Distributed Second Order Sliding Modes for Optimal Load Frequency Control

Michele Cucuzzella¹, Sebastian Trip², Claudio De Persis² and Antonella Ferrara¹

Abstract—This paper proposes a Distributed Second Order Sliding Mode (D-SOSM) control strategy for Optimal Load Frequency Control (OLFC) in power networks, where besides frequency regulation also minimization of generation costs is achieved. Because of unknown load dynamics and possible network parameters uncertainties, the sliding mode control methodology is particularly appropriate for the considered control problem. This paper considers a power network partitioned into control areas, where each area is modelled by an equivalent generator including second-order turbine-governor dynamics. On a suitable designed sliding manifold, the controlled system exhibits an incremental passivity property that allows us to infer convergence to a zero steady state frequency deviation minimizing the generation costs.

I. INTRODUCTION

As a result of power mismatch between generation and demand, the frequency in the power system can deviate from its nominal value. Regulating the frequency by Load Frequency Control (LFC) in power networks composed of interconnected Control Areas (CAs) is a challenging issue and it is unsure if current implementations are adequate to deal with an increasing share of renewable energy sources [1]. Traditionally, the LFC is performed at each CA by a primary droop control and a secondary Proportional-Integral (PI) control. To cope with the increasing uncertainties affecting a CA and to improve the controllers performance, advanced control techniques have been proposed to redesign the conventional LFC schemes, such as Model Predictive Control (MPC) [2], adaptive control [3], fuzzy control [4] and Sliding Mode (SM) control. However, due to the predefined power flows through the tie-lines, the possibility of achieving economically optimal LFC is lost [5]. Besides improving the stability and the dynamic performance of power systems, new control strategies are additionally required to reduce the operational costs of LFC [6]. In this paper we propose a novel distributed Optimal LFC (OLFC) scheme that incorporates the economic dispatch into the LFC, departing from the conventional tie-line requirements.

In order to obtain OLFC, the vast majority of solutions appearing in the literature fit in one of two categories. First, the economic dispatch problem is distributively solved by a primal-dual algorithm converging to the solution of the associated Lagrangian dual problem [7]–[9]. This approach generally requires measurements of the loads or the power flows, which is undesirable in a LFC scheme. This issue is avoided by the second class of solutions, where a distributed consensus algorithm is employed to converge to a state of identical marginal costs, solving the economic dispatch problem in the unconstrained case [10]–[13]. The proposed solution in this work fits in the second category, where we utilize a distributed sliding model control scheme to achieve consensus in the marginal costs.

Sliding mode control [14], [15] has been used to improve the conventional LFC schemes [16], possibly together with fuzzy logic [17] and disturbances observers [18]. However, the proposed use of SM to obtain a distributed OLFC scheme is new and can offer a few advantages over the previous results on OLFC. Foremost, it is possible to incorporate the widely used second-order model for the turbine-governor dynamics that is currently neglected in the analytical OLFC studies.

In this paper, we adopt a nonlinear model of a power network partitioned into control areas having an arbitrarily complex and meshed topology. The generation side is modelled by an equivalent generator including second-order turbine-governor dynamics, where the proposed control scheme continuously adjusts the governor set point. Conventional SM controllers can suffer from the notorious drawback known as chattering effect, due to the discontinuous control input. To alleviate this issue, we incorporate the well known Suboptimal Second Order Sliding Mode (SSOSM) control algorithm [19].

Relying on an incremental passivity property of the power network [10], [20], we design a suitable sliding manifold, such that, when the controlled system is constrained to this manifold, the frequency deviation asymptotically converges to zero and the total generation costs are minimized. This result is obtained by avoiding the measurement of the power demand and the use of observers [21], which is an element concuring to the ease of practical implementation of the proposed control strategy.

