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Optimal Frequency Regulation in AC Mobile Power Grids Exploiting Bilinear Matrix Inequalities

Hamidreza Javanmardi, Maryam Dehghani, *Senior Member, IEEE*, Mohsen Mohammadi, Navid Vafamand, and Tomislav Dragičević, *Senior Member, IEEE*

Abstract—By day-to-day improvement in MicroGrid (MG) control, frequency regulation in the shipboard alternating current (AC) MGs has received much interest in the past decade. The shipboard MGs involve renewable energy sources (RESs) which are unable to produce reliable and constant energy. This important fact vividly demonstrates the requirement of modern frequency regulation techniques. This paper proposes a novel dynamic output feedback controller (DOFC) for load frequency control (LFC) in a sample shipboard MG. The considered AC MG involves fuel cell, gas turbine, and diesel generator as the controllable power generators; photovoltaic array, and sea wave energy converter as the renewable energy sources; and batteries and flywheels as the storage units. The existing approaches almost exploit linearization for solving the problem, which imposes restrictions on the problem and arises conservative constraints resulting in shrinking the solution space. This paper suggests a simple approach that effectively reduces such limitations through the formulation of the sufficient conditions on the controller design in the form of bilinear matrix inequalities (BMIs). These consequences in a less conservative solution compared to the previous methods. To show the merits of the developed approach, OPAL real-time (RT) simulations are executed and the results are compared to the other state-of-the-art-methods which prove the efficacy of the suggested approach. Also, the results of our proposed method (DOFC $n=2$, $n=3$) is compared to the typical H_∞ optimization, μ -synthesis, fuzzy type-1, and intelligent-PI methods. The comparisons between norms of the frequency deviation verify the efficacy of the proposed controller in this paper.

Index Terms— Shipboard AC Micro Grids; Bilinear Matrix Inequality (BMI); Dynamic Output Feedback Control (DOFC); Frequency Regulation.

NOMENCLATURE

BMI	Bilinear Matrix Inequalities
DEG	Diesel Generator

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DOFC	Dynamic Output Feedback Controller
ESS	Energy Storage System
FC	Fuel Cell
GS	Gas Turbine
LMI	Linear matrix inequality
MG	Micro Grid
PV	Photovoltaic
RES	Renewable Energy Sources
RT	Real-Time
S-LFC	Secondary Load Frequency Control
SMG	Shipboard MG
WEC	Wave energy converter

Shipboard AC MG parameter

x, A, B_u, B_w, C	The state vector and the state-space matrices of the system
ΔA	system uncertainty
D	Damping coefficient
M	Inertia constant
Δf	Frequency deviation
T_{GT}, T_{DEG}	Time constant of GT and DEG
T_{FC}, T_{PV}	Time constant of FC and PV
$T_{BES}, T_{FES}, T_{WEC}$	Time constant of BES, FES, WEC
$\Delta P_{GT}, \Delta P_{DEG}$	GT and DEG power change
$\Delta P_{FC}, \Delta P_{PV}$	FC and PV power change
$\Delta P_{BES}, \Delta P_{FES}, \Delta P_{WEC}$	BES, FES, WEC power change
P_{Load}	Load power

CONTROLLER PARAMETER

x_c, A_c, B_c, C_c, D_c	The state vector and the state-space matrices of the controller
n_c	Order of the output feedback dynamics

I. INTRODUCTION

Over the last decades, new directions to integrate energy storage systems (ESSs) and RESs to generate power are governed due to fossil fuel shortage and high price, pollution, and environmental issues [1]–[3]. Unfortunately, RESs cannot produce constant, reliable energy, which leads to power outage or fluctuation, and if it is not compensated, the poor performance of MGs happens. This issue is even more concerning in the case of islanded MGs, such as shipboard AC MGs, than the grid-connected mode. Storage elements (e.g., flywheels, ultra-capacitors, batteries) must be allocated [4] to compensate for fluctuations in power production and result in reliable operation and high-quality of MGs.

In general, since the generated energy from the solar and wind depends on the weather situation, it is not desired to be used for the secondary frequency regulation in the islanded AC-MGs [5], [6]. The diesel engine generators (DEGs) and micro-turbines (MTs) afford power for the load to compensate for the energy fluctuations. Nonetheless, owing to their slow response time, they may fail to completely compensate for the unexpected fast fluctuations in renewable energy power and load. In this regard, for enhancing the overall performance of the frequency regulation mechanism, coordination with ESSs is vital to deal with the fluctuations, rapidly [7]. Matching the generated power with the load demands, characterized as load frequency control (LFC), is a crucial factor to assure the desired operation of practical power grids vulnerable to disturbances and faults.

