Improved Load Frequency Control of Time-Delayed Electric Vehicle Aggregators via Direct Search Method

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Abstract—This paper investigates the issue of frequency regulation of a single-area alternating current (AC) power system connected to an electric vehicle (EV) aggregator through a nonideal communication network. It is assumed that the command control action is received by the EV aggregator with constant delay and the power system experiences uncertain parameters. A novel effective iterative algorithm, direct search, is proposed for the time-delayed system to design the gains of a proportional-integral (PI) controller. The proposed direct search algorithm can find a feasible solution whenever at least one solution lays in the space search. Thus, by choosing a wide space search, we can expect that the PI controller assures the closed-loop stability, theoretically. The proposed approach has low conservative results over the existing approaches. For the uncertain time-delayed system, a robust PI controller is designed, which is resilient against the system uncertainties and time delay. Numerical simulations are carried out to show the merits of the developed controller.

Index Terms—Frequency control, EV aggregator, Robust control, Direct search algorithm, Time delay.

I. INTRODUCTION

Load frequency control (LFC) is a key issue in alternating current (AC) power systems, which are vulnerable to the inconsistency of consuming and generating electrical power. Moreover, emerging renewable and pollution-free sources offer the merits of reducing the environmental pollution and challenges of degrading power quality [1].

In this regard, the role of batteries and fast response generators is becoming more and more important. On the other hand, emerging electric vehicles (EVs) and vehicle-to-grid (V2G) technology is a promising solution dealing with the degrading influence of renewable energy sources on the LFC system. EVs’ Batteries are classified as fast response elements in the LFC system. In comparison to conventional generators, by operating as both loads or generators, the EV batteries regulate the electric power of AC grids remarkably faster and enhance the dynamic performance of the LFC system [2].

Instead of connecting each of the EV units, EV aggregators are required. As their name suggests, they aggregate and control several EVs, which are available in the parking lots. The EV aggregators communicate with the AC power system and the LFC center by sending their status of available battery capacities and electric power and receiving the control commands to regulate the charging and discharging actions of the EVs [3]. From a practical point of view, the EV aggregators use a communication network with low cost and bandwidth to transfer data. Therefore, the communication link is vulnerable to delays and data missing [4]. These issues adversely affect LFC system performance and stability [5].

To tackle the robust stability of LFC systems, advanced control techniques emerged, some of them are sliding mode [6], event-triggered [7], sampled-data [8], μ-synthesis [1], and heuristic [9] approaches. More recently, the LFC issue under communication delay [2], [10]–[13] received much attention. In [10], a proportional integral derivative (PID) was suggested for time-delayed LFC, and, sufficient controller design conditions were re-formulated in terms of linear matrix inequality (LMI) constraints. In [11], a predictive method was suggested based on state-feedback to regulate the frequency in the presence of time-delayed control input. The controller design conditions are stated in terms of LMIs.

In [12], based on the Lyapunov stability theory and LMI, the stability delay margin of an LFC system was analyzed. In [13], the stability delay margin was investigated based on the frequency response of a LFC system by deploying a frequency sweeping test and the binary iteration algorithm. In [2], the stability analysis is performed based on the stability boundary locus. The effect of time-delay and control command participation on the PI controller gains was investigated. In [14], a graphical method to compute the stabilizing PI values is presented. Although such advanced control methods were successful in satisfying the desired performances, the computational burden and conservativeness of such techniques have been reported as their common drawbacks. Also, the effect of system uncertainties on the closed-loop time delayed LFC has not been studied, yet.
To sum up, this paper considers the robust controller design of LFC systems with EV aggregator. The developed controller ensures the stability of the closed-loop system based on its time-delayed uncertain characteristic equation. Initially, the nonlinear characteristic equation is approximated by the Rekasius approach [15] to achieve a quasi-polynomial representation. Then, a novel direct search algorithm is developed to numerically find feasible solutions for the controller gains.

The developed numerical approach does not use the Lyapunov stability theory, because it only offers sufficient conditions. The proposed approach uses the characteristic quasi-polynomials and Routh table to search for the unknown controller gains. The suggested numerical method provides a systematic and simple algorithm to assure the closed-loop stability in the presence of system uncertainties and time delay terms. To show the merits of the suggested method, numerical simulations are conducted and the effect of system parameters and time delay value on the closed-loop stability margin and controller gains are studied.