II. NETWORK MODEL

In this section the dynamic model of a power grid partitioned into control areas is presented. The dynamic behaviour of a single control area is described by an equivalent thermal power plant with a non-reheat turbine, which is commonly
We now write system (1) and the turbine-governor dynamics in (2) compactly for all nodes $i \in \mathcal{V}$ as
\[
\begin{align*}
\dot{\delta}_i &= 2\pi f_i \delta_i \\
f_i &= -\frac{1}{T_p} f_i + \frac{\kappa_t}{T_p} P_i - \frac{\kappa_g}{T_p} P_{di} - \frac{\kappa_t}{T_p} \sum_{j \in N_i} V_{ij}^* V_j^* \sin (\delta_i - \delta_j),
\end{align*}
\tag{1}
\]
where $N_i$ is the set of nodes (i.e., control areas) connected to the $i$-th node by transmission lines. Note that we have assumed that the network is lossless, which is generally the case in high voltage transmission networks. Moreover, $P_i$ in (1) is the power generated by the $i$-th thermal plant, and it can be expressed as the output of the following second order dynamic system that describes the behaviour of both the governor and the turbine of the thermal power plant, i.e.,
\[
\begin{align*}
\dot{P}_i &= -\frac{1}{T_g} P_i + \frac{1}{T_g} P_{di} \\
\dot{P}_{di} &= -\frac{1}{T_{ri}} f_i - \frac{1}{T_{gi}} P_i + \frac{1}{T_{gi}} u_i.
\end{align*}
\tag{2}
\]
The main symbols used in systems (1) and (2) are described in Table I, and a block diagram of the considered system with two control areas is represented in Fig. 1.

We now write system (1) and the turbine-governor dynamics in (2) compactly for all nodes $i \in \mathcal{V}$ as
\[
\begin{align*}
\dot{\delta}_i &= 2\pi D^T f \\
f_i &= -T_p^{-1} f + K_p T_p^{-1} P_i - K_p T_p^{-1} P_d \\
&= -K_p T_p^{-1} D^T \sin (\eta),
\end{align*}
\tag{3a}
\]
where $\eta = D^T \delta \in \mathbb{R}^m$, $f \in \mathbb{R}^n$, $P_i \in \mathbb{R}^n$, $P_d \in \mathbb{R}^n$, $\Gamma = \text{diag}(\gamma_1, \ldots, \gamma_m)$, and $\sin (\eta) = [\sin (\eta_1), \ldots, \sin (\eta_m)]^T$. Matrices $T_p, T_i, T_g, K_p, R$ are suitable $n \times n$ diagonal matrices.

To permit the controller design, the following assumption is introduced.

**Assumption 1** The variables $f_i, P_i, P_d$ are locally available at control area $i$. The unmatched disturbance $P_{di}$ is unknown, constant and can be bounded as
\[
|P_{di}| \leq D_i,
\tag{4}
\]
where $D_i$ is a positive constant available at control area $i$.

### III. PROBLEM FORMULATION

**Optimal LFC** has two main objectives. First, the control scheme needs to regulate the frequency towards its nominal value, i.e.
\[
\lim_{t \to \infty} f = 0.
\tag{5}
\]
Second, the OLFC should obtain an economic dispatch, i.e. it needs to minimize the total costs $C(P_i)$ of the power generation required to control the frequency
\[
\min_{P_i} C(P_i) = \min_{P_i} \sum_{i \in \mathcal{V}} C_i(P_i)
\tag{6}
\]
s.t. $0 = 1^T f - 1^T P_d$, where $1_n \in \mathbb{R}^n$ is the vector containing all ones, while the equality constraint follows from the requirement of a zero
frequency deviation at steady state. Before further elaborating on this, we make the assumption of existence of a steady state of the system under a constant control input \( \bar{u} \).

**Assumption 2** Given a constant power demand \( P_d \), there exist \( \bar{u}, \bar{\pi} \in \mathcal{R}(D^f), \bar{\tau} \in \mathcal{N}(D^g) \), \( \overline{P}_i \in \mathbb{R}^n \) and \( \overline{P}_g \in \mathbb{R}^n \) such that \((\overline{\tau}, \overline{\pi}, \overline{P}_i, \overline{P}_g)\) satisfies
\[
\begin{alignat}{2}
0 &= 2\pi D^T \bar{\tau} \\
0 &= -T_c^{-1} \bar{\tau} + K_P T_p^{-1} \overline{P}_i - K_P T_p^{-1} \overline{P}_g \\
&\quad - K_p T_p^{-1} D^T \sin(\bar{\pi}),
\end{alignat}
\]
(7a)
\[
\begin{alignat}{2}
0 &= -T_i^{-1} \overline{P}_i + T_i^{-1} \overline{P}_g \\
0 &= -R_i^{-1} \bar{\tau} - T^{-1} \overline{P}_i + T^{-1} \overline{P}_g.
\end{alignat}
\]
(7b)