In the secondary load frequency control (S-LFC), a robust and high-efficient control method restores the AC MG frequency to the set-point. In this branch of the AC MG control, many researches try to enhance the performance of LFC [8]. The challenges and opportunities of the secondary LFC are reviewed in [9]. In [10], a new optimal fuzzy PID control is presented for adaptive control of S-LFC in a small MG. The main idea in that work is based on fusing the fuzzy system with classical controllers. However, the authors did not consider the effects of disturbances which completely affect the model. A new model-free sliding mode controller for the time-delayed islanded modern power grid is introduced in [11], in which, the authors use a new type of nonlinear controller to stabilize the islanded MG with electric vehicle systems. Moreover, in order to have optimal performance, a new modified population-based optimization algorithm is applied to tune the parameters of the proposed nonlinear model-free controller. In [12], a new time-varying fuzzy-PI controller is applied to the secondary frequency regulation on the AC stand-alone MG. The main disadvantage of the suggested intelligent controller is that since renewable energy sources have an inherent uncertain output, the proposed controller is not robust to the fluctuations.

Recently, great attention is devoted to approaches that formulate the S-LFC design through mathematical theories, mostly matrix inequalities [13]–[16]. In [5], [17], matrix inequalities were used to design robust H_∞ controllers. Although the paper formulates the S-LFC problem as an LMI optimization, the approach deals with conservative methods for this transformation. Obviously, conservatism lowers the overall performance by shrinking the design space.

A challenge in the formulation of the S-LFC problem in literature is that the main problem results in Bilinear Matrix

Inequalities (BMI) and there are restricted approaches for dealing with BMIs. To solve BMIs, different approaches are presented including Alternate Minimization (AM) [18], [19], Inner Convex Approximation Method (ICAM) [20] Iterative linear matrix inequalities (ILMIs) [21], [22], two-step process [23], Sequential Parametric Convex Approximation (SPCA) [24], [25], Branch and Bound (BB) [26], path-following methods [27] and Method of Reduction of Variables (MRV) [28]. However, all existing approaches have some drawbacks. The BB approach is only able to compute the unknown terms in vector form, and it is not able to deal with unknown matrix variables. Also, the AM and ILMI methods divide the problem into two separate Linear Matrix Inequalities (LMIs) and solve each separately, which surely do not converge to the unique BMI response, and there has not presented any convergence proof for them. ICAM methods are not applicable to unknown variables with special structure. The approaches SPCA and ICAM depend on a feasible initial condition and its determination is not easy. MRV formulates the problem as an structured BMI and since it is not easy to be solved, it uses heuristic algorithms for finding the optimal solution. Vividly, the approach doesn't result in convex optimization and no convergence proof can be given for the solution. Overall, all the presented approaches are highly conservative and shrink the solution space of the problem. Therefore, it still needs much effort to solve BMIs more effectively and systematically.

This paper considers the S-LFC problem of a shipboard MG (SMG) and solves the problem by a novel approach which is less conservative than the previous approaches. To regulate frequency in the system, the paper considers a nonfragile controller and tries to design the controller suitably. The nonfragile controller problem is truly in the form of a BMI problem similar to problems arising in designing less-complex controllers. Many previous approaches didn't consider its bilinear terms appropriately, even when they want to design simple controllers. This paper considers them completely and writes the BMI constraint in a simpler form through Eigen-value decomposition and change of variables. Then, in 3 different cases, based on the eigenvalues of a matrix in the BMI problem, the feasibility analysis of the BMI constraint is examined. According to these three cases, the overall optimal response is obtained.

The organization of this paper is as follows. In Section II, a brief introduction to isolated MG is presented. In Section III, the stability analysis of the closed-loop system is discussed, and sufficient conditions for designing DOFC are derived in terms of BMIs. In Section IV, a novel approach to solve BMI conditions is proposed. In Section V, simulation of DOFC for the sample shipboard AC MG is given, and comparison results are provided. By comparing the proposed method to other existing ones, the superiority of the suggested approach is highlighted. Finally, some remarking conclusions are presented in Section VI.

