Reduced-order dynamic model for droop-controlled inverter/converter-based low-voltage hybrid AC/DC microgrids – part 1: AC sub-microgrid

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Abstract: This study focuses on reduced-order dynamical modelling of droop-controlled inverter-based low-voltage AC sub-microgrid in a hybrid AC/DC microgrid. The authors aim to develop a comprehensive reduced-order model for the low-voltage AC side in this part. The reduced-order models are preferred in real-time calculations. In hybrid microgrids, electrical power is exchanged between the AC and DC sub-microgrids by a bidirectional AC/DC converter. The distributed energy resources are connected to the main AC bus through power inverters. Voltage and frequency commands are generated by droop controllers exchanged between the AC and DC sub-MGs by a bidirectional AC/DC converter. The amount of power to be imported or exported is determined by centralised or arbitrary secondary control loops can be implemented to adjust reference values used by inner droop control loops. On the other hand, cost-effective power electronics-based systems have paved the way for using main AC and DC links in a MG. While such hybrid MGs eliminate most of the transmission and distribution losses, they could also avoid the waste of energy concerned with the conversion of AC to DC and vice versa [2]. DC power consumers are increased in the last decade, because most of the electrical loads such as LED lights, variable-speed drives, computers, televisions and many other electronic consumers, which require AC to DC converters, are in fact DC loads. Hence they can be used in a DC power network directly [3]. Hybrid MGs are also able to maintain operation under different loading situations. In hybrid MGs, electrical power is exchanged between the AC and DC sub-MGs by a bidirectional AC/DC converter. The amount of power to be imported or exported is determined by centralised or decentralised power management schemes [4]. All the resources and loads are connected to a common AC link in AC sub-MG and DC link in DC sub-MG, as it is shown in Fig. 1. Moreover, it can be proved that all the network topologies can be transformed to a common bus topology of Fig. 1 using superposition law and Thevenin equivalent. The common AC and DC buses are connected to each other via the interlinking converters.

Given the rising trend of using hybrid MGs, deriving a comprehensive model for such MGs is vital for the sake of design, analysis, modifications, predictions and operational management of such systems. The basic motivation of deriving the proposed model is to use it for setpoint cyber-attack detection by a model-based

Nomenclature

\[
P = \left(\frac{d}{dr}\right) \quad \text{derivative operator}
\]

\[
K_{\text{inv},i}, \quad \text{small signal gain of the } i\text{th inverter}
\]

\[
v^* \quad \text{phase root mean square (RMS) voltage setpoint for inverters}
\]

\[
v_{\text{ref,ac}} \quad \text{phase RMS voltage reference for AC link}
\]

\[
f^*_i \quad \text{frequency setpoint for the } i\text{th inverter}
\]

\[
f_{\text{ref,ac}} \quad \text{frequency reference for AC link}
\]

\[
P_i \quad \text{output active power of the } i\text{th inverter}
\]

\[
Q_i \quad \text{reactive power of the } i\text{th inverter}
\]

\[
R_{\text{P,f},i} \quad \text{droop coefficient for active power}
\]

\[
R_{\text{Q,f},i} \quad \text{droop coefficient for reactive power}
\]

\[
v_i \quad \text{output voltage of the } i\text{th inverter in AC sub-microgrid}
\]

\[
f_i \quad \text{frequency of the } i\text{th inverter in AC sub-microgrid}
\]

\[
\delta_i \quad \text{phase angle with reference to AC link voltage for } i\text{th inverter}
\]

\[
i_i \quad \text{output current of the } i\text{th inverter in AC sub-microgrid}
\]

\[
i_{\text{ref},i} \quad \text{output current setpoint of the } i\text{th inverter in AC sub-microgrid}
\]

\[
v_{\text{ac}} \quad \text{AC link voltage}
\]

\[
X_i \quad \text{inductance of the } i\text{th inverter line to AC link}
\]

\[
R_i \quad \text{resistance of the } i\text{th inverter line to AC link}
\]

\[
Z_i \quad \text{impedance of the } i\text{th inverter line to AC link}
\]

\[
P_{\text{load}} \quad \text{active power of AC loads}
\]

\[
Q_{\text{load}} \quad \text{reactive power of AC loads}
\]

\[
I_{\text{load}} \quad \text{current of AC loads}
\]

\[
\theta_{\text{P,load}} \quad \text{phase angle of constant current AC loads}
\]

\[
Z_{\text{load}} \quad \text{impedance of constant impedance AC loads}
\]

\[
\theta_{\text{Q,load}} \quad \text{phase angle of constant impedance AC loads}
\]

\[
P_{\text{ex}} \quad \text{exchanging power from DC to the AC sub-microgrids at DC side}
\]

\[
K_{\text{PP}} \quad \text{ratio of reactive power to active power for the main converter at AC side}
\]

- small signal variations of variables, inputs, outputs and disturbances
- steady-state values of variables, inputs, outputs and disturbances
fault detection observer. As it is explained in [5], a communication link is needed for sending the secondary control output to each DG. This data is the reference values for primary control. Cyber attack may happen in this communication channel. Although there are some precise models in literature, they cannot be used for this application, because of two reasons: first design of real-time calculating observers because of their heavy calculation load imposing on the processor; second the selected inputs–outputs for the system are not proper for this application. Considering these reasons, it can be claimed that the previous proposed models are not the desired model for such applications. The proposed model in this paper uses only six states for each inverter; a model which is more compact for online calculating observers than the previous models. It should be noted that since generally such MGs are formed in the distribution level, they involve low-voltage (LV) AC systems. Therefore, instead of using conventional droop control schemes in which resistance of the power lines are neglected, modified droop control for LV systems is utilised (Fig. 2).