From algebraic manipulations of (7) it follows that the steady state frequency deviation is given by
\[
\bar{\tau} = I_n \frac{1}{K_p} (\overline{P}_i - \overline{P}_g).
\]
(8)

From (8) it becomes clear that we indeed require the equality constraint in (6) to have a zero frequency deviation at steady state. The generation costs associated to control area \( i \) are commonly described by a strictly convex linear-quadratic cost function
\[
C_i(P_i) = \frac{1}{2} q_i P_i^2 + z_i P_i + s_i,
\]

such that the total costs in the power network can be expressed as
\[
C(P) = \frac{1}{2} Q P + Z P + I_n^T S,
\]
(9)

where \( Q \) is a \( n \times n \) positive definite diagonal matrix and \( Z, S \in \mathbb{R}^n \). It is now possible to explicitly characterize the solution \( \overline{P}_i^{\text{opt}} \) to the optimization problem (6).

**Lemma 1** Given the cost function (9) with \( Q \) a positive definite diagonal matrix, the solution \( \overline{P}_i^{\text{opt}} \) to the optimization problem (6) satisfies
\[
\overline{P}_i^{\text{opt}} = Q^{-1}(1_n \bar{\lambda} - Z),
\]
(10)

with
\[
\bar{\lambda} = \frac{1}{2} I_n^T P_i + I_n^T Q^{-1} Z \\
+ \frac{1}{2} I_n^T Q^{-1} I_n \in \mathbb{R}.
\]
(11)

From (10) it follows that \( Q \overline{P}_i^{\text{opt}} + Z = 1_n \bar{\lambda} \in \mathcal{R}(I_n) \). Consequently, at the economic dispatch all the marginal costs associated to power generation are equal. However, note that in (11) the value of \( P_i \) is required, which is generally unavailable in practical cases. The proposed solution in the next section overcomes this issue by simultaneously solving (6) and controlling the frequency without load measurements.

Now we are in a position to formulate the control problem: Let Assumptions 1 and 2 hold. Given system (3) and the optimization problem (6), design a distributed control scheme achieving frequency regulation and minimizing, at the steady state, the generation costs.

**IV. THE PROPOSED SOLUTION**

In this section a Distributed Suboptimal Second Order Sliding Mode (D-SSOM) control algorithm is proposed to solve the aforementioned control problem. To do so, we will employ the well established SSOM controller proposed in [19] to each power network augmented with a distributed control scheme proposed in [20], leading to an overall distributed solution.

In order to define (and converge to) a sliding manifold on which a useful passivity property of the turbine-governor can be established (see Lemmas 3 and 4), and to enforce optimality at steady state (see the proof of Theorem 1), we augment the state of system (3) with additional state variables \( \vartheta_i, i = 1, \ldots, n \). Their dynamics are given by
\[
T_d \vartheta_i = P_i - \vartheta_i - a_i \sum_{j \in N_i^{\text{comm}}} (q_i \vartheta_i + z_i - (q_j \vartheta_j + z_j)),
\]
(12)

where \( N_i^{\text{comm}} \) is the set of the nodes that communicate with node \( i \), and \( a_i \) is a positive constant. Note that the induced communication is required to achieve optimality.

**Remark 1** The topology of the communication network is described by the Laplacian matrix \( L_c \). The dynamics in (12) can now be expressed compactly for all nodes \( i \in \mathcal{V} \) as
\[
T_d \vartheta = P_i - \vartheta - A L_c (Q \vartheta + Z),
\]
(13)

where \( A \in \mathbb{R}^{n \times n} \) is a positive definite diagonal matrix suitably selected. A possible choice of \( A \) is provided in the next section.