II. SHIPBOARD MICROGRID MODEL

The isolated shipboard AC MG, which is shown in Fig. 1 is considered as the system under study in this paper. A practical SMG involves LFC and automatic voltage regulator (AVR) equipment on each of its generators. Small changes in active

(reactive) power are dependent on deviations of frequency (voltage magnitude). Thereby, due to their different sources, the LFC and AVR issues can be analyzed, independently [29]. Based on Fig. 1, the islanded AC MG includes several varying loads and energy storage systems such as flywheel energy storage (FES) and battery energy storage (BES) systems and distributed generators such as wave energy converter (WEC), photovoltaic (PV) cell, fuel cell (FC), diesel generator (DEG), and gas turbine (GT), which their power satisfy

$$P_{Load} = \Delta P_{BES} + \Delta P_{FES} + \Delta P_{WEC} + \Delta P_{PV} + \Delta P_{FC} + \Delta P_{DEG} + \Delta P_{GT} \quad (1)$$

Considering (1) and based on Fig. 2, the model is formulated as the following time-invariant linear space-state equation:

$$\begin{cases} \dot{x}(t) = (A + \Delta A)x(t) + B_u u(t) + B_w w(t) \\ y(t) = Cx(t) \end{cases} \quad (2)$$

In the above model, $x \in \mathbb{R}^n$ is the state variable vector, $y \in \mathbb{R}^{n_y}$ is the measured output, $u \in \mathbb{R}^{n_u}$ is the input and $w \in \mathbb{R}^{n_w}$ is the vector of disturbances of the system, and $x(t)$, $w(t)$, A , B_u , C , and B_w are given in (3) [8], and ΔA represents the system uncertainty.

$$x(t) = \begin{bmatrix} \Delta P_{WEC} \\ \Delta P_{PV} \\ \Delta P_{DEG} \\ \Delta P_{FC} \\ \Delta P_{GT} \\ \Delta P_{BES} \\ \Delta P_{FES} \\ \Delta f \end{bmatrix}, w(t) = \begin{bmatrix} \Delta P_{Wave} \\ \Delta P_{Solar} \\ \Delta P_{Load} \end{bmatrix}, u(t) = \begin{bmatrix} u_{DEG} \\ u_{FC} \\ u_{GT} \end{bmatrix}$$

$$A = \begin{bmatrix} \frac{-1}{T_{WEC}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{-1}{T_{PV}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{T_{DEG}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{T_{FC}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{T_{GM}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{BES}} & 0 & \frac{1}{T_{BES}} \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{FES}} & \frac{1}{T_{FES}} \\ \frac{1}{M} & \frac{1}{M} & \frac{1}{M} & \frac{1}{M} & \frac{1}{M} & \frac{1}{M} & \frac{1}{M} & -\frac{D}{M} \end{bmatrix},$$

$$B_u = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_{DEG}} \\ \frac{1}{T_{FC}} \\ \frac{1}{T_{GT}} \\ 0 \\ 0 \\ 0 \end{bmatrix}, B_w = \begin{bmatrix} \frac{1}{T_{WEC}} & 0 & 0 \\ 0 & \frac{1}{T_{PV}} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{M} \end{bmatrix}, C = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}^T. \quad (3)$$

The SMG frequency is controlled and regulated by the diesel generator (DEG), the gas turbine (GT), and the fuel cell (FC). The battery and the Flywheel are placed to promptly act to fast frequency variations. In addition, the power of photovoltaic (PV) cell, the power of load, and the power of the wave energy converter (WEC) are considered to be time-varying and disturbance-like behavior, i.e., they are considered as disturbance inputs. The values of the SMG parameters are given in Table I.

Fig. 1. Scheme of shipboard AC MG.

controller such that it can be implemented in practice. By using the system equations (2) and controller (4), the closed-loop system equations can be represented by the following model:

$$\begin{cases} \dot{x}_{cl} = (\bar{A} + \Delta\bar{A})x_{cl} + \bar{B}w \\ z = \bar{C}x_{cl} \end{cases}, x_{cl} = \begin{bmatrix} x \\ x_c \end{bmatrix} \in \mathbb{R}^{n+n_c} \quad (5)$$

Where

$$\begin{aligned} \bar{A} &= \begin{bmatrix} A & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 0 & B_u \\ I & 0 \end{bmatrix} \begin{bmatrix} A_c & B_c \\ C_c & D_c \end{bmatrix} \begin{bmatrix} 0 & I \\ C & 0 \end{bmatrix} = \bar{A}_c + \bar{A}_l G_c \bar{A}_r \\ \Delta\bar{A} &= \begin{bmatrix} \Delta A & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 0 & B_u \\ I & 0 \end{bmatrix} \begin{bmatrix} \Delta A_c & \Delta B_c \\ \Delta C & \Delta D \end{bmatrix} \begin{bmatrix} 0 & I \\ C & 0 \end{bmatrix} \\ \bar{B} &= \begin{bmatrix} B_w \\ 0 \end{bmatrix}, \bar{C} = [C \quad 0] \end{aligned} \quad (6)$$

where $G_c = \begin{bmatrix} A_c & B_c \\ C_c & D_c \end{bmatrix}$ contains the unknown controller dynamics, which should be found in the design procedure, while the

other matrices depend on the MG model. For simplicity, assume that $\Delta A = B_u \Delta A_1 C$, where ΔA_1 is a new uncertainty system.

