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New trends of Reactive Power Sharing Control for Islanded Microgrids: A Cyber-Physical Review

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***Abstract*—The Microgrid (MG) concept has been proposed as an effective way to achieve the Smart Grid objectives. Although different implementation challenges of the MGs have been overcome, issues related to reactive power sharing control have been researched recently and new trends have been proposed. These new control strategies have in common the use of different cybernetic characteristics including virtual components and communication systems. This paper discusses these new trends based on a cyber physical methodology, where the communication architectures, as well as, cyber-physical (CP) modelling modules are developed to analyse their potential advantages and drawbacks from a cyber physical perspective.**

I. Introduction

Microgrids have been proposed as an interesting way to achieve the main objectives in a smart grid including reliability, self-healing, load control and satisfying the environmental issues [1]. Although the MG concept offers different benefits including a systematic scheme to integrate renewable energy sources, these advantages typically imply implementation challenges related to the integration of inverter-based distributed generators (IDGs), which require DC-AC inverter interfaces [2]. Hence, diverse control techniques to approach the reliability and quality energy challenges in MGs with IDGs have been developed, including voltage and frequency regulation, active and reactive power sharing and harmonics issues [3].

Even though the MG control strategies have shown effective solutions to the technical challenges related to active power sharing [4], the reactive power sharing seems to be an open challenge. Many of the early approaches to deal with the power sharing problem in MGs were communication-based techniques such as central and master/slave control [5], [6]. Although these approaches showed a proper power sharing performance, high bandwidth communications requirements typically implied higher implementation cost and lower system expendability and reliability [7]. In order to improve these drawbacks, local information based-control techniques were developed, including conventional droop control approaches [8], virtual impedance output loop techniques [9], virtual frame transformation [10], and these variants [11]–[14]. These proposals have shown good performance in terms of power sharing using only local information. Nevertheless, these strategies imply potential disadvantages such as the need of voltage and frequency recovery, accurate knowledge of the physical parameters, and a line parameter dependency. A complete review of each category introduced above can be find in [7].

Recently, new research have been developed to tackle with the reactive power sharing problem. In this paper the open challenges in power sharing control are analyzed and discussed based on a cyber-physical approach, as a result of the new control trends have in common the use of cybernetic components including distributed or central communications and virtual elements. Thus, the new control strategies are analyzed and classified using a cyber physical energy system (CPES) modelling methodology proposed in [15], and CPES modules for IDGs are developed for each controller studied. This approach leads to a clear identification of internal and external cybernetic and physical signals of each studied controller and offers a proper flexibility to perform future reliability and stability analysis for AC-MGs since a cyber-physical perspective. The remainder of this paper is organized as follows. Firstly, the reactive power sharing problem for MGs is discussed in Section II. Secondly, in Section III a CPES modelling approach is illustrated and the new trends of reactive sharing control are analyzed and compared. Finally, conclusions and a comparison summary are given in Section IV.

II. Reactive Power Sharing Problem in Islanded Microgrids

An appropriate balance between the active and reactive power is an important operation requirement for a reliable operation of a MG [16]. In islanded operation mode the Distributed Generators (DGs) of a MG should share the total power demand according to their respective ratings [10]. In order to illustrate this requirement a classical architecture of an islanded MG is shown in Fig. 1. As we can see in this figure, a MG is composed of DGs (1,2,...,N) and loads (1,2,...,M) connected to a point of common coupling (PCC). For simplicity and without loss of generality the DGs are assumed as Voltage Controlled Source and the loads as constant impedances. To achieve a proper performance in terms of power sharing, an active and reactive balance

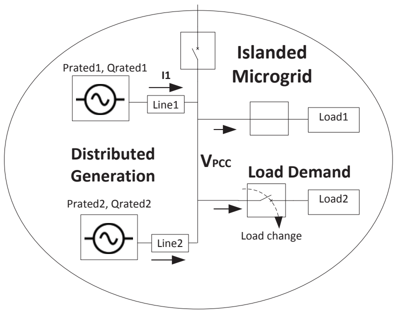

Figure 1. MG Architecture

power should be guaranteed under load changes and stable conditions.