This paper is continued as follows: In Section II, the LFC problem with EV aggregator and time delay is presented. In Section III, the proposed direct search algorithm to design the frequency controller is discussed. In Section IV, simulations are conducted. Section V ends this paper by evoking some concluding remarks and future perspectives.

II. SINGLE-AREA LFC SYSTEM MODEL WITH EV AGGREGATOR

EV aggregator units facilitate frequency regulation for EVs in parking lots. The EV aggregators are connected to control centers and receive the controller commands to inject or absorb electric power and allocate it among each of the participating EVs. To investigate the stability of the power system, a single-area LFC system is connected to an EV aggregator. Generally, the LFC systems contain nonlinear elements. For the small-signal stability analysis, the nonlinear LFC system is linearized around an equilibrium point, and then linear representation can be obtained.

The schematic of a typical single-area LFC system including a generator, an EV aggregator, delay block, and the droop and PI controllers is drawn in Fig. 1. As can be seen in Fig. 1, the deviation of AC power system frequency, $\Delta f$, is the deviation of AC power system frequency. $\Delta P_g$, $\Delta P_m$, and $\Delta P_d$ are electrical power output, EV aggregator power output, and load disturbance, respectively.

The sum of the powers will affect the AC power system frequency. $\Delta X_p$ and $\Delta P_m$ are the valve position and mechanical power output, respectively. Furthermore, $D$ and $M$ are the damping coefficient and generator inertia constant, $R$ is the speed droop, $F_p$, $T_g$, $T_r$, and $T_c$ are the fraction of the total turbine power, the time constant of the governor, reheat and turbine, respectively, $\beta$ is the frequency bias factor, and $\alpha_0$ and $\alpha_1$ are the participation factors.

The PI controller gains are $K_p$ and $K_i$. The control signal is fragmented among the generator and the EV by $\alpha_0$ and $\alpha_1$ and transmitted to the EV through the communication networks with the delay $\tau$. As can be seen in Fig. 1, a communication delay between the controller and the generator is not considered, because it is ignorable compared to the EV link.

The objective is to choose the PI controller gains $F = [K_p, K_i]^T$ for regulating the frequency. This issue is highly influenced by the communication delay $\tau$ and the participation factor vector $\alpha = [\alpha_0, \alpha_1]^T$. If these parameters are not involved in the design procedure, the overall stability will be ruined.

Based on Fig. 1, the characteristic equation can be written as follows:

$$q(s, F, \alpha, \tau) = P(s, F, \alpha) + W(s, F, \alpha)e^{-\tau s} \quad (1)$$

where $P(\cdot)$ and $W(\cdot)$ are polynomials with real coefficients in terms of system parameters, as follows:

$$P(\cdot) = p_6s^6 + p_5s^5 + p_4s^4 + p_3s^3 + p_2s^2 + p_1s + p_0 \quad (2)$$

$$W(\cdot) = w_4s^4 + w_3s^3 + w_2s^2 + w_1s + w_0 \quad (3)$$

Fig. 1. The schematic of a single-area LFC system.
and
\[
\begin{align*}
&w_4 = a_1 \beta RK_{EV} K_p T_c T_r T_c \\
&w_3 = a_1 \beta RK_{EV} (K_p T_c T_r + K_p T_r T_c) \\
&w_2 = a_1 \beta RK_{EV} (K_p T_c + K_p T_r + K_p g) \\
&w_1 = a_1 \beta RK_{EV} (K_p + K_i T_c + K_i T_r + K_i g)
\end{align*}
\]
(4)

Finally, the simplex is divided to smaller parts such that a feasible solution for the controller gains is found. In a simple manner, the mechanism to halve the active simplex is to check the corner points and the edges of the simplex.

The original direct search algorithm [18] is applicable for stability analysis with any number of controller design parameters, and it is adopted for the LFC system of Section II. Since the PI controller of the LFC comprises two gains $K_p$ and $K_i$, the design space is turned into a two-dimensional triangular space, as shown in Fig. 2(a). To check a feasible solution in the triangular space of Fig. 2(a), we start with checking the stability of the corner points, as shown in Fig 2(b).