A survey on different structures for hybrid MGs has been reported in [6]. This paper has classified different types of control schemes and power management methods which can be used in hybrid MGs. Hybrid MGs can be defined by different network structures such as AC-coupled, DC-coupled or AC/DC-coupled networks. Each of these structures has different operational modes such as grid-connected or stand-alone operation. Grid-connected mode can be on dispatched mode or undispatched mode. In [7], the authors have classified AC converters used in AC MGs as grid forming, grid feeding and grid supporting. Grid-forming converters have the role of voltage source which dictates both voltage and frequency in MGs. Grid-feeding converters have the role of current source which provide active and reactive power to MG. Grid-supporting converters can have role of both current or voltage sources in MGs. They regulate the output voltage and current to keep the value of voltage frequency and amplitude of the MG close to the corresponding rated values. These converters can implement the droop control philosophy in modern converter based MGs. A hierarchical control approach for parallel operation of AC/DC converters in a hybrid MG is introduced in [9]. However, there are other control strategies such as [10] which are more complicated but more robust for hybrid AC/DC MGs. A detailed study on distributed control for autonomous operation of hybrid MGs is reported in [11]. This study proposes an approach which coordinates the AC and DC sub-MG’s droop controls.

On the other hand, there are some reports on mathematical modelling of DGs or MGs in the literature (e.g. [12–15]). In [16], a small-signal model of a typical AC MG containing asynchronous generator based wind turbine, synchronous diesel generator, power electronic based energy storage and power network is given and then the overall model is set up. In [17], a state-space model is derived for an AC MG using the node-incidence matrix and circuit parameters. In [18–20], models for MG subsystems such as photovoltaic, micro-turbine and wind turbine resources, and ESS are introduced and utilised for control and energy management. A new linear state-space model for inverter-based MGs and active loads is proposed in [21] and then the model is corrected using a time-step simulation. A survey on modelling of MGs is given in [22]. The survey paper has introduced the reader to the MG concept with the main focus of providing a detailed procedure for the model derivation of a three-phase inverter-based MG. In particular, it has been shown how – and under which assumptions – the MG models usually used in the literature can be obtained from a significantly more complex model derived from fundamental physical laws. In [23], the Kron-reduced MG is introduced, which is formed by \( n \geq 1 \) nodes, each of which represents a DG unit interfaced via an AC inverter. Two nodes \( i \) and \( k \) of the MG are connected via a complex non-zero admittance, while active and reactive power flows from node \( i \) to node \( k \) are given. Then, the inverters are modelled as AC voltage sources in which the amplitude and frequency can be defined by designer. It is also assumed that the frequency regulation is instantaneous, but the voltage control happens with a delay. Then, for dominantly inductive networks, simple proportional controllers are given [23]. In [24], the authors show that a network of loads and DC/AC

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**Fig. 1** Conceptual block diagram of a hybrid AC/DC MG [6]

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**Fig. 2** Procedure of achieving state-space form from dynamics basic equations

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inverters equipped with power-frequency droop controllers can be cast as a Kuramoto model of phase-coupled oscillators. This novel description, along with results from the coupled oscillators’ theory, characterises the behaviour of the network of inverters and loads in an AC MG. Although the dynamical model of [25] is a comprehensive and accurate model, it is a high-order dynamic. Using high-order dynamics for designing fault detection observers is not ideal, because it makes the calculation load of real-time observer heavy. This model has employed 13 states for each inverter, 2 states for each line of network and 2 states for each load node. There are also some non-droop control decentralised methods such as game theoretic approaches introduced in [26], which can be studied in future works.

Although there are other dynamical models of AC MGs, in this paper a novel comprehensive reduced-order state-space dynamical model is achieved which can be very useful in implementing of real-time observers particularly for cyber-attack detection observers. The dynamics are derived for droop-controlled inverter-based LVAC sub-MG in hybrid AC/DC MG. From a system representation perspective, the reference values generated by outer or secondary controllers are regarded as system inputs. Measured values of the main bus voltage and frequency are regarded as system outputs, and the load fluctuations are considered as imposed disturbances. In deriving the state-space representation of the MG, voltage amplitudes and phase angles of the inverters are designated as state variables. Equations that describe voltage magnitude and frequency of the main AC bus are derived for such a MG. Moreover, steady-state values of the phase angles and injected power of the inverters are calculated. The overall non-linear dynamical and algebraic equations are derived for the LVAC side, and then linearised around the operating point. To the best of our knowledge, this is the least degree dynamics with meaningful physical states which is reported for a LV AC sub-MG in hybrid AC/DC MGs. The proposed reduced-order model paves the way for hybrid MG real-time observer design and implementation purposes as it will be done in future studies.

The following charts illustrate the agenda of paper. In Section 2, the basic equations are introduced. These equations lead to equations for dynamic and steady-state values of variables. Bus voltage and frequency are output variables and inverter voltages and phase angles are state variables. From equations in Section 2, linearised equations are derived in Section 3. Finally, the linearised equations lead to state-space form in Section 4.

2 Modelling of droop-controlled inverter-based AC side in hybrid MG

2.1 Standard loads in AC sub-MG

To have the least-order dynamic model of MG, a united comprehensive static model for all the loads is used, instead of using individual dynamic models for each load. Based on IEEE standard 399-1997 [27], electrical loads are categorised into three classes of constant current, constant power and constant impedance loads or combination of them. To have a comprehensive model, all these types of loads are regarded in this paper. AC loads are combination of active and reactive loads. Also it can be claimed that, the exchanging power between utility grid and MG in grid-connected dispatched mode can be modelled as a constant negative or positive power load. Therefore, the total active and reactive load powers are given as follows:

\[
P_{\text{AC load}} = P_{\text{load}} + 3 \frac{v_{\text{ac}}^2}{R_{\text{load}}} \cos \delta_{\text{load}} + 3 v_{\text{ac}} P_{\text{load}} \cos \delta_{\text{load}}
\]

\[
Q_{\text{AC load}} = Q_{\text{load}} + 3 \frac{v_{\text{ac}}^2}{q_{\text{load}}} \sin \delta_{\text{load}} - 3 v_{\text{ac}} f_{\text{load}} \sin \delta_{\text{load}}
\]

