated in hybrid AC/DC microgrids.

**NOMENCLATURE**

- $C$: DC-link capacitance of the WECS
- $C_b$: Battery capacitance
- $C_{Bi}, C_{vi}$: Input filter capacitance of the battery energy storage and the variable load converter
- $C_{Bo}, C_{vo}$: Output filter capacitance of the battery energy storage and the variable load converter
- $C_{ch}, C_{pi}, C_{ci}$: Input filter capacitance of sources converter
- $C_{cl}, C_{po}, C_{co}$: Output filter capacitance of sources converter
- $C_{load}$: Constant load capacitance
- $D$: Duty cycle of buck converters
- $G$: Kalman gain
- $i_{a}, i_{b}, i_{c}$: Input currents of WECS rectifier
- $i_{Batt}$: Output currents of battery energy storage
- $i_{dc}$: Output current of WECS rectifier
- $i_{l2}$: Input current of the variable load
- $i_{Bi}$: Input current of the battery converter
- $i_{Bo}$: Output current of the battery energy storage converter
- $i_{Bi}, i_{pi}, i_{ci}$: Input currents of sources converter
- $i_{Bi}, i_{po}, i_{co}$: Output currents of sources converter
- $i_{lv}$: Filter current of the variable load
- $i_W, i_{PV}, i_{Conv}$: Output currents of sources
- $k$: Number of discrete samples
- $L_a, L_b, L_c$: AC filter inductance of the WECS
- $L_{Bi}, L_{pl}$: Line inductance of sources
- $L_{bo}$: Input filter inductance of the battery energy storage converter
- $L_{bi}, L_{cl}$: Line inductance of the battery energy storage and the variable load
- $L_{bo}$: Output filter inductance of the battery energy storage converter
- $L_{bi}, L_{pl}, L_{ci}$: Input filter inductance of sources converter
- $L_{bi}, L_{po}, L_{co}$: Output filter inductance of sources converter
- $L_{v}$: Output filter inductance of the variable load converter

**Parameters**

- $Q$: Measurement noise
- $R$: Process noise
- $R_a, R_b, R_c$: AC filter resistance of the WECS
- $R_p$: Internal resistance of battery energy storage
- $R_{bi}, R_{pl}, R_{cl}$: Line resistance of sources
- $R_{Bi}$: Input filter resistance of the battery converter
- $R_{Bi}, R_{cl}$: Line resistance of the battery energy storage and the variable load
- $R_{Bi}, R_{pl}, R_{co}$: Input filter resistance of sources converter
- $R_{load}, R_{v}$: Constant and variable loads resistance
\( T_S \) Sampling time
\( V_0 \) Initial voltage of battery energy storage

**Variables**

\( V_{\text{bus}} \) Common DC bus voltage
\( V_{\text{cb}} \) Voltage of capacitance \( C_b \)
\( V_{\text{cBi}} \) Capacitor voltage of input filter of battery energy storage converter
\( V_{\text{cBo}} \) Capacitor voltage of output filter of battery energy storage converter
\( V_{\text{ch}}, V_{\text{cpi}}, V_{\text{cei}} \) Capacitor voltage of input filter of sources converter
\( V_{\text{clf}}, V_{\text{cpo}}, V_{\text{cco}} \) Capacitor voltage of output filter of sources converter
\( V_{\text{cvi}} \) Capacitor voltage of input filter of the variable load converter
\( V_{\text{cvo}} \) Capacitor voltage of output filter of the variable load converter
\( V_{\text{dc}} \) DC-link voltage of WECS
\( V_{\text{ge}}, V_{\text{gb}}, V_{\text{ge}} \) Three-phase voltage of the WECS
\( V_{\text{ref}} \) Reference voltage
\( V/\chi_p, V/\chi_c \) Voltage of PV and conventional sources
\( \varepsilon \) The prediction square error
\( \Psi \) The forgetting factor (\( \alpha \) value between [0;1])

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