For each of these points, one has a solution vector $F_i = [K_{pi} K_{ri}]$ for $i = 1,2,3$. By substituting $F_i$ into (6), one gets three polynomials, as follows:

\[
\hat{q}_i(s, F_i, \alpha, T) \quad \text{for} \quad i = 1,2,3
\]
(7)

For the admissible ranges of $T$ and $\alpha$, the stability of polynomial $\hat{q}_i(s, F_i, \alpha, T)$ should be checked [19]. This stage is called checking method 1 (CM1). The CM1 can be done by checking the polynomial roots. If all of its roots have negative real values, the polynomial and its corresponding closed-loop system are stable. If for any of the points $F_i$, the roots of $\hat{q}_i(s, F_i, \alpha, T) < 0$, a feasible solution is found and the controller is designed. Otherwise, we need to proceed with the direct search algorithm.

In the next step, we are sure that the corner polynomials are infeasible and none of them can stabilize the characteristic polynomial in (6). We want to check whether the whole simplex is infeasible or there may be a feasible solution inside the simplex. For this aim, the stability of the edges of the triangular space should be checked. Since the places of the corner points are known, it is a simple task to find the representation of the edges. The edge or line segment representation can be obtained by the convex combination of its corresponding corner points $F_i$ and $F_j$, as follows:

\[
F_{ij} = \gamma F_i + (1 - \gamma) F_j \quad \text{for} \quad i < j = 1,2,3 \quad \text{and} \quad 0 \leq \gamma \leq 1
\]
(8)

As can be seen in Fig. 2(c), for each edge $F_{ij}$ for $i < j = 1,2,3$, three sets of polynomials with respect to the $\gamma$ value are obtained, as follows:

\[
\hat{q}_{ij}(s, F_{ij}, \alpha, T, \gamma) \quad \text{for} \quad i < j = 1,2,3
\]
(9)

Now the stability of polynomials (9) is checked. This step is called checking method 2 (CM2). If none of the polynomials in (9) have pure imaginary roots, then the whole simplex is infeasible and we cannot find any solution to the problem [15].

### III. DIRECT SEARCH METHOD

Inspired from [18], this paper proposes a numerical solving algorithm that seeks the controller gains so that the uncertain time delayed closed-loop system is stabilized, theoretically. The main idea is that it starts with a large simplex space search. Then, based on a mechanism, this large simplex space is halved to new simplexes, at each iteration. Finally, the simplexes are divided to smaller parts such that a feasible solution for the controller gains is found. In a simple manner, the mechanism to

<table>
<thead>
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<th>Parameter</th>
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<th>Parameter</th>
<th>Value</th>
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<tbody>
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<td>$T_g$</td>
<td>0.2 s</td>
<td>$R$</td>
<td>1.11 Hz/p.u. MW</td>
</tr>
<tr>
<td>$T_i$</td>
<td>0.3 s</td>
<td>$K_{EV}$</td>
<td>1 s</td>
</tr>
<tr>
<td>$T_r$</td>
<td>12 s</td>
<td>$M$</td>
<td>8.8</td>
</tr>
<tr>
<td>$T_{EV}$</td>
<td>0.1 s</td>
<td>$D$</td>
<td>1</td>
</tr>
<tr>
<td>$F_p$</td>
<td>1.6</td>
<td>$a_0$</td>
<td>$\in [0.7, 1]$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>21</td>
<td>$a_1$</td>
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<td>$\gamma$</td>
<td>$\in [0, 1]$</td>
<td>$\alpha$</td>
<td>$\in [0, 1]$</td>
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The LFC power system parameters are given in Table I. Using the Rekasius approach [16], the nonlinear term $e^{-ts}$ is substituted by $\frac{1}{1+Ts}$ $\frac{1}{1+Ts}$. Thereby, the following polynomial characteristics equation is obtained [17]:

\[
q(s, F, \alpha, T) \equiv \hat{q}(s, F, \alpha, T)
\]
(6)
Fig. 2: Each step of the direct search iteration algorithm. Otherwise, there may still be a feasible solution in the active simplex. In this step, the current simplex is halved with respect to its largest edge, as shown in Fig. 2(d). Then, for one of the randomly selected sub-simplexes (i.e. (I) or (II)), the new active simplex space is chosen and the net integration is performed. If a feasible solution cannot be found in the active simplex (for instance, i.e. (I) in Fig 2(d)), then the other space will be checked (for instance, i.e. (II)) and the algorithm continues.