Generated active and reactive power by DRs in companion with exchanged power from DC sub-MG to AC sub-MG, excluding the power losses in lines provide the AC load demand, hence

\[
P_{\text{ex}} + \sum_{i=1}^{m} (P_i - P_{\text{loss}i}) = P_{\text{ex}} + 3 \sum_{i=1}^{m} \frac{v_{\text{ac}}}{R_i} (v_i - v_{\text{ac}}) = P_{\text{AC load}}
\]

\[
K_{PF} P_{\text{ex}} + \sum_{i=1}^{m} Q_i = K_{PF} P_{\text{ex}} + 3 \sum_{i=1}^{m} \frac{v_i}{v_{\text{ac}}} v_{\text{ac}} \delta_i = Q_{\text{AC load}}
\]

2.2 Droop control modelling in LVAC sub-MG

In this part, droop control scheme in LVAC sub-MG and inverters’ closed control loops are modelled. For this end, the converters are selected to be grid supporting as it is defined in [7]. In LVAC MGs, resistances of power lines are much bigger than the corresponding inductive impedances [28]. Therefore, unlike conventional droop scheme, here line inductance is ignored in deriving droop control equations. Active and reactive powers of each converter in LVAC side are related to the voltage magnitude and small angle, respectively, as it is shown in Fig. 3, and as follows [7, 29]:

\[
\begin{align*}
    P_i &= 3 \frac{v_i}{R_i} (v_i - v_{\text{ac}} \cos \delta_i) = 3 \frac{v_i}{R_i} (v_i - v_{\text{ac}}) \\
    Q_i &= - 3 \frac{v_i}{Q_i} (v_i \sin \delta_i) = - 3 \frac{v_i}{Q_i} v_{\text{ac}} \delta_i
\end{align*}
\]

Consequently, droop control equations for LV system are given as follows [30, 31]:

\[
\begin{align*}
    v_i &= v_{\text{ref,ac}} - R_{P,i} P_i \\
    f_i &= f_{\text{ref}} + R_{Q,i} Q_i
\end{align*}
\]

In which

\[
\begin{align*}
    R_{P,i} &= \frac{v_{\text{max}} - v_{\text{min}}}{P_{\text{max}}} \\
    R_{Q,i} &= \frac{f_{\text{max}} - f_{\text{min}}}{Q_{\text{max}}}
\end{align*}
\]

The reasons for using this type of droop equations and the stability analysis are brought in the mentioned references. Fig. 3 shows the relation of voltage and frequency with respect to active and reactive power in droop control equations.

2.3 Inverter control loop modelling in AC sub-MG

The block diagrams of control loops for power inverters in AC side are shown in Fig. 4. The voltage amplitude is regulated by a closed-loop controller but frequency is generated in an open-loop
manper. In order to regulate voltage amplitude, Proportional-Integral controllers are utilised.

On the other hand, it is obvious that the amplitude of output current of inverter is

\[ i_i = \frac{\sqrt{P_i + Q_i}}{3V_i}, \quad i = 1, 2, \ldots, m \]  

(6)

Since the inverter has no closed-loop control for frequency, it can be concluded that \( f = f' \). Hence from droop control equations given in (3) and also from (6), it can be concluded that

\[
\begin{align*}
\dot{v}_i &= \left( v_{ref} - 3R_i P_i \frac{v_i}{R_i} (v_i - v_{ac}) \right) \left(K_{P,i} + \frac{K_{I,i}}{p}\right) v_i - 3P \sum_{i=1}^{m} \frac{v_i}{R_i} v_{ac} = -3 \sum_{i=1}^{m} \frac{v_i(f_i - f)}{R_i} v_{ac} \quad (12) \\
\dot{\delta}_i &= \frac{p}{2\pi} P_i \sum_{i=1}^{m} \frac{v_i}{R_i} v_{ac} = -3 \sum_{i=1}^{m} \frac{v_i(f_i - f)}{R_i} v_{ac} \\
\end{align*}
\]

(7)

2.4 Determination of AC bus voltage and frequency in AC sub-MG

The bus voltage of the AC side can be calculated using active power equations in (1) and (2), as follows:

\[ a v_{ac}^2 + b v_{ac} + c = 0, \quad v_{ac} = \left(-b + \sqrt{b^2 - 4ac}\right)/2a \]

In which

\[ a = 3 \cos \theta_{load} + 3 \sum_{i=1}^{m} \frac{1}{R_i}, \]

\[ b = 3I_{load}\cos \theta_{load} - 3 \sum_{i=1}^{m} \frac{v_i}{R_i}, \]

\[ c = P_{load} - P_{ex} \]

If there is no constant impedance load, then

\[ a = 3 \sum_{i=1}^{m} \frac{1}{R_i} \]  

(9)

The common AC link voltage is regarded as the reference for phase angle; therefore phase angle and frequency of each inverter are given by

\[ \delta_i = f \sigma (f_i - f) \mathrm{d}t, \quad \frac{p\delta_i}{2\pi} = f_i - f \]  

(10)

The main bus frequency in AC sub-MG is determined using derivative of reactive power equations in (1) and (2)

\[ -3 \frac{p}{2\pi} \sum_{i=1}^{m} \frac{v_i}{R_i} v_{ac} = -3 \sum_{i=1}^{m} \frac{v_i(f_i - f)}{R_i} v_{ac} \]

Hence (11) can be rewritten using (12) as follows:

\[ \sum_{i=1}^{m} \frac{v_i(f_i - f)}{R_i} v_{ac} = \frac{P_{load}}{2}\pi \]  

(13)

or

\[ \sum_{i=1}^{m} \frac{v_i(f_i - f)}{2\pi R_i} v_{ac} = \frac{P_{load}}{2}\pi \]

(14)

Substituting \( f_i \) from (7), \( f \) can be achieved as an output of system and a function of state variables, disturbances and inputs

\[ f = \frac{1}{3 \sum_{i=1}^{m} \frac{v_i}{R_i}} \left( \frac{P_{load}}{R_i} - \frac{P_{load}}{2\pi} \right) \left( \frac{3}{R_i} \sum_{i=1}^{m} \frac{v_i}{R_i} \right) \]

