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Brief paper

Stability and active power sharing in droop controlled inverter interfaced microgrids: Effect of clock mismatches☆

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ABSTRACT

Stability and power sharing properties of droop controlled inverter-based microgrid systems depend on various design factors. Little explored is the effect of component mismatches and parameters drifts on the stability, steady state behaviour and power sharing properties of these systems. In this paper, the behaviour of frequency droop controlled inverter based microgrid systems in the presence of non-identical clocks is analysed. It is shown that power sharing between converters in a microgrid can be sensitive to clock mismatches. Our proposal shows that a coordination control that uses sparse inter-node communications is useful in ensuring desired active power sharing. Conditions are derived to ensure stability in the presence of the proposed controller and simulation results are presented.

1. Introduction

Integration of renewable energy has been proposed as a feasible technique to elude the increasing electricity prices and simultaneously alleviate carbon emissions. Most often, the renewable energy sources are spatially distributed making domestic consumption, through traditional radial power flow, a lossy system. Microgrids and storage, therefore, appear as natural extensions to this decentralization of renewable energy generation. Traditional generation (using rotating machines) is well understood and its availability is deemed to be very important to easily maintain the voltage and frequency levels. Despite the fact that microgrids are envisioned as exciting opportunities, the majority of the sources within them are power electronic converter (inverter) based. There are some technical challenges that have to be addressed before there can be large scale deployment of modern microgrids.

Parallel operation and power sharing between inverter based sources through frequency droop control was first proposed in Chandorkar, Divan, and Adapa (1993). Drawing motivation from the operation of synchronous generators, frequency droop controlled inverters measure their real and reactive power output and accordingly modify their frequency and voltage, respectively. Certain design criteria are used to ensure proportional power sharing between inverters in such systems. Various aspects of frequency droop controlled microgrid systems have been discussed in Guerrero, Garcia de Vicuna, Matas, Castilla, and Miret (2004) and Simpson-Porco, Dorfler, and Bullo (2013).

Frequency/clock mismatches affect frequency droop controlled systems. The majority of the work in inverter interfaced microgrids based on droop control focuses on the stability and efficiency of these systems under some assumptions. A few papers (Shoeiby, Holmes, McGrath, & Davoodnezhad, 2013; Zhong, 2013) have commented on the significance of computational delays, numerical errors and parameter uncertainties and acknowledged their effect on the power sharing between droop controlled systems.

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In Zhong (2013) a qualitative analysis is performed to demonstrate the contribution of these component mismatches to inaccuracy in power sharing (specifically those arising from voltage mismatches when real power–voltage droop control is used). A robust voltage controller is then proposed to mitigate these effects. Simulation results in Shoeiby et al. (2013) show that unequal response times between inverters may lead to network instability. However, neither work discusses the effect of parameter mismatches on the stability of the overall system from a qualitative perspective, particularly when the mismatches are in the form of frequency. Some authors have acknowledged the issues arising from these mismatches. Papers (Vandoorn, Renders, Meersman, Degroote, & Vandevelde, 2010; Zhong, 2013) showed some simulation results illustrating the issues. In Schiffer, Ortega, Hans, and Raisch (2015) the mismatches arising from clock drifts are well addressed but their assumption on line resistance and small drifts are considered and questioned in the present work. While it is possible to have frequency mismatches arising from various scenarios like, crystal inaccuracies, inaccurate pre-synchronization of inverter interconnection (Vandoorn et al., 2010) and so on, an assumption that the clock is very stable and accurate pervades the microgrid literature.

1.1. Contribution

In this work, the effectiveness of classical frequency droop control is revisited in the context of clock drifts. The main contributions of this work are twofold. Firstly, small frequency variations are natural in inverters and it is shown that their mere presence will disturb the power distribution equilibrium and may potentially impact stability. Inspired by consensus-based frequency restoration (Simpson-Porco et al., 2013) and consensus-based droop control techniques (Lu & Chu, 2014), a modified version of droop control is presented to restore the desired power distribution equilibrium. Secondly, taking our control technique into account, we establish stability for a constant impedance load based microgrid. Moreover, the proposed control technique is supplementary to traditional frequency droop control, unlike some works, for example Chang and Zhang (2016), thereby retaining the stability and power sharing properties of the former under communication outages. We provide stability conditions for a Kron reduced network using our proposed controller through Lyapunov's indirect method. We show that there are multiple zero eigenvalues for the linearized state transition matrix and therefore use dimensionality reduction to emphasize that the zeros arise from redundancy in the controller implementation. Our proposal provides improved power sharing performance for smaller droop coefficients also thereby reducing frequency deviation. This will in-turn assist in improving model accuracy. Simulation results that demonstrate the efficacy of the proposed controller are also presented.