Therefore (6) can be written as,

$$\Delta\bar{A} = \begin{bmatrix} 0 & B_u \\ I & 0 \end{bmatrix} \left(\begin{bmatrix} 0 & 0 \\ 0 & \Delta A_1 \end{bmatrix} + \begin{bmatrix} \Delta A_c & \Delta B_c \\ \Delta C & \Delta D \end{bmatrix} \right) \begin{bmatrix} 0 & I \\ C & 0 \end{bmatrix} = \bar{A}_l \Delta_G \bar{A}_r \quad (7)$$

B. Controller design procedure

In this sub-section, the robust H_∞ control for the LFC system (2)-(3) with the non-fragile DOFC (4) is designed. The goal is to find a controller G_c such that the closed-loop system (5) is robustly stable, and also the ∞ -norm from disturbance input w to controlled output z is smaller than a specified positive number γ , (i.e. $\|T_{wz}\|_\infty < \gamma$) [30]. Fig. 3 shows the closed-loop system for the H_∞ synthesis. In order to achieve this goal, it is necessary to satisfy the following inequality:

$$\dot{V} + \gamma^{-1} z^T z - \gamma w^T w < 0 \quad (8)$$

where V is the Lyapunov candidate. Considering a quadratic Lyapunov function $V = x_{cl}^T P x_{cl}$ and substituting its time derivative along with the dynamics (5) and the uncertainty structure (7) into (8) results in:

$$x_{cl}^T \{ (\bar{A} + \bar{A}_l \Delta_G \bar{A}_r)^T P + P(\bar{A} + \bar{A}_l \Delta_G \bar{A}_r) + \gamma^{-1} \bar{C}^T \bar{C} \} x_{cl} + x_{cl}^T P \bar{B} w + w^T \bar{B}^T P x_{cl} - \gamma w^T w < 0 \quad (9)$$

Assuming that the uncertainty term is bounded as $\Delta_G^T \Delta_G < R$ and using Lemma 2 of [31] on (9), provide:

$$\begin{aligned} & x_{cl}^T \{ \bar{A}^T P + P \bar{A} + \varepsilon^{-1} P \bar{A}_l \bar{A}_l^T P + \varepsilon \bar{A}_r^T R \bar{A}_r + \gamma^{-1} \bar{C}^T \bar{C} \} x_{cl} + x_{cl}^T P \bar{B} w + w^T \bar{B}^T P x_{cl} - \gamma w^T w \\ &= \begin{bmatrix} x_{cl} \\ w \end{bmatrix}^T \begin{bmatrix} \bar{A}^T P + P \bar{A} + \varepsilon^{-1} P \bar{A}_l \bar{A}_l^T P + \varepsilon \bar{A}_r^T R \bar{A}_r + \gamma^{-1} \bar{C}^T \bar{C} & P \bar{B} \\ \bar{B}^T P & -\gamma I \end{bmatrix} \begin{bmatrix} x_{cl} \\ w \end{bmatrix} < 0 \end{aligned} \quad (10)$$

Fig. 3. H_∞ standard configuration.

Applying Schur complement on (10), one has

$$\begin{bmatrix} \bar{A}^T P + P \bar{A} + \varepsilon \bar{A}_r^T R \bar{A}_r & P \bar{B} & \bar{C}^T & P \bar{A}_l \\ \bar{B}^T P & -\gamma I & 0 & 0 \\ \bar{C} & 0 & -\gamma I & 0 \\ \bar{A}_l^T P & 0 & 0 & \varepsilon I \end{bmatrix} < 0 \quad (11)$$

Since the goal is to minimize the H_∞ threshold γ , the following optimization problem with BMI constraints is obtained:

$$\min_{G_c, \gamma, Y} \gamma \quad (12)$$

Subject to (11) and $P^T = P > 0$.

To solve the problem (12), it is needed to find a positive definite matrix P such that (11) is satisfied. As it can be seen in term $\bar{A}^T P + P \bar{A} + \varepsilon \bar{A}_r^T R \bar{A}_r$, two unknown variables P and $\bar{A}$ are multiplied together. Therefore, the optimization problem is in the form of a BMI. Additionally, the unknown matrices P and G_c do not appear successively and it is seen in the second term that matrix $\bar{A}_l$ is multiplied in the middle. All of these make challenges in solving the above BMI.