(15)

2.5 Determination of steady-state values of phase angles

In steady state, all frequencies are equal. Hence the following equation holds:

\[ \dot{f}_i = f_j \]

\[ \frac{p\delta_i}{2\pi} = f_i - f \]  

(16)

It can be concluded that

\[ R_i \frac{v_i}{R_i} \delta_i = R_j \frac{v_j}{R_j} \delta_j, \quad i = 1, 2, \ldots, m \]

(17)

Since

\[ K_{PP} P_{ex} + \sum_{i=1}^{m} Q_i = K_{PF} P_{ex} + 3 \sum_{i=1}^{m} \frac{v_i}{R_i} \delta_i = Q_{load} \]

(18)

Therefore, two above equations yield
Since obtained for each inverter's output voltage: (see (28))

\[
\hat{p}_i = \left( K_{P_P} + R_i \right) \frac{\dot{v}_i}{\dot{v}_i} - 3 K_{P_I} R_i \frac{\dot{v}_i}{\dot{v}_i} \quad i = 1, 2, \ldots, m
\]

Using linearisation rules given above and also following (7) approaches to

\[
\hat{p}_i = \frac{P_{load}}{R_i} + 3(\frac{\dot{v}_i}{\dot{v}_i} + \dot{v}_i) \cos \theta_{load} \cos \theta_{load} - 3(\frac{\dot{v}_i}{\dot{v}_i} + \dot{v}_i) \cos \theta_{load} - P_{ref}
\]

\[
\dot{\theta} = \frac{1}{\gamma} \left[ \frac{v_i}{R_i} \sum_{i=1}^{m} \left( 1/R_{ref} \right) \right] + \dot{\phi} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load}
\]

\[
\dot{\phi} = \frac{1}{\gamma} \left[ \frac{v_i}{R_i} \sum_{i=1}^{m} \left( 1/R_{ref} \right) \right] + \dot{\phi} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load}
\]

Hence, considering \( \dot{\phi} = \dot{p}_i \), the following dynamical equation is obtained for each inverter's output voltage:

\[
\dot{p}_i = \left( K_{P_P} + R_i \right) \frac{\dot{v}_i}{\dot{v}_i} - 3 K_{P_I} R_i \frac{\dot{v}_i}{\dot{v}_i} \quad i = 1, 2, \ldots, m
\]

Hence, considering \( \dot{\phi} = \dot{p}_i \), the following dynamical equation is obtained for each inverter's output voltage: (see (28))

\[
\dot{p}_i = \frac{P_{load}}{R_i} + 3(\frac{\dot{v}_i}{\dot{v}_i} + \dot{v}_i) \cos \theta_{load} \cos \theta_{load} - 3(\frac{\dot{v}_i}{\dot{v}_i} + \dot{v}_i) \cos \theta_{load} - P_{ref}
\]

Using linearisation rules given above and also following (7) approaches to

\[
\dot{\theta} = \frac{1}{\gamma} \left[ \frac{v_i}{R_i} \sum_{i=1}^{m} \left( 1/R_{ref} \right) \right] + \dot{\phi} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load}
\]

\[
\dot{\phi} = \frac{1}{\gamma} \left[ \frac{v_i}{R_i} \sum_{i=1}^{m} \left( 1/R_{ref} \right) \right] + \dot{\phi} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load}
\]

Hence, considering \( \dot{\phi} = \dot{p}_i \), the following dynamical equation is obtained for each inverter's output voltage:

\[
\dot{p}_i = \left( K_{P_P} + R_i \right) \frac{\dot{v}_i}{\dot{v}_i} - 3 K_{P_I} R_i \frac{\dot{v}_i}{\dot{v}_i} \quad i = 1, 2, \ldots, m
\]

Hence, considering \( \dot{\phi} = \dot{p}_i \), the following dynamical equation is obtained for each inverter's output voltage: (see (28))

\[
\dot{p}_i = \frac{P_{load}}{R_i} + 3(\frac{\dot{v}_i}{\dot{v}_i} + \dot{v}_i) \cos \theta_{load} \cos \theta_{load} - 3(\frac{\dot{v}_i}{\dot{v}_i} + \dot{v}_i) \cos \theta_{load} - P_{ref}
\]

Using linearisation rules given above and also following (7) approaches to

\[
\dot{\theta} = \frac{1}{\gamma} \left[ \frac{v_i}{R_i} \sum_{i=1}^{m} \left( 1/R_{ref} \right) \right] + \dot{\phi} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load}
\]

\[
\dot{\phi} = \frac{1}{\gamma} \left[ \frac{v_i}{R_i} \sum_{i=1}^{m} \left( 1/R_{ref} \right) \right] + \dot{\phi} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load}
\]

\[
\dot{p}_i = \left( K_{P_P} + R_i \right) \frac{\dot{v}_i}{\dot{v}_i} - 3 K_{P_I} R_i \frac{\dot{v}_i}{\dot{v}_i} \quad i = 1, 2, \ldots, m
\]

Hence, considering \( \dot{\phi} = \dot{p}_i \), the following dynamical equation is obtained for each inverter's output voltage:

\[
\dot{p}_i = \frac{P_{load}}{R_i} + 3(\frac{\dot{v}_i}{\dot{v}_i} + \dot{v}_i) \cos \theta_{load} \cos \theta_{load} - 3(\frac{\dot{v}_i}{\dot{v}_i} + \dot{v}_i) \cos \theta_{load} - P_{ref}
\]