The details of the steps CM1 and CM2 and the convergence proof can be found in [18]. The overall iterative algorithm is given in Fig. 3.

IV. SIMULATION RESULTS

In this section, by using the proposed direct search algorithm, the closed-loop stability of the LFC system is evaluated and the effect of system uncertainties and time delay value on the stability in the \((K_p, K_I)\)-plane is investigated. Also,
the PI controller gain regions for which the closed-loop system is stable will be obtained. Finally, validation studies employing time-domain simulations are given.

A. Scenario 1 (Effect of system uncertainties on the stability region)

To show the impact of the system uncertainties on the closed-loop stability, in this scenario, the time delay values are fixed by $\tau = 0.5$ and $\tau_1$ and two ranges for the participation factors $\alpha_0$ and $\alpha_1$ are considered as shown in Table II. Deploying the direct search algorithm, Figs. 4 and 5 are obtained.

As can be seen in Figs. 4 and 5, by approaching the range of $\alpha_0$ to one and $\alpha_1$ to zero, the stability region is enlarged. The reason is that whenever $\alpha_1$ tends to zero, the effect of EV aggregator with the delay term is decreased. This relaxes the stability analysis and eases finding a feasible solution. So, a larger stability range is obtained. Also, the regions of Figs. 4(a) and 5(a) are a subregion of those in Figs. 4(b) and 5(b), respectively.

B. Scenario 2 (Effect of time delay on the stability region)

In a similar manner to Scenario 1, to show the impact of the time delay on the closed-loop stability, in this scenario, the system uncertainty range is fixed by $\alpha_0 = [0.9,1]$ and $\alpha_1 = [0,0.1]$. On the other hand, two values for the time delay are chosen as $\tau = 0.5$ and $\tau = 1.5$, as summarized in Table III.

Utilizing the direct search algorithm of Section III, Fig. 6 is achieved. Fig. 6 reveals that the time delay adversely affects the stability region. Although the obtained region for $\tau = 1.5$ is smaller than that of $\tau = 0.5$, Fig. 6(a) is not a subset of Fig. 6(b). This can be inferred that the time delay affects the stability region nonlinearly, which is also evident from (1).

C. Scenario 3 (Time-domain closed-loop model simulation)

To show the effectiveness of the proposed approach, for the system parameters of Fig. 6(b) the closed-loop model input and system output evolutions are provided. The load power variation is set as $\Delta P_L = 0.2$. Fig. 7 shows that the system is robust against load power changes and a time-delayed EV aggregator.

### Table II. The parameters of LFC system in Scenario 1.

<table>
<thead>
<tr>
<th>Figure number</th>
<th>$\tau$</th>
<th>$\alpha_0$</th>
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<tr>
<td>4(a)</td>
<td>0.5 s</td>
<td>[0.7,1]</td>
<td>[0.03]</td>
</tr>
<tr>
<td>4(b)</td>
<td>0.5 s</td>
<td>[0.9,1]</td>
<td>[0.01]</td>
</tr>
<tr>
<td>5(a)</td>
<td>1 s</td>
<td>[0.7,1]</td>
<td>[0.03]</td>
</tr>
<tr>
<td>5(b)</td>
<td>1 s</td>
<td>[0.9,1]</td>
<td>[0.01]</td>
</tr>
</tbody>
</table>

### Table III. The parameters of LFC system in Scenario 2.

<table>
<thead>
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<th>Figure number</th>
<th>$\tau$</th>
<th>$\alpha_0$</th>
<th>$\alpha_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6(a)</td>
<td>0.5 s</td>
<td>[0.9,1]</td>
<td>[0.0,1]</td>
</tr>
<tr>
<td>6(b)</td>
<td>1.5 s</td>
<td>[0.9,1]</td>
<td>[0.0,1]</td>
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characteristic equation of the closed-loop system controlled by a PI controller was derived. Then, a numerical iterative direct search algorithm was proposed to find a feasible solution for the controller gains that assured the robust closed-loop stability against system uncertainties. Several scenarios were presented to show the impact of time delay and EV aggregator participation on the single-area LFC stability and frequency response. It was shown that by increasing the participation of the EV aggregator, the stability region was reduced. The same impact was inferred by increasing the time delay. For future work, considering uncertainties on the LFC system and optimal controller design are suggested.

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