1.2. Preliminaries and notation

In an n inverter (node) system we define the n-dimensional column vector $x = col(x_i) = [x_1, x_2, \dots, x_n]^T$ where $(\cdot)^T$ represents a transpose function. Let $diag(x_i)$ be a $(n \times n)$-dimensional diagonal matrix with x_i in the ith row and ith column and 0 elsewhere. The $(n \times n)$-dimensional identity matrix is given by $\mathbf{I}_n = diag(1)$. The matrix $1_{n\times n}$ is a $(n \times n)$-dimensional matrix with all elements equal to 1. If $\underline{y} = a + jb$ is a complex number with $j = \sqrt{-1}$, then the real part is given by $\Re\{\underline{y}\} = a$ and the imaginary part is given by $\Im\{\underline{y}\} = b$. The notation $(\cdot)^*$ denotes complex conjugate of a complex number. A communication network is represented as a connected graph $\mathbf{G}_c = (\mathbf{V}_c, \mathbf{E}_c)$, where $\mathbf{V}_c$ is the set of nodes and $\mathbf{E}_c$ is the set of edges which represent the communication links between nodes. We define the communication degree matrix $\mathbf{D}_c := diag(\deg(i))$, where $\deg(i)$ is the number of communication links connected to the ith node. Adjacency matrix $\mathbf{A}_c$ represents the connections between nodes in the communication graph with $a_{ij} = a_{ji} = 1$ if the nodes i and j are connected, and $a_{ij} = a_{ji} = 0$ otherwise. Self loops are avoided, meaning $a_{ii} = 0$ for any node i. We denote the communication graph Laplacian $\mathbf{L}_c = \mathbf{D}_c - \mathbf{A}_c$. The vector 1_n is basis of the kernel of $\mathbf{L}_c$ i.e., for any vector $c = \theta 1_n$, $\theta \in \mathbb{R} \setminus \{0\}$ we have $\mathbf{L}_c c = 0_n$ and since the matrix is symmetric we also have $c^T \mathbf{L}_c = 0_n^T$. Its eigenvalues $\{\lambda_{c,1}, \lambda_{c,2}, \dots \lambda_{c,n}\}$ obey the relationship (Olfati-Sabre, Fax, & Murray, 2007): $0 = \lambda_{c,1} < \lambda_{c,2} \leq \dots \lambda_{c,n}$.

Table 1
Drifts in commercial inverters.

Reference	$\lvert\eta\rvert$ (Hz)	γ
Schneider Electric (2014)	0.05	1 ± 0.001
Emerson Network Power (2014)	0.025	1 ± 0.0005
Magnum Dimensions (2014)	0.05	1 ± 0.001
Power Stream (2016)	0.06	1 ± 0.001
Yueqing Sandi Electric Co., Ltd (0000)	0.025	1 ± 0.0005

2. System set-up

2.1. Modelling clock drifts

To facilitate an analysis that considers the clock drift effect, we denote the voltage at each inverter in terms of a common reference time t. The common time reference, in most cases, is fictitious and not available for measurement. We can represent the local time t_i with respect to a reference time t as shown in (1) (Schiffer et al., 2015):

$$t_i = t\,(1 + \epsilon_i)\,, \tag{1}$$

where ϵ_i is the time invariant drift of the local clock with respect to the reference clock. As emphasized earlier, this drift is natural in clock based systems and must be included for a complete analysis. As in Simpson-Porco et al. (2013) we model the ith inverter as an averaged voltage source:

$$v_i(t) = V_i \cos(\omega t_i + \delta_i) = V_i \cos(\omega_i t + \delta_i),$$

where V_i is the voltage amplitude; $\omega_i = \omega + \eta_i$ is the new frequency with $\eta_i = \epsilon_i \omega$ and ω is the set-point frequency. Here η_i is the drift in the frequency at the inverter arising from individual non-ideal clocks. Since the literature does not suggest how fast ϵ_i varies with time we have not considered a time varying drift. Using commonly reported values for the clock drift, ϵ_i, a frequency drift in the order of 0.03 Hz (for reference frequencies around 50 or 60 Hz) is to be expected, as seen in Table 1. The table lists $\eta = \epsilon\omega$ as well as the corresponding per unit time scale variable $\gamma = 1/(1 + \epsilon)$.

Therefore, an approximate steady state drift $|\epsilon_i|$ of the order of 10^{-3} p.u to 10^{-6} p.u can be subsequently derived. It should be noted that the local integration process at each inverter is affected by the clock drifts. Using (1) we can redefine the local integrator/differentiator as (Schiffer et al., 2015):

$$\frac{d(\cdot)}{dt_i} = \gamma_i \frac{d(\cdot)}{dt} := \gamma_i \dot{(\cdot)},$$

where $\gamma_i = (1 + \epsilon_i)^{-1}$. Observe that any local state will be affected by the clock deviation. Hence, the dynamical system model must take this into account.

2.2. Droop control and power sharing

According to Chandorkar et al. (1993), the amount of real power flowing between two nodes can be controlled by altering the phase angle δ between them. This forms the basis of so-called *frequency*