To guarantee an optimal coordination throughout the whole network the following assumption is made:

**Assumption 3** The undirected graph corresponding to the topology of the communication network is connected.

Consider now the power network (3) augmented with (13). We select the sliding variables vector \( \sigma \in \mathbb{R}^n \) as
\[
\sigma = M_1 f + M_2 P_i + M_3 P_g + M_4 \vartheta,
\]
(14)

\( M_1, \ldots, M_4 \) being constant \( n \times n \) diagonal matrices suitable selected in order to assign the dynamics of the augmented system when \( \sigma = 0 \). The permitted values for \( M_1, \ldots, M_4 \) follow from the stability analysis and should be chosen to enforce a useful passivity property of the turbine-governor on the corresponding sliding manifold. A further discussion is provided in Lemmas 3 and 4 in the next section.

**Remark 2** Because \( M_1, \ldots, M_4 \) are diagonal matrices, each sliding variable \( \sigma_i \) is defined by only local variables at node \( i \).

We now continue by describing the controller that guarantees the convergence to the sliding manifold \( \sigma = \sigma = 0 \). Since the
The relative degree is the minimum order \( r \) of the time derivative \( \xi^{(r)} \), of the sliding variable associated to the \( i \)-th node in which the control \( u_i \), \( i = 1, \ldots, n \), explicitly appears.

\(^1\)
Assumption 5 Let $M_1 > 0, M_2 \geq 0, M_3 > 0$ and $M_4 = -(M_2 + M_3)$ in (14). Furthermore, let $A = (M_2 + M_3)^{-1}M_1 Q$ in (13).

Note that this assumption can always be fulfilled. We first characterize this sliding manifold in the lemma below.

Lemma 3 Let Assumptions 2 and 5 hold. System (3b) augmented with (13) converges in a finite time $t_i$ to the sliding manifold where

$$P_g = -M_3^{-1}(M_1 f + M_2 P_t + M_4 \dot{\theta}), \forall t \geq t_i. \quad (24)$$

The proof follows from applying the SSOSM controller (19)–(21) to each control area such that a second order sliding mode is enforced. As a result of Lemma 3 we can substitute (24) in (3), $\forall t \geq t_i$, obtaining the following reduced order system

$$\dot{\eta} = 2\pi D^T f$$
$$T_p K_p \dot{f} = -K_v \dot{f} + P_t - P_d - D \Gamma \sin(\eta), \quad (25a)$$

$$M_1^{-1} M_3 \dot{P}_t = -M_1^{-1}(M_2 + M_3)P_t - f - M_1^{-1} M_4 \dot{\theta}$$
$$\dot{\theta} = P_t - f - A L_c (Q \dot{\theta} + Z)$$
$$\sigma = 0, \quad (25b)$$

where the dynamics of the governor has been replaced by the equality constraint $\sigma = 0$. Indeed, one can observe that the dynamics of the governor can be obtained by differentiating (24). Incremental passivity of (25b) can now be proven.

Lemma 4 Let Assumptions 1, 2 and 5 hold. System (25b) with input $-f$ and output $P_t$ is an incrementally passive system, with respect to the steady state satisfying

$$0 = -M_1^{-1}(M_2 + M_3)P_t^{\text{opt}} - 0 - M_1^{-1} M_4 \overline{\theta}$$
$$0 = P_t^{\text{opt}} - \overline{\theta} - A L_c (Q \overline{\theta} + Z). \quad (26)$$

Namely, the storage function

$$U_2 = \frac{1}{2} (P_t - P_t^{\text{opt}})^T M_1^{-1} M_3 (P_t - P_t^{\text{opt}})$$
$$+ \frac{1}{2} (\theta - \overline{\theta})^T M_1^{-1}(M_2 + M_3) \overline{\theta} \quad (27)$$

satisfies the following incremental dissipation inequality

$$U_2 = -(P_t - \overline{\theta})^T M_1^{-1}(M_2 + M_3)(P_t - \overline{\theta})$$
$$- (Q \overline{\theta} + Z)^T L_c(Q \overline{\theta} + Z) - (P_t - P_t^{\text{opt}})^T f, \quad (28)$$

along the solutions to (25b).