IV. PROPOSED BMI SOLVER APPROACH

As can be seen, the DOFC design for the AC-MG system is in the form of a BMI problem. In this section, a systematic approach for solving the above BMI is presented.

Consider the BMI problem as follows:

$$BMI(\alpha, \beta) \leq 0 \quad (13)$$

where

$$BMI(\alpha, \beta) = \alpha^T F \beta + \beta^T F \alpha + H^T \alpha + M^T \beta + f \quad (14)$$

In (14), $F \in \mathbb{R}^{m \times m}$ is a symmetric matrix, H, M, f are appropriate constant matrices and $\alpha, \beta \in \mathbb{R}^{m \times 1}$ are unknown vectors.

For solving BMI problem (13), first, this constraint is written as follows:

$$BMI(\alpha, \beta) = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}^T \underbrace{\begin{bmatrix} 0 & F \\ F & 0 \end{bmatrix}}_{\mathcal{W}} \underbrace{\begin{bmatrix} \alpha \\ \beta \end{bmatrix}}_{\mathcal{Z}} + \underbrace{\begin{bmatrix} H^T & H^T \end{bmatrix}}_{\mathcal{N}^T} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} + f = Z^T \mathcal{W} Z + \mathcal{N}^T Z + f \quad (15)$$

As can be seen, eigenvalues of matrix $\mathcal{W}$ depend on the matrix F . So, $\mathcal{W}$ generally is an indefinite symmetric matrix. Based on Eigen-value decomposition of the symmetric matrix $\mathcal{W}$, one has:

$$\mathcal{W} = T \Lambda T^{-1} \quad (16)$$

In (16), $T \in \mathbb{R}^{m \times m}$ is the orthonormal matrix where i -th column of T is the eigenvector t_i of $\mathcal{W}$, and $\Lambda = \begin{bmatrix} [a_i] & 0 \\ 0 & [-b_i] \end{bmatrix}$ is the diagonal matrix which $a_i, -b_i$ are the corresponding eigenvalues of $\mathcal{W}$, where a_i, b_i are non-negative real numbers. By defining a new variable $\begin{bmatrix} X \\ Y \end{bmatrix} = T^{-1}Z$, the BMI constraint (15) can be written as follows:

$$\begin{bmatrix} X & Y \end{bmatrix}^T \Lambda \begin{bmatrix} X \\ Y \end{bmatrix} + \mathcal{N}^T T \begin{bmatrix} X \\ Y \end{bmatrix} + f = \sum_{i=1}^{N_p} a_i x_i^2 - \sum_{j=1}^{N_n} b_j y_j^2 + \sum_{i=1}^{N_p} c_i x_i + \sum_{j=1}^{N_n} d_j y_j + f < 0 \quad (17)$$

where $X = [x_1 \ \dots \ x_{N_p}]^T, Y = [y_1 \ \dots \ y_{N_n}]^T$, N_p, N_n are the number of positive and negative eigenvalues of matrix $\mathcal{W}$, respectively. To solve the problem (15), according to the eigenvalues of matrix $\mathcal{W}$, the following 3 cases are considered:

Case 1: All eigenvalues of the matrix $\mathcal{W}$ are positive (all $a_i \neq 0, b_j = 0$): In this case, problem (15) is a convex function which can be rewritten as follows:

$$\sum_{i=1}^{N_p} a_i x_i^2 + \sum_{i=1}^{N_p} c_i x_i + \sum_{j=1}^{N_n} d_j y_j + f < 0 \quad (18)$$

By considering $y_j = \varepsilon d_j$, one has:

$$\sum_{i=1}^{N_p} a_i x_i^2 + \sum_{i=1}^{N_p} c_i x_i + \sum_{j=1}^{N_n} \varepsilon d_j^2 + f < 0 \quad (19)$$

The minimum value of the function $f(x) = \sum_{i=1}^{N_p} a_i x_i^2 + \sum_{i=1}^{N_p} c_i x_i$ in (19) occurs at the point $x_i = \frac{c_i}{-2a_i}$. Therefore, consider the following inequality instead of inequality (19):

$$\varepsilon \sum_{j=1}^{N_n} d_j^2 < \sum_{i=1}^{N_p} \frac{c_i^2}{4a_i} - f \quad (20)$$