Using linearisation rules given above and also following (7) approaches to

\[
\dot{\theta} = \frac{1}{\gamma} \left[ \frac{v_i}{R_i} \sum_{i=1}^{m} \left( 1/R_{ref} \right) \right] + \dot{\phi} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load}
\]

\[
\dot{\phi} = \frac{1}{\gamma} \left[ \frac{v_i}{R_i} \sum_{i=1}^{m} \left( 1/R_{ref} \right) \right] + \dot{\phi} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load} - 3 \frac{\dot{v}_i}{\dot{v}_i} \cos \theta_{load}
\]

\[
\dot{p}_i = \left( K_{P_P} + R_i \right) \frac{\dot{v}_i}{\dot{v}_i} - 3 K_{P_I} R_i \frac{\dot{v}_i}{\dot{v}_i} \quad i = 1, 2, \ldots, m
\]
\[
\frac{\dot{v}_{ac}}{2\pi} = f_{ref} - f - 3R_0\frac{\delta_{e}}{R_c}v_{ac} - 3R_0\frac{\dot{\delta}_{e}}{R_c}v_{ac}
\]

\[3R_0\frac{\delta_{e}}{R_c}v_{ac} \quad i = 1, 2, \ldots, m\]  

(30)

3.4 Linearisation of the algebraic equation for bus voltage amplitude

From (8) and (24), the following equation is attained:

\[
\begin{align*}
\dot{v}_{ac} &= \left(3P_{\text{load}}\cos\theta_{\text{load}} - \sum_{i=1}^{m} m_i \frac{v_i}{R_i} + 6\cos\theta_{\text{load}}v_{ac} + 6\sum_{i=1}^{m} \frac{v_i}{R_i}\right)
\end{align*}
\]

\[
\dot{v}_{ac} = 3\frac{v_{ac}^2}{Z_{load}} \bar{Z}_{load} - 3v_{ac}\sum_{i=1}^{m} \frac{1}{R_i} v_i = 0,
\]

(31)

which results in the bus voltage small signal equation given by

\[
\begin{align*}
\dot{v}_{ac} &= \left(3P_{\text{load}}\cos\theta_{\text{load}} - \sum_{i=1}^{m} m_i \frac{v_i}{R_i} + 6\cos\theta_{\text{load}}v_{ac} + 6\sum_{i=1}^{m} \frac{v_i}{R_i}\right)
\end{align*}
\]

\[
\dot{v}_{ac} = 3\frac{v_{ac}^2}{Z_{load}} \bar{Z}_{load} - 3v_{ac}\sum_{i=1}^{m} \frac{1}{R_i} v_i = 0,
\]

(32)

3.5 Linearisation of the algebraic equation for bus voltage frequency

Linearisation of (15) using general approximations given in (24) results in (see (33) and (34)). Therefore, AC bus voltage small signal equation is given by (see (34)).

4 Deriving dynamical state space model of the AC sub-MG

\[
R_{i} \frac{\dot{v}_{ac}}{K_{\text{inv},i}} = \frac{2v_{ac} - 2v_{ac}}{2\sqrt{v_{ac}^2 + v_{ac}^2}} \left(pK'_{p,i} + K'_{1,i}\right)\frac{\dot{v}_{ac}}{v_{ac}}
\]

\[+ \left(2v_{ac} - 2v_{ac}\right) \left(pK'_{p,i} + K'_{1,i}\right)\frac{v_{ac}}{v_{ac}} \]

\[+ \left(2v_{ac} - 2v_{ac}\right) \left(pK'_{p,i} + K'_{1,i}\right)\frac{v_{ac}}{v_{ac}} \]

\[+ \left(2v_{ac} - 2v_{ac}\right) \left(pK'_{p,i} + K'_{1,i}\right)\frac{v_{ac}}{v_{ac}} \]

\[i = 1, 2, \ldots, m
\]

\[3\sum_{i=1}^{m} \frac{v_{ac}^2}{R_i} \frac{\dot{v}_{ac}}{R_i} + \left(3\sum_{i=1}^{m} \frac{v_{ac}^2}{R_i} \right) - \frac{3P_{\text{load}}\cos\theta_{\text{load}}}{R_c} \left(v_{ac} + \frac{3P_{\text{load}}\cos\theta_{\text{load}}}{R_c}\right)
\]

\[+ P_{\text{ex}} Q_{\text{load}} - \frac{3\sum_{i=1}^{m} \frac{v_{ac}^2}{R_i} \frac{\dot{v}_{ac}}{R_i}}{R_i} \left(\frac{v_{ac}}{R_i}\right)
\]

\[+ P_{\text{ex}} Q_{\text{load}} - \frac{3\sum_{i=1}^{m} \frac{v_{ac}^2}{R_i} \frac{\dot{v}_{ac}}{R_i}}{R_i} \left(\frac{v_{ac}}{R_i}\right)
\]

\[\frac{v_{ac}}{R_i} = 0
\]

\[\dot{j} = \frac{-1}{\sum_{i=1}^{m} (v_{ac}R_i/R_i^2)} \left[\sum_{i=1}^{m} \frac{v_{ac}^2}{R_i} \frac{\dot{v}_{ac}}{R_i} + \frac{v_{ac}^2}{R_i} \frac{\dot{v}_{ac}}{R_i} + \frac{v_{ac}^2}{R_i} \frac{\dot{v}_{ac}}{R_i} + \frac{v_{ac}^2}{R_i} \frac{\dot{v}_{ac}}{R_i} + \frac{v_{ac}^2}{R_i} \frac{\dot{v}_{ac}}{R_i} + \frac{v_{ac}^2}{R_i} \frac{\dot{v}_{ac}}{R_i}
\]

\[+ \frac{P_{\text{ex}} Q_{\text{load}} - \frac{3\sum_{i=1}^{m} \frac{v_{ac}^2}{R_i} \frac{\dot{v}_{ac}}{R_i}}{R_i} \left(\frac{v_{ac}}{R_i}\right)}{R_i} \left(\frac{v_{ac}}{R_i}\right)
\]

\[+ \frac{P_{\text{ex}} Q_{\text{load}} - \frac{3\sum_{i=1}^{m} \frac{v_{ac}^2}{R_i} \frac{\dot{v}_{ac}}{R_i}}{R_i} \left(\frac{v_{ac}}{R_i}\right)}{R_i} \left(\frac{v_{ac}}{R_i}\right)
\]

\[\frac{v_{ac}}{R_i} = 0
\]