Without any type of power sharing control (it is fixing references values of angular frequency (ω) and amplitude voltage E in each DG) the balance power can be achieved. However, the power sharing between DGs typically is non-proportional to their power ratings. To illustrate this phenomena, a simulation of the power transient response to a load change of a MG with two single phase DGs and equal power ratings was performed. The MG architecture is shown in Fig. 1, where the line parameters generate a mismatched scenario (L_{line1} = 0.3 mH, L_{line2} = 0.6 mH). In t=0.5 s an additional load (Load2) is connected to the PCC; consequently, each generator changes their respective active and reactive power outputs (P_1, P_2, Q_1 and Q_2) as it is shown in Fig 2. As we can see in this figure, although the dynamic response is stable, the DG1 operates in an overload conditions after the change of load demand. This condition could be avoided if each DG shares power proportionally to its rating. Additionally, the current sharing performance is affected by the inaccurate reactive power sharing, which can be analyzed in this case with the instantaneous circulating power parameter (I_1-I_2). As it can be seen in Fig. 2, after the load change the circulating current between DGs is increased until amplitude levels of 50 A. This situation could affect the reliability of the MG.

Different authors have shown that this situation of non-accurate power sharing mainly depends on the effect of mismatched feeder impedances between DGs and loads [17]. A common approach to tackle with this problem is the conventional droop control method [8]. This technique is based on the assumption of a dependency between the active and reactive power injected by each DG with the frequency and the amplitude voltage respectively. Hence, the angular frequency and magnitude voltage references are defined as:

$$\omega = \omega^* - m \cdot P_m \tag{1}$$

$$E = E^* - n \cdot Q_m \tag{2}$$

where ω^* and E^* are the nominal angular frequency and voltage of the DGs respectively; ω and E are the reference frequency and voltage magnitude of each DG; n and m are the droop coefficients, and P_m and Q_m are the measured active and reactive powers [18]. It has been shown that conventional droop control strategy results in a finite reactive power sharing error (ΔQ), which depends on mismatched impedances and the droop constant value (n_i) [19]. The Q-sharing error might produce another co-lateral issues related with over-voltage and overload power capabilities on the MG, which could affect critically the system reliability [20]. In the next section, an CP methodology to evaluate advantages and drawbacks of the different approaches is introduced.

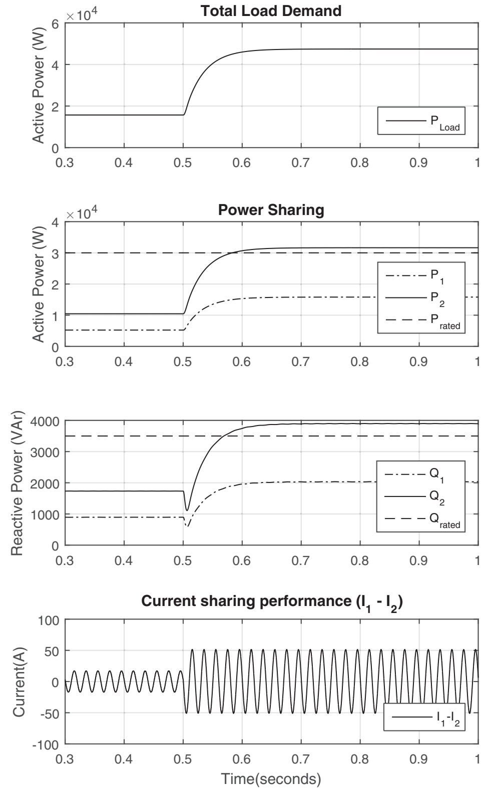

Figure 2. Transient response to a load change in a MG without power sharing control

III. Cyber Physical review of new trends for reactive power sharing control

Recent proposals for MG control typically use cybernetic tools like communications, cooperative control techniques, estimation parameters and virtual components. In this context, the CPES modelling approach proposed in [15] was identified as an interesting tool to characterize a MG with IDGs owing to the different advantages that it offers in front to the conventional modelling approaches, which could lead to neglect essential cybernetic interactions and affect the system's reliability including stability issues owing to time delays in communications [21]. In contrast, the use of a CPES methodology offers different advantages respect to the classical modelling approaches. Firstly, this approach allows a flexible integration of the different components in a MG, which provides zooming-in and zooming-out capabilities to characterize specific system components and interactions between modules. Additionally, the methodology has been designed as a systematic method to integrate unconventional energy sources to the future energy systems; consequently, this approach leads to a modular representation of a IDG as a main component of a AC-MG.