Finally, by selecting $\varepsilon < \frac{\left(\sum_{i=1}^{N_p} \frac{c_i^2}{4a_i} - f\right)}{\sum_{j=1}^{N_n} d_j^2}$, the following vector is an answer to the problem (15).

$$Z = T \begin{bmatrix} -\frac{c_1}{2a_1} & \dots & -\frac{c_{N_p}}{2a_{N_p}} & \varepsilon d_1 & \dots & \varepsilon d_{N_n} \end{bmatrix}^T \quad (21)$$

Case 2: All eigenvalues of the matrix $\mathcal{W}$ are negative (all $a_i = 0, b_j \neq 0$): In this case, problem (15) is reformulated as follows:

$$\sum_{i=1}^{N_p} c_i x_i < \sum_{j=1}^{N_n} b_j y_j^2 - \sum_{j=1}^{N_n} d_j y_j - f \quad (22)$$

The minimum value of the function $f(x) = \sum_{j=1}^{N_n} b_j y_j^2 - \sum_{j=1}^{N_n} d_j y_j$ in (22) occurs at the point $y_j = \frac{d_j}{2b_j}$. Therefore, according

to (22), the following equation is always valid:

$$\sum_{i=1}^{N_p} c_i x_i < - \sum_{j=1}^{N_n} \frac{d_j^2}{4b_j} - f \quad (23)$$

By considering $x_i' = \begin{cases} c_i x_i & c_i \neq 0 \\ 0 & c_i = 0 \end{cases}$ and $f' = - \sum_{j=1}^{N_n} \frac{d_j^2}{4b_j} - f$, equation (23) can be rewritten as follows:

$$\|x'\|_1 < f' \quad (24)$$

where $\|x'\|_1$ denotes the H_1 norm of vector x' .

Finally, by solving (24), the following vector is an answer to the problem (15):

$$Z = T \begin{bmatrix} x'_1 & \dots & x'_{N_p} & \frac{d_1}{2b_1} & \dots & \frac{d_{N_n}}{2b_{N_n}} \end{bmatrix}^T \quad (25)$$

Case 3: $\mathcal{W}$ is an indefinite matrix and has both negative and positive eigenvalues (at least one of the a_i and one of the b_j are non-zero): In this case, it is assumed that $a_i \geq 0$ and $b_j > 0$. At first, (15) is rewritten as follows:

$$\sum_{i=1}^{N_p} a_i x_i^2 + \sum_{i=1}^{N_p} c_i x_i < \sum_{j=1}^{N_n} b_j y_j^2 - \sum_{j=1}^{N_n} d_j y_j - f \quad (26)$$

Similar to case 1, assuming a constant x_i as $\bar{x}_i = \begin{cases} \frac{c_i}{-2a_i} & a_i \neq 0 \\ 0 & a_i = 0 \end{cases}$, inequality (26) becomes as (27):

$$\sum_{i=1}^{N_p} a_i \bar{x}_i^2 + \sum_{i=1}^{N_p} c_i \bar{x}_i < \sum_{j=1}^{N_n} b_j y_j^2 - \sum_{j=1}^{N_n} d_j y_j - f \quad (27)$$

So:

$$\sum_{j=1}^{N_n} b_j \left(y_j - \frac{d_j}{2b_j} \right)^2 > f - \sum_{i=1}^{N_p} a_i \bar{x}_i^2 - \sum_{i=1}^{N_p} c_i \bar{x}_i - \sum_{j=1}^{N_n} \frac{d_j^2}{4b_j} \quad (28)$$

By considering $y_j' = \sqrt{b_j} y_j - \frac{d_j}{2\sqrt{b_j}}$ and $f' = f - \sum_{i=1}^{N_p} a_i \bar{x}_i^2 - \sum_{i=1}^{N_p} c_i \bar{x}_i - \sum_{j=1}^{N_n} \frac{d_j^2}{4b_j}$, (28) can be rewritten as follows:

$$\|y'\|_2^2 > f' \quad (29)$$

where $\|y'\|_2$ denotes the H_2 norm of vector y' . Finally, by solving (29), the following vector is an answer to the problem (15):

$$Z = T \begin{bmatrix} \bar{x}_1 & \dots & \bar{x}_{N_p} & \frac{y'_1}{\sqrt{b_1}} + \frac{d_1}{2b_1} & \dots & \frac{y'_{N_n}}{\sqrt{b_{N_n}}} + \frac{d_{N_n}}{2b_{N_n}} \end{bmatrix}^T \quad (30)$$

Remark 1: If at least one of the eigenvalues of the matrix $\mathcal{W}$ is negative, then there is definitely a feasible solution.