(34)
For the first group of equations corresponding to \( i_i \), the submatrices can be determined from (26) as follows:

\[
M_{ac, 11} = I_{ac \times m}
\]

\[
M_{ac, 12}(i, j) = -3K_p R_p \frac{\delta v_i}{R_i} C_{ac,i}(j + m)
\]

\[
+ \begin{cases} 
K_p + K_p \frac{6v_i R_p}{R_i} - 3K_p \frac{R_p}{R_i} v_{i \delta c} & i = j, \quad i, j = 1, \ldots, m \\
0 & \text{else} 
\end{cases}
\]

\[
M_{ac, 11} = 0_{m \times m}
\]

(see equation below)

\[
A_{ac, 11} = 0_{m \times m}
\]

\[
C_{ac, 1}(i) = \frac{1}{(l_{load} \cos \theta_{\delta c load} - \sum_{i=1}^{m} (v_{i \delta c / R_i} + 2 \cos \theta_{\delta c load} / Z_{load}) \bar{v}_{ac} + 2 \sum_{i=1}^{m} (v_{ac / R_i})} \times \begin{cases} 
0 & \text{for } i = 1, \ldots, m \\
\bar{v}_{ac} / R_0 & \text{for } i = m + 1, \ldots, 2m \\
0 & \text{for } i = 2m + 1, \ldots, 3m \\
\frac{1}{3} & \text{for } i = 3m + 1
\end{cases}
\]

\[
D_{ac, 1} = [0 \quad 0]
\]

\[
F_{ac, 1} = \frac{1}{(l_{load} \cos \theta_{\delta c load} - \sum_{i=1}^{m} (v_{i \delta c / R_i} + 2 \cos \theta_{\delta c load} / Z_{load}) \bar{v}_{ac} + 2 \sum_{i=1}^{m} (v_{ac / R_i})} \times \begin{cases} 
-\frac{1}{3} & 0 \\
-\frac{\cos \theta_{\delta c load}}{Z_{load}} & \bar{v}_{ac \delta c}
\end{cases}
\]

\[
C_{ac, 2}(i) = \frac{1}{-\sum_{j=1}^{m} \bar{v}_{i \delta c / R_j} \sum_{j=1}^{m} \begin{cases} 
\frac{v_i \delta_i ref - \bar{v}_{i \delta c / R_i} + 6R_Q \bar{v}_{i \delta c} \delta_i \bar{v}_{i \delta c} / R_i^2 - \bar{v}_{i \delta c / R_i} \delta_i / 2\pi \bar{v}_{i \delta c} \delta_i / 2 & \text{for } i = 1, \ldots, m \\
0 & \text{for } i = m + 1, \ldots, 2m \\
-\bar{v}_{ac \delta c / R_i} + 3\bar{v}_{ac \delta c} / 2\pi R_i & \text{for } i = 2m + 1, \ldots, 3m \\
-\bar{v}_{ac \delta c / R_i} & \text{for } i = 3m + 1
\end{cases}
\]

\[
+ \begin{cases} 
-p/2\pi & 0 \\
-\bar{v}_{ac \delta c / R_i} \sin \theta_{\delta c load} \bar{v}_{ac / Z_{load}} & \text{for } i = 1, \ldots, m \\
0 & \text{for } i = m + 1, \ldots, 2m \\
-\bar{v}_{ac \delta c / R_i} \sin \theta_{\delta c load} \bar{v}_{ac / Z_{load}} & \text{for } i = 2m + 1, \ldots, 3m \\
0 & \text{for } i = 3m + 1
\end{cases}
\]

\[
D_{ac, 2} = [0 \quad 1]
\]

\[
F_{ac, 2} = \frac{-1}{\sum_{j=1}^{m} \bar{v}_{i \delta c / R_j} \sum_{j=1}^{m} \begin{cases} 
\frac{v_i \delta_i ref - \bar{v}_{i \delta c / R_i} + 6R_Q \bar{v}_{i \delta c} \delta_i \bar{v}_{i \delta c} / R_i^2 - \bar{v}_{i \delta c / R_i} \delta_i / 2\pi \bar{v}_{i \delta c} \delta_i / 2 & \text{for } i = 1, \ldots, m \\
0 & \text{for } i = m + 1, \ldots, 2m \\
-\bar{v}_{ac \delta c / R_i} + 3\bar{v}_{ac \delta c} / 2\pi R_i & \text{for } i = 2m + 1, \ldots, 3m \\
-\bar{v}_{ac \delta c / R_i} & \text{for } i = 3m + 1
\end{cases}
\]

\[
+ \begin{cases} 
-p/2\pi & 0 \\
-\bar{v}_{ac \delta c / R_i} \sin \theta_{\delta c load} \bar{v}_{ac / Z_{load}} & \text{for } i = 1, \ldots, m \\
0 & \text{for } i = m + 1, \ldots, 2m \\
-\bar{v}_{ac \delta c / R_i} \sin \theta_{\delta c load} \bar{v}_{ac / Z_{load}} & \text{for } i = 2m + 1, \ldots, 3m \\
0 & \text{for } i = 3m + 1
\end{cases}
\]

\[
M_{ac, 2}(i, j) = \begin{cases} 
\frac{l_{load} \cos \theta_{\delta c load} - \sum_{i=1}^{m} (v_{i \delta c / R_i} + 2 \cos \theta_{\delta c load} / Z_{load}) \bar{v}_{ac} + 2 \sum_{i=1}^{m} (v_{ac / R_i})}{2K_p R_p} & i = j \\
0 & \text{else}
\end{cases}
\]
\[ M_{ac,13}(i, j) = \begin{cases} K_{P} \left( \frac{2v_{ac}^2 \delta_i}{2v_{ac}^2 + v_{ac}^2 - 2v_{ac}^2 + v_{ac}^2 \delta_i} \right) & i = j \\ 0 & i \neq j \end{cases} \]