Remark 4 Note that the term $-A L_c (Q \dot{\theta} + Z)$ in (25b) is not needed to enforce the discussed passivity property, but is required to prove convergence to the economic efficient generation $P_t^{\text{opt}}$. In fact, setting $A = 0$ still permits to infer frequency regulation in Theorem 1 below.

Now, we can prove the main result of this paper concerning the evolution of the augmented system controlled via the proposed D-SSOSM control strategy.

Theorem 1 Let Assumptions 1–5 hold. Consider system (3), augmented with the distributed averaging integrators (13) and controlled via (14)–(21). Then, the solutions of the closed-loop system starting in a neighbourhood of the equilibrium $(\overline{P}, \overline{f} = 0, \overline{P}_t^{\text{opt}}, \overline{\theta} = \overline{P}_t^{\text{opt}})$ approach the largest invariant set where $\overline{f} = 0$ and $P_t = P_t^{\text{opt}}$.

The proof follows from evaluating the incremental storage function $U = U_1 + U_2$ along the solution to the reduced order system (25) and applying LaSalle’s invariance principle.

VI. SIMULATION RESULTS

In this section, the proposed control solution is assessed in simulation by implementing a power network partitioned into four control areas (e.g. the IEEE New England 39-bus system [26]). The topology of the power network is represented in Figure 2 together with the communication network (dashed lines). The line parameters are $\gamma_1 = 5.4$ p.u., $\gamma_2 = 5.0$ p.u., $\gamma_3 = 4.5$ p.u. and $\gamma_4 = 5.2$ p.u., while the network parameters and the power demand $\Delta P_{bi}$ of each area.
TABLE II

<table>
<thead>
<tr>
<th>Network Parameters and Power Demand</th>
</tr>
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<tbody>
<tr>
<td>Area 1</td>
</tr>
<tr>
<td>$T_0$ (s)</td>
</tr>
<tr>
<td>$T_i$ (s)</td>
</tr>
<tr>
<td>$T_{ii}$ (s)</td>
</tr>
<tr>
<td>$K_w$ (Hz p.u.$^{-1}$)</td>
</tr>
<tr>
<td>$R_i$ (Hz p.u.$^{-1}$)</td>
</tr>
<tr>
<td>$\Delta P_i$ (p.u.)</td>
</tr>
</tbody>
</table>

are provided in Table II, where a base power of 1000 MW is assumed. The matrices in (14) are chosen as $M_1 = 3I_4, M_2 = I_4, M_3 = 0.1I_4$ and $M_4 = -(M_2 + M_3), I_4 \in \mathbb{R}^{4 \times 4}$ being the identity matrix, while the control amplitude $\alpha$ is chosen as $\alpha = 1$.

Based on a suitable chosen sliding manifold, the system is initially at the steady state, implying that all the sliding variables are equal to zero. Then, at the initial time instant $t_0 = 0$ s, the power demand in each area is increased according to the values reported in Table II. From Figure 3, one can observe that the frequency deviations converge asymptotically to zero after a transient where the frequency drops because of the increasing load. Indeed, one can note that the proposed controllers increase the power generation in order to reach again a zero steady state frequency deviation. Moreover, the total power demand is shared among the areas, minimizing the total generation costs. More precisely, by applying the proposed D-SSOSM, the total generation costs are 10% less than the generation costs when each area would produce only for its own demand.

VII. CONCLUSIONS

A distributed suboptimal second order sliding mode control scheme is proposed to solve an optimal load frequency control problem in power systems affected by unmatched disturbances due to fluctuations in load demand. In the paper, we adopted the model of a power network partitioned into control areas, where each area is represented by an equivalent generator including second-order turbine-governor dynamics. Based on a suitable chosen sliding manifold the system, constrained to this manifold, possesses an incremental passivity property that is exploited to prove that the frequency deviation asymptotically converges to zero and economic optimality is achieved. An important feature of the proposed distributed control approach is that each controller does not require neither the measurement of the power demand nor load observers, increasing the practical applicability.

REFERENCES