Remark 2 (advantages of the proposed approach): The developed BMI-based H_∞ dynamic controller has the following superiorities over the state-of-the-art methods considering the same issue:

1. Comparing with LMI-based approaches [3], the proposed BMI-based controller design leads to less conservative results. This means that the closed-loop S-LFC system is more robust against the variations of the RES and load power.
2. The conventional μ -synthesis and H_∞ control methods [6] mandate a very high order of the controller. For instance, in [6], the order of the designed controller is 10. Thereby, the computation burden of those approaches is high. On the other hand, the proposed dynamic controller not only has a smaller order than [6] but also provides better closed-loop performance.
3. In comparison with online-tuning-based methods [32], [33], and nonlinear control law with a high implementation burden, the developed approach offers an offline design procedure. Thereby, its implementation is cost-effective.

The abovementioned advantages make the proposed approach a suitable alternative for the existing LFC techniques.

The proposed algorithm for designing non-fragile DOFC for the problem (12) is summarized in Fig. 4.

V. SIMULATION RESULTS

In this section, the sample MG in Fig. 2 with the information given in Table I is simulated. Four scenarios are considered to show the advantages of the proposed controller over existing results and its performance against uncertainties, load power high variation and generator disconnection. By applying the proposed BMI algorithm, the control gain matrices for the DOFC are given in Table II.

A. Scenario 1 (Comparative results)

In this scenario, the non-fragile DOFC is applied to the AC MG problem and the performance of the proposed approach to minimize the effects of the external wind speed, solar radiation, and load demand variations on the frequency of the AC MG and the results are compared to the intelligent-PI [33], typical H_∞ optimization [5], fuzzy type-1 [32] and μ -synthesis [5]. Moreover, the power fluctuations ΔP_{Load} , ΔP_{wave} , and ΔP_{Solar} are shown in Fig. 5. The proposed approach approximately results in a constant frequency pattern, while the others demonstrate some fluctuations.

Fig. 6 illustrates the frequency response of the closed-loop LFC problem, by the robust H_∞ based DOFC via BMI, typical H_∞ optimization, μ -synthesis, fuzzy type-1, and intelligent-PI methods. As can be seen in Fig. 6, the proposed approach is more robust against power fluctuations of the RESs compared to state-of-the-art techniques.

Fig. 4. The proposed algorithm for designing non-fragile DOFC.

TABLE II
Controller matrices for DOFC

Ord.	1	2	3
A_c	$[-6.450]$	$\begin{bmatrix} -5.554 & -0.781 \\ -2.849 & -5.339 \end{bmatrix}$	$\begin{bmatrix} -3.197 & -1.622 & -3.075 \\ -0.869 & -2.453 & -2.229 \\ -0.492 & -2.297 & -4.609 \end{bmatrix}$
B_c	$[-71.306]$	$\begin{bmatrix} -43.764 \\ -59.274 \end{bmatrix}$	$\begin{bmatrix} -45.122 \\ -32.484 \\ -48.411 \end{bmatrix}$
C_c	$[-8.225]$	$[-5.987 \quad -6.989]$	$[-4.521 \quad -4.012 \quad -6.780]$
D_c	-121.45	-159.395	-153.100

Fig. 5: Fluctuations in the load, wave converter, and PV powers [5].

The proposed approach approximately results in a constant frequency pattern, while the others demonstrate some

fluctuations. Additionally, according to the results presented in Table III, it can be seen that the L_2 and L_∞ norms of the proposed method are smaller compared to other controllers' results, which means the disturbances have fewer effects on the suggested approach.

The controller input signals of considered approaches are shown in Fig. 7.

Fig. 6. Frequency response using different control approaches: (a) intelligent-PI [33], (b) fuzzy type-I [32], (c) μ -approach [5], (d) H_∞ approach [5], (e) Non-fragile DOFC for $n_c = 2$.

Fig. 7. Controller Signal of different control approaches: (a) intelligent-PI [33], (b) fuzzy type-I [32], (c) μ -approach [5], (d) H_∞ approach [5], (e) Non-fragile DOFC for $n_c=2$.

Fig. 7 reveals that the proposed controller, μ -synthesis [5] and typical H_∞ optimization [5] approaches act faster when the

SMG frequency experiences fluctuations. Thus, the closed-loop frequency response of these approaches outperforms the intelligent-PI [33], and fuzzy type-1 [32]. To the contrary, the maximum amplitude control input of the approaches DOFC, μ -synthesis, and H_∞ are almost the same as the intelligent-PI [33], and fuzzy type-1 [32].