\[ M_{ac,13}(i, 1) = \left( \frac{2v_{ac} - 2v_{i} + 2v_{ac}^2}{2v_{ac} + v_{ac} - 2v_{ac} + v_{ac}^2 \delta_i} \right) K_{P} C_{ac,13}(m + 1) \]

\[ A_{ac,13}(i, j) = \begin{cases} R_{K_{1},i} & i = j \\ 0 & i \neq j \end{cases} \]

\[ A_{ac,13}(i, 1) = \left( \frac{2v_{ac} - 2v_{i} + 2v_{ac}^2}{2v_{ac} + v_{ac} - 2v_{ac} + v_{ac}^2 \delta_i} \right) K_{P} C_{ac,13}(m + 1) \]

\[ A_{ac,23}(i, j) = \begin{cases} -K_{1} \left( \frac{2v_{ac}^2 \delta_i}{2v_{ac}^2 + v_{ac}^2 - 2v_{ac}^2 + v_{ac}^2 \delta_i} \right) & i = j \\ 0 & i \neq j \end{cases} \]

\[ A_{ac,23}(i, 1) = \left( \frac{2v_{ac} - 2v_{i} + 2v_{ac}^2}{2v_{ac} + v_{ac} - 2v_{ac} + v_{ac}^2 \delta_i} \right) K_{P} C_{ac,23}(m + 1) \]

\[ B_{ac,3}(i, :) = 0_{m \times 1} \]

\[ E_{ac,i}(i, :) = \left( \frac{2v_{ac} - 2v_{i} + 2v_{ac}^2}{2v_{ac} + v_{ac} - 2v_{ac} + v_{ac}^2 \delta_i} \right) (pK_{P,i} + K_{1,i}) F_{ac,1}^{i}, \quad i = 1, 2, \ldots, m \] (41)

For the third group of equations corresponding to \( \delta_{y} \), the submatrices can be determined from (30) as follows:

\[ M_{ac,31}(i, j) = \begin{cases} 1/2\pi & i = j \\ 0 & i \neq j \end{cases}, \quad i, j = 1, 2, \ldots, m \]

\[ M_{ac,31} = 0_{m \times m}, \quad M_{ac,32} = 0_{m \times m}, \quad M_{ac,32} = 0_{m \times 1} \]

\[ A_{ac,31}(i, j) = 0 \]

\[ A_{ac,31}(i, j) = -3R_{Q} \frac{\delta_{y}}{R} C_{ac,i}(j + m) - C_{ac,i}(j + m) \]

\[ + \left( -3R_{Q} \frac{\delta_{y}}{R} \right), \quad i = j, \quad i, j = 1, 2, \ldots, m \]

\[ 0, \quad i \neq j \]

\[ A_{ac,31}(i, j) = -C_{ac,i}(2m + j) + \left( -3R_{Q} \frac{\delta_{y}}{R} \right), \quad i = j \]

\[ 0, \quad i \neq j \]

\[ A_{ac,31}(1, 1) = -C_{ac,i}(3m + 1) \]

\[ -3R_{Q} \frac{\delta_{y}}{R} C_{ac,i}(3m + 1) \]

\[ B_{ac,3} = 0_{m \times 1} \]

\[ E_{ac,i}(i, :) = -3R_{Q} \frac{\delta_{y}}{R} F_{ac,1}^{i} - F_{ac,2}^{i}, \quad i = 1, 2, \ldots, m \] (42)

Since in the above parameters the derivative operator \( p \) appears, in order to determine conventional state-space equations, change of coordinates, or in other words, state vector transformation is used to overcome this problem.

### 4.3 Transformation of the AC subsystem dynamical model

It should be noted that the derived model and equations are completed once merged with the DC sub-MG model and equations, and also \( P_{ex} \) equation, as it is will be given in part II of this paper. Nevertheless, the standard state-space model of standalone AC sub-MG with \( P_{ex} = 0 \) is given as follows by defining new state vector to remove \( p \)-operator from model parameters. In fact, the state vector \( x \) is decomposed by \( X_{ac} = X_{ac,1} + X_{ac,2} \).

Consequently, the dynamical equations obtained in Section 4.2 is transformed to

\[ M_{ac} X_{ac} = A_{ac} X_{ac} + B_{ac} U_{ac} + E_{ac} W_{ac} \]

In which

\[ A_{1} + p A_{2} = \begin{bmatrix} A_{ac,11} & A_{ac,12} & A_{ac,13} \\ A_{ac,21} & A_{ac,22} & A_{ac,23} \\ A_{ac,31} & A_{ac,32} & A_{ac,33} \end{bmatrix} \]

\[ B_{1} + p B_{2} = \begin{bmatrix} B_{ac,1} \\ B_{ac,2} \\ B_{ac,3} \end{bmatrix}, \quad E_{ac} + p E_{ac} = \begin{bmatrix} E_{ac,1} \\ E_{ac,2} \\ E_{ac,3} \end{bmatrix} \]

\[ C_{1} + p C_{2} = \begin{bmatrix} C_{ac,1} \\ C_{ac,2} \end{bmatrix} \]

\[ D_{1} + p D_{2} = \begin{bmatrix} D_{ac,1} \\ D_{ac,2} \\ D_{ac,3} \end{bmatrix}, \quad F_{ac} + p F_{ac} = \begin{bmatrix} F_{ac,1} \\ F_{ac,2} \\ F_{ac,3} \end{bmatrix} \]

and \( A_{1}, M_{1}, B_{1}, B_{2}, E_{1}, E_{2}, C_{1}, C_{2}, D_{1}, D_{2}, F_{1} \) and \( F_{2} \) do not contain \( p \)-operator any more. Considering \( x = x_{1} + x_{2} \), system output is recalculated as follows:

\[ x_{1} \]
\[
Y_{ac} = (C_1 + C_2 M_1^{-1} A_1) X_{ac1} + (C_1 + C_2 M_1^{-1} A_1) X_{ac2} \\
+ (D_1 + C_2 M_1^{-1} B_1) U_{ac1} \\
+ (D_2 + C_2 M_1^{-1} B_2) U_{ac2} \\
+ (F_{d1} + C_2 M_1^{-1} E_{d1}) W_{ac1} \\
+ (F_{d2} + C_2 M_1^{-1} E_{d2}) W_{ac2}
\]