In this way, the methodology in [15] is followed and two main modelling steps have been performed for each reactive sharing control strategy studied. Firstly, a CPES module for each IDG is built, characterized by physical and cybernetic input and output signals as well as internal dynamics, and local sensing and actuation. Secondly, a communication and power network architecture is developed to integrate CPES modules following network constrains. The physical layer network (power network) used in this review is shown in Fig. 1. On the other hand, the cybernetic layer network depends on the information requirements of each approach studied. The different control approaches are classified based on two main categories: communication-based strategies and local information-based strategies. In the following section, different approaches of each category will be analysed and characterized by an IDG-CPES module.

A. Communication Based Strategies

Communication based approaches have been recently proposed to tackle the reactive power sharing problem in islanded microgrids [17], [22]–[24]. We have identified three main communication architectures used for the new reactive power sharing approaches namely: (i) Centralized: (communications between each DG with an Energy Management System (EMS)) (ii) Distributed: (communication links among neighbour DGs) (iii) Hybrid (using centralized and distributed architectures together). These categories of communication architectures are illustrated in Fig. 3. Based on these communication architectures, four new approaches for reactive power sharing have been identified, and will be discussed next.

1) Consensus based approach: Recently, some cooperative approaches to cope with the reactive sharing challenges in AC microgrids has been proposed. On the other hand, in [25] a cooperative technique based on population games methods and a hierarchical structure and centralized communications architecture to regulate both active and reactive power set points including economic criteria is proposed. However, the need for a MG central controller could imply reliability and implementation cost problems associated. In a similar manner, Schiffer et al. in [22] propose a consensus-based distributed voltage control to solve the power sharing issue based on distributed architecture. This approach only uses sparse communication among inverters without central communications and provides necessary and sufficient conditions for local exponential stability. A CPES module for an IDG based on this strategy is shown in Fig. 4. The dynamic model of the

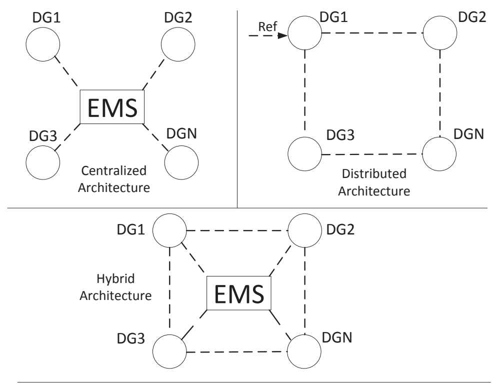

Figure 3. Communication Architectures for Reactive Power Control

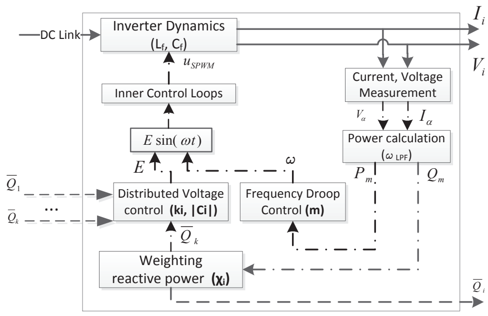

Figure 4. IDG CPES module. (Consensus Protocol Approach)

power calculation, and the frequency droop control are the same as the conventional strategies in Section II. In addition, a distributed voltage controller is proposed as:

$$E = E^{*} - k_i \int_0^t e_i(\tau) d\tau \tag{3}$$

where $e_i(\tau) = \sum_{k\sim C_i} \left(\frac{Q_i^m}{\chi_i} - \frac{Q_k^m}{\chi_k} \right)$, k_i is a feedback gain, C_i is the set of neighbor nodes of node i with which the node i can exchange information, and χ_i and χ_k are the weighting factors which guarantee a proportionally reactive power sharing. Even though this strategy presents different benefits in comparison with the conventional approaches in terms of stability and less communication interactions, the model does not include dynamic components of the low level inner controls, inverter filters and dynamic loads, which may affect the general reliability of the MG control [26].