TABLE III
NORM 2 AND ∞ FOR DIFFERENT APPROACHES.

Approach	$\ \Delta f\ _2$	$\ \Delta f\ _\infty$
DOFC $n_c = 2$	0.2781	0.0107
DOFC $n_c = 3$	0.2847	0.0103
μ -synthesis	1.7992	0.0820
H_∞	0.7491	0.0345
PI	4.0016	0.1488
Fuzzy type-I	1.1650	0.0964

B. Scenario 2 (generator disconnection)

It is assumed that each of the generators is disconnected for some interval based on the following profile:

$$\begin{cases} 0 \leq t < 150 & : \text{All generators are connected} \\ 150 \leq t < 250 & : \text{DEG is disconnected} \\ 250 \leq t < 350 & : \text{FC is disconnected} \\ 350 \leq t < 450 & : \text{GT is disconnected} \end{cases} \quad (31)$$

From (31), one can see that for the time interval $0 \leq t \leq 150$ seconds, all generators are connected to the system and it operates, normally. On the other hand, in the interval $150 \leq t \leq 450$ seconds, each of the generators is disconnected for 100 seconds. The designed controller with $n_c = 2$ is utilized in this scenario. Fig. 8(a)–(c) show the load power variation, frequency variation, and control input for this case compared to the nominal system. As can be seen in Fig. 8(b), the frequency deviation whenever DEG is disconnected is higher than the other situations and, the results of the cases in which the FC or the GT are disconnected are almost the same.

Fig. 8. The results of Scenario 2: (a) load power variation, (b) frequency deviation, and (c) control input.

C. Scenario 3 (large load power deviation)

Different stepwise changes in the power load are considered and the proposed controller with $n_c = 2$ is applied to keep the frequency deviation as small as possible. The load power changes in a pulsing and ascending manner as shown in Fig. 9(a). Also, Figs. 9(b) and (c) show the frequency variation and control input for this load profile. As can be seen, by increasing the amplitude of the load power variation, the frequency deviates further. For the worst case of sudden 1 (pu) change in the load power, the frequency changes about 0.18 (Hz). This shows that the controller regulates the frequency even for the large changes in the load power.

Fig. 9. The results of Scenario 3: (a) load power variation, (b) frequency deviation, and (c) control input.

D. Scenario 4 (Parameter uncertainties)

To evaluate the robustness of the proposed controller against the system parameter uncertainties and variations, six uncertain parameters are involved, as shown in Table IV. According to Table IV, the robustness of the proposed control scheme against the system uncertainties is evaluated by applying a variation of the parameters and the results are provided in Fig. 10(a) and (b).

TABLE IV
UNCERTAIN PARAMETERS OF THE MG SYSTEM

Parameters	Variation Range	Parameters	Variation Range
D	-50%	T_{BES}	+50%
M	+50%	T_{WEC}	-50%
T_{DEG}	-25%	T_{PV}	+50%

(c) (d)

Fig. 10. The results of Scenario 4: (a) frequency deviation of uncertain system, (b) frequency deviation of nominal system, (c) control input of uncertain system, and (d) control input of nominal system.

Further, the L_2 and L_∞ norms of the proposed method in this case are given in Table V.

TABLE V
NORM 2 AND ∞ FOR SCENARIO 4.

Approach	$\ \Delta f\ _2$	$\ \Delta f\ _\infty$
Nominal sys.	0.2781	0.0107
Uncertain sys.	0.2870	0.0127

VI. CONCLUSION

In this paper, a BMI-based dynamic output feedback controller approach was presented for load frequency regulation of an AC-MG. The DOFC for the AC-MG system has been formulated as a BMI, which is robust against fluctuations in the load, wind turbine, and PV powers. A novel method was proposed to reduce the conservative conditions for solving the BMI problem. The main feature of the proposed method was that it could decompose the original BMI to a BMI problem and an LMI problem, and then it reduces the dimension and complexity of the iterative algorithm. The results illustrated that the proposed method improves the performance of the frequency response against existing controllers such as H_∞ , μ , fuzzy type-1, and intelligent-PI methods, based on the norms 2 and ∞ indices. These performance improvements increase the lifetime of the batteries and flywheels by reducing their charging/discharging actions. Also, the effects of uncertainty and generator disconnection on the closed-loop system are evaluated. It means that the controller is easily implemented, and the proposed approach can be used in practice. In future work, a data driven, model free method for load frequency control (LFC) is suggested. Additionally, some issues such as time-delay, faults and short circuit should be involved to make the proposed approach more reliable.

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