hence

\[
Y_{ac} = (C_1 + C_2 M_1^{-1} A_1) X_{ac1} + (C_1 + C_2 M_1^{-1} A_1) X_{ac2} \\
+ ((C_1 + C_2 M_1^{-1} A_1) M_1^{-1} B_1 + D_1 + C_2 M_1^{-1} B_1) U_{ac1} \\
+ (D_2 + C_2 M_1^{-1} B_2) U_{ac2} \\
+ ((C_1 + C_2 M_1^{-1} A_1) M_1^{-1} E_{d1} + F_{d1} + C_2 M_1^{-1} E_{d1}) W_{ac1} \\
+ (F_{d2} + C_2 M_1^{-1} E_{d2}) W_{ac2}
\]

Finally if the direct effect of \( u \) and \( u_d \) on outputs are ignored, in case that \( u \) and \( u_d \) are not rich signals, we have

\[
\begin{align*}
M_{ac} &= Ax_{ac} + Bu_{ac} + E_d W_{ac} \\
Y_{ac} &= Cx_{ac} + Du_{ac} + F_d W_{ac}
\end{align*}
\]

In which

\[
\begin{align*}
x_{ac} &= \begin{bmatrix} X_{ac1} \\ X_{ac2} \end{bmatrix} \\
M &= \begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} \\
A &= \begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix} \\
B &= \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \\
E_d &= \begin{bmatrix} E_{d1} \\ E_{d2} \end{bmatrix} \\
C &= [(C_1 + C_2 M_1^{-1} A_1) M_1^{-1} A_1] \\
D &= [(C_1 + C_2 M_1^{-1} A_1) M_1^{-1} B_1 + D_1 + C_2 M_1^{-1} B_1] \\
F_d &= [(C_1 + C_2 M_1^{-1} A_1) M_1^{-1} E_{d1} + F_{d1} + C_2 M_1^{-1} E_{d1}]
\end{align*}
\]

5 Verification in PSCAD and Matlab/Simulink

In this section, a hybrid MG is modelled using PSCAD and the proposed mathematical model is developed in Matlab/Simulink. The results are compared to validate the proposed model. The studied AC sub-MG has two power sources, as shown in Fig. 5. This sub-MG consists of the following components:

• **Main power converter**: Bidirectional CPF-OCC AC–DC converter which connects AC MG to DC MG,
• **AC Resource 1 with output PWM inverter**
• **AC Resource 2 with output PWM inverter**
• **AC Load 1**: A resistive-inductive load
• **AC Load 2**: An induction motor which can be considered as a constant power load

There are also some other DC resources and loads on DC bus in DC sub-MG which parameters are mentioned in part II of this paper. The parameters of DC–AC bidirectional main converter in hybrid MG and calculation of its reference power are also given in part II.

The parameters of AC sub-MG are given in Tables 1–3. Although the displacement reactive power of CPF-OCC converter is zero, it has distortion reactive power which is modelled by \( Q_{load} \) in this paper.

The comparative results of step response for a +4V setpoint change and also disturbance response for a 33% impedance decrease in the dynamical model and PSCAD simulation have been shown in Figs. 6–9. These comparative results show that the proposed dynamical model approximates a reduced-order dynamic for the real system and can be utilised for MG analysis and design purposes. As it can be seen in Fig. 8, the active and reactive power models contain some transients which cannot be seen in PSCAD simulation results. This is because of utilisation of low-pass filters on the power signals. As a result, comparing with previous models it can be seen that although the derived model is a reduced-order dynamic model it has demonstrated an acceptable performance.

The simulation has also considered more complex condition than the previous studies. The complexities contain control loops dynamics, droop control equations, exchanging power dynamics and 3-types-of-loads models. The proposed model can be very helpful in design of model-based fault detection and diagnosis observers. The reduced-order models are more desirable for such applications, because they decrease the load of real-time calculations. The application of this dynamical model will be approved in future studies, where a cyber-attack detection will be derived using model-based fault detection observers.

6 Conclusions

This paper has presented a reduced-order dynamical model of droop-controlled, LVAC sub-MG of a hybrid AC/DC MG. Considering all types of standard loads, active and reactive power demand equations are obtained. Using modified droop control scheme for LV systems, and incorporating inner voltage regulation loop, the closed-loop mathematical description of the system is derived. Steady-state values of the phase angles and injected power
of the inverters are calculated. The overall non-linear dynamical
and algebraic equations are derived for the LVAC side, and then
linearised to form a state-space representation of the sub-MG, in
which current references, voltage amplitudes and phase angles of
the inverters are designated as state variables. The proposed
mathematical model is simulated and the results are compared with
PSCAD outputs. These comparative results show that the proposed
dynamical model approximates a reduced-order model for the real
system which can be utilised for MG analysis and design purposes,
such as model-based fault detection observers. Reduced-order
models are much more desirable for such applications. Since the
inputs of model are the signals sent from secondary control loop,
this model is a proper model for cyber-attack detection using
model-based fault detection observers.

Fig. 6  Step response of dynamical model and PSCAD simulation for AC sub-MG state variables. Left: +4v change command in reference voltage of inverters; right: 33% decrease in $Z_{\text{load}}$ magnitude

Fig. 7  Step response of dynamical model and PSCAD simulation for DC sub-MG state variables. Left: +4v change command in reference voltage of inverters; right: 33% decrease in $Z_{\text{load}}$ magnitude

Fig. 8  Step response of dynamical model and PSCAD simulation for outputs. Left: +4v change command in reference voltage of inverters; right: 33% decrease in $Z_{\text{load}}$ magnitude
Fig. 9 Step response of dynamical model and PSCAD simulation for inverters powers. Left: +4v change command in reference voltage of inverters; right: 33% decrease in Zload magnitude

7 References

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