2) Cooperative-free droop secondary control: Nasirian et al. propose a similar cooperative free-droop secondary control to deal with the reactive power sharing, which uses neighbor communications and a limited centralized communication (hybrid architecture) [23]. A CPES IDG module for this approach is shown in the Fig. 5. It regulates the voltage and reactive power adjusting the set point voltage magnitude (E) by two

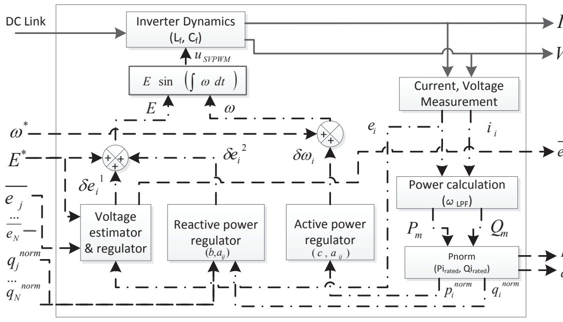

Figure 5. IDG CPES module (Cooperative Free-Droop Approach)

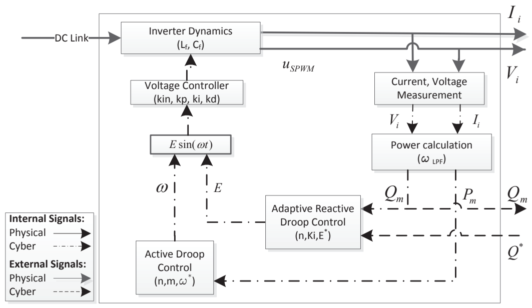

Figure 6. IDG CPES module (Adaptive Droop Control)

corrections terms, δe_i^1 and δe_i^2, as $E = E^* + \delta e_i^1 + \delta e_i^2$, where δe_i^1 is the output of a PI controller, which has as input the error signal produced by the comparison between the rated voltage (E) and the estimated average voltage $\overline{e_i}$. The average estimated voltage is calculated besed on a dynamic consensus protocol as [23]:

$$\overline{e_i} = e_i + \int_0^t \sum_{j \in N_i} (\overline{e_j} - \overline{e_i}) \tag{4}$$

where N_i denotes the set of all neighbors of the node i and $\overline{e_j}$ and $\overline{e_i}$ the average estimated voltage in the ith and jth node respectively. In a similar manner, the second voltage correction term δe_i^2 is adjusted to control the reactive power supplied trough the neighborhood reactive loading mismatch mq_i, defined as $mq_i = \sum_{j \in N_i} ba_{ij} \left(q_j^{norm} - q_i^{norm} \right)$, where b is a design parameter, a_{ij} is an element of the adjacency matrix obtained from the communication graph and q_j^{norm} and q_i^{norm} are the normalized measured reactive power from the IDG_i and their neighbours IDG_j. Similarly, the active power regulator calculates the frequency correction factor $\delta\omega_i$ like the loading mismatch as $\delta\omega_i = \sum_{j \in N_i} ca_{ij} \left(p_j^{norm} - p_i^{norm} \right)$, where c is a design parameter and p_j^{norm} and p_i^{norm} are the normalized measured reactive power from the IDG_i and their neighbours IDG_j. In the Fig 5, it can be seen that this approach requires both centralized communication with the tertiary control unit in order to obtain the cybernetic signals E^* and ω^* and also sparse communications with the neighbours IDG_j to obtain the cybernetic signals of $\overline{e_j}$, q_j^{norm} and p_j^{norm}.

3) Adaptive Voltage Droop Control: Mahmood et al. in [17] propose a control strategy based on the conventional droop control strategy, which with the use of centralized communication with a central energy management system (EMS) may achieve accurate reactive power sharing and robustness to eventual communication interruptions and delays. The EMS receives the measured reactive power (Q_m) of each DG and calculates the reactive power reference (Q^*) based on the unit ratings and the demanded total load. Thus, each DG tunes the parameter $\tilde{n}$ using a integral action under the reactive power error as it is shown in the equation (5). Finally, the conventional reactive power droop control parameter (n) is adjusted with the adaptive parameter ($\tilde{n}$) as:

$$\tilde{n} = K_i \int_0^t (Q_m - Q^*) \tag{5}$$

where $E = E^* - (n + \tilde{n})Q_m$. A CPES module for the adaptive droop control is presented in Fig. 6. As we can see in this figure this approach require only one external cybernetic signal input and output (Q^* and Q_m respectively), which are sent and received from and to the EMS. Although this architecture require centralized communications, the authors claims that the approach uses low bandwidth communication links and is non-vulnerable to communication failure and communication delays. According to the best knowledge of the author of this paper, these cyber-physical characteristics have not been demonstrated rigorously.

4) Adaptive Virtual Impedance: A similar approach using virtual components was recently proposed in [24]. A CPES module for this control strategy was developed as is shown in Fig. 7. This approach modifies the conventional virtual impedance method, which emulates a dominant virtual output impedance to reduce the effect of feeder impedance mismatch[1]. Hence, two additional droops (δV_d and δV_q) are introduced on the voltage droop references (V_d^* and V_q^*) in a $d-q$ reference frame as: $V_d = V_d^* - (K_v \cdot i_d + K_v \cdot i_q)$ and $V_q = V_q^* - (K_v \cdot i_d - K_v \cdot i_q)$, where i_d and i_q are the measured output currents in d-q frame and K_v is the virtual impedance parameter (it can be noted that in this approach the virtual resistance (R_v) is assumed equal to the virtual reactance (X_v), it is $K_v = R_v = X_v$. Finally, a integral action adjusts adaptively the virtual impedance parameter K_v as following:

$$K_v = K_i \int_0^t (Q^* - Q) \tag{6}$$

Similarly to the adaptive voltage droop control approach, this method uses a centralized communication architecture, where

[1]The conventional virtual impedance approach is not covered in this paper, but further details can be found in [18].

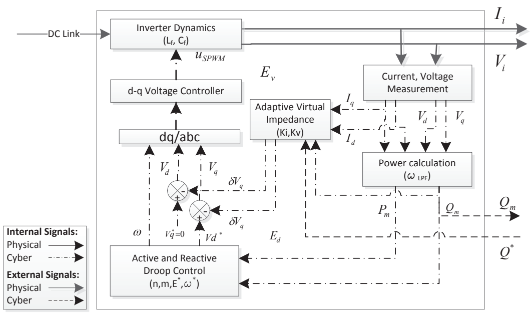

Figure 7. IDG CPES module. (Adaptive Virtual Impedance)

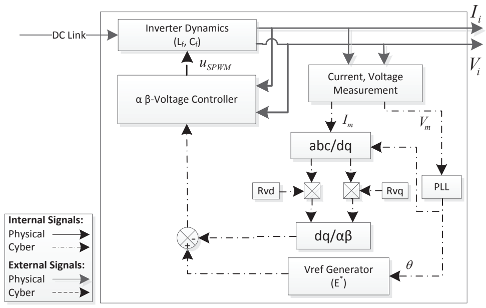

Figure 8. IDG CPES module. (SRF Virtual Impedance Loop)

the virtual impedance parameter is determined by a cybernetic signal (Q^*) sent from the EMS, as well as, the reactive power measured (Q_m) is sent to the EMS. Using this approach, an accurate reactive power sharing is achieved and in case of possible communication faults after the tuning process of the parameter K_v, the errors are reduced to lower values that the conventional approaches (virtual impedance and droop control). Likewise, the authors in [24] claim that this approach is insensitive to communications time delays. However, an inadequate design of the virtual impedance values (R_v and X_v) could affect the system stability and the dynamics performance [12], [13]; additionally, the robustness to time delays and communication faults have not been rigorously analyzed.

B. Local Information based Strategies

1) Synchronous-Reference-Frame (SRF) Virtual Impedance: Even though most recent power sharing control proposals have been developed using different types of communication architectures, the benefits of local information-based methods for reliability, plug and play functionalities and lower implementation cost have been highlighted by different authors [27]. In this way, the authors in [28] propose a new power sharing control strategy, which does not require communications and power calculations. A CPES module of this approach is illustrated in Fig. 8. As it can be seen, this control strategy uses a resistive virtual impedance to control the reactive and active power flow based on a I_q - ω and I_d - V droop characteristics of each inverter. Hence the output current relationships of each inverter can be generalized for N distributed generators as: $I_{d1} \cdot R_{vd1} = I_{d2} \cdot R_{vd2} = ... = I_{dN} \cdot R_{vdN}$ and $I_{q1} \cdot R_{vq1} = I_{q2} \cdot R_{vq2} = ... = I_{qN} \cdot R_{vqN}$, where R_{vdi} and R_{vqi} ($i = 1, 2, ..., N$), are the resistance virtual output impedance in d and q reference frame respectively. Considering the relationship introduced above, the active and reactive power output may be accurately shared as: $P_1 \cdot R_{vd1} = P_2 \cdot R_{vd2} = ... = P_N \cdot R_{vdN}$ and $Q_1 \cdot R_{vq1} = Q_2 \cdot R_{vq2} = ... = Q_{qN} \cdot R_{vqN}$.

It is important to note that this approach assumes a dominant virtual resistance in comparison with the feeder and real output impedances of the physical system. This assumption limits the scope of this strategy in terms of maximum inductive and resistive line impedance [28]. On the other hand, the use of local signals ($d-q$ output currents (I_d and I_q)) leads to not need local power calculation methods, which typically require slow first order filters; consequently, this strategy could offer a faster response than methods based on power calculation approaches including conventional methods and most of the new trends shown in this paper.

IV. Conclusion

This paper has analysed recent approaches for reactive power sharing control in islanded MGs. These new trends have been classified in two main categories namely: communication-based strategies and local information-based strategies. Owing to the fact that these new control strategies have common cybernetic characteristics such as virtual components and communication infrastructure, a CPES module has been developed for each DG control strategy. Likewise, three main communication architectures are identified and illustrated for the communication based methods (see Fig. 3). As a result, Table I shows a comparison of the different control strategies analysed including advantages and disadvantages of the different proposals. As it was presented in Section III-B, although the different communication based strategies offer accurate reactive power sharing (which is the main drawback of the conventional approaches), both centralized as distributed strategies might imply disadvantages in terms of reliability, plug and play functionalities and implementation cost. On the other hand, local information based strategies offer advantages owing to their faster response and free-droop characteristics. Thus, a standardized control method for reactive power sharing seems to be an open challenge in the MGs area; this control strategy is likely to include cybernetic components such as adaptive virtual impedances and cooperative strategies. In addition, SRF virtual impedance methods may be implemented to improve plug and play capabilities and reliability.

Table I
REACTIVE POWER SHARING CONTROL STRATEGIES SUMMARY

Category	**Potential Advantages**	**Potential Disadvantages**	**Comm. Arch. (See Fig. 3)**
Adaptive Voltage Droop Control [17] Adaptive Virtual Impedance [24]	Accurate Power sharing Interruptions and Delays Robustness Line impedance independency	Centralized communications required Voltage and Frequency Recovery	Centralized
Consensus based approach [22]	Accurate power sharing Impedance parameters independency Not Central Communication required	Voltage and Frequency Recovery Distributed Communications required	Distributed
Cooperative-free Droop [23]	Accurate power sharing Not require V and f recovery	Distributed Communications required	Hybrid
SRF Virtual Impedance [28]	Use of local information Free active/reactive power calculation Faster response	Require Voltage recovery Line impedance restrictions PLL based synchronization required	N/A

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