Dynamic Power Tracking Performance and Stability Analysis of Integrated Wind-to-Hydrogen System

Han Mu\textsuperscript{1}, Dongsheng Yang\textsuperscript{1}, Yin Sun\textsuperscript{1}, and Lucia Beloqui Larumb\textsuperscript{1}

\textsuperscript{1}Affiliation not available

March 29, 2024
Dynamic Power Tracking Performance and Stability Analysis of Integrated Wind-to-Hydrogen System

Han Mu, Student Member, IEEE, Dongsheng Yang, Senior Member, IEEE, Yin Sun, Member, IEEE, Lucia Beloqui Larumb, Member, IEEE,

Abstract—To achieve the 2050 global climate target, offshore wind will increase to meet the growing demand of the direct and indirect electrification (e.g. green hydrogen production for the hard-to-abate sector). To keep up with the rapid increase of offshore wind generation, the energy balancing challenges due to the intermittency nature of wind and the network congestion/capacity challenges resulting from structural network capacity planning latency are to be addressed with the system integration technology. In this paper, it is proposed that the hydrogen electrolysis plant be co-located with the wind farm, of which the power consumption is controlled to track the wind generation profile accurately to cancel the intermittency wind generation, and reduce the required grid connection capacity, and thereby avoid the expensive grid expansion. However, this power tracking control introduces a cross-plant feedback path from the wind farm to the hydrogen plant, posing challenges for system partitioning in stability analysis, which also makes it difficult to design the power tracking control with a good trade-off between the tracking performance and stability margins. To address this issue, this paper proposes an equivalent transformation to eliminate the cross-plant feedback path. Then, the dynamic power stability analysis with different partition methods is examined, which are mathematically proven to be equivalent in terms of stability conditions, but provide different insights. An optimal partition method is then proposed in this paper, which not only provides clear insight on the ideal and non-ideal power tracking performances but also can also identify the stability issues of different minor loops individually. Finally, the proposed optimal partition method and its valuable insights into power tracking performance and stability analysis are validated through time-domain simulations of a 180 MW integrated wind-to-hydrogen plant with a realistic complexity.

Index Terms—wind-to-hydrogen system, cross-plant feedback, power tracking performance, dynamic power stability, frequency coupling dynamics, black-box modeling

I. INTRODUCTION

CLIMATE change is an urgent global issue, so there is an increasing need for sustainable and renewable energy sources[1], [2]. In particular, large-scale offshore wind farms offer the scale of economy to supply the load center near the coast[3], [4], [5]. However, one of the challenges that limit the growth of wind energy is its intermittency and the system’s impact on energy balancing. The increased proportion of intermittent renewable energy sources in the power grid has introduced great challenges to the security, stability, and power quality of the power system [6], [7], [8]. Hydrogen electrolysis plants [9] are widely seen as crucial technologies to offer pathways for the hard-to-abate sector (e.g. cement, steel) where direct electrification is not viable. Additionally, hydrogen electrolysis plants can potentially offer power consumption flexibility. When co-located with wind power generation, the hydrogen plant can be controlled as a flexible load by adjusting its power consumption [10], which can transform the fluctuated renewable electricity into hydrogen on a large scale [11], [12], [13]. This, in turn, can provide not only temporal energy output (i.e. energy balancing) but also spatial power flow (i.e. congestion management) flexibility for the power system.

To operate the hydrogen plant as a flexible load, the power tracking controller is used to actively regulate the power consumption of the hydrogen plant to track the real-time power output of a wind farm [14]. Fast power tracking control with high control bandwidth allows real-time power matching between the hydrogen plant and the wind farm to ensure green hydrogen produced meets the EU RED II additionally and temporal correlation requirement now and in the future [15]. Thus a tight power matching controller avoids “contamination” of grey electricity imported from the power grid. This can significantly reduce the required AC grid capacity and thus avoid very expensive grid expansion [16]. However, increasing the power tracking control bandwidth may destabilize the system. Therefore, it’s crucial to reveal the stability impact of the power tracking control explicitly to make a good trade-off between power tracking performance and system stability.

A significant hurdle in conducting stability analysis for integrated wind-hydrogen systems lies in the presence of a cross-plant feedback path from the wind farm to the hydrogen power plant. This introduces additional coupling among the different sub-systems, impeding the partitioning of the system for stability analysis and hindering the further power tracking performance analysis as well.

Several partition methods have been proposed over the past decades for system-level stability analysis. One of the typical solutions is to partition the entire system into two parts at a single point of connection (PoC) and represent the partitioned two subsystems with the impedance or admittance models [17], [18]. The paper [19] focuses on the dynamic interactions between the MMC-HVDC and the offshore wind farm based on the complete impedance model of the wind turbine. Recent research efforts [20], [21] have been applied to investigate the stability of offshore wind farms connected to HVDC by developing a detailed impedance model. Partitioning the system at the single PoC can only reveal the dynamic interaction between the wind farm and the rest of the system, while it is difficult to reveal the internal stability of the subsystem.

Besides the partition method at a single PoC, the system
can be partitioned at multiple PoCs simultaneously to obtain a global view of the system dynamics. In papers [22], [23], the multi-input multi-output (MIMO) transfer function matrix is used to reflect the MIMO interfaces between the converters and the passive network, and then the small signal stability boundary of PLL (phase-locked loop) parameters is derived. [24] applies the single input single output (SISO) Nyquist stability criterion (NSC) and the participation factor analysis to the MIMO open loop impedance matrix at the system level to provide a global view of oscillation modes, the root cause of oscillations, and insight into the most effective damping control.

Although the aforementioned partition methods can reveal the impact of subsystems on system stability from various perspectives, they could not be directly applied to the wind-to-hydrogen system due to the cross-plant feedback introduced by power tracking control. This paper fills this gap by proposing an optimal partition method that distinctly identifies the stability issues stemming from the power-tracking loop and different system-level interactions individually and enables the power-tracking control design to achieve a good trade-off between power-tracking performance and system stability.

The rest of this article is organized as follows: In Section II, the equivalent representation of the power tracking controller and system-level block diagram is given. Based on this, three different partition methods are analyzed and compared in Section III. Then an optimal partition method is proposed in Section IV together with its insight into the hydrogen plant tracking performance and system stability. In Section V, simulation validation is carried out on a 180 MW wind-to-hydrogen system. Finally, Section VI concludes this article.

II. SYSTEM REPRESENTATION

A. System Description

Fig. 1 shows the simplified circuit diagram of the integrated wind-to-hydrogen power system. It consists of three key subsystems: the offshore wind farm, the hydrogen electrolysis plant, the power-tracking controller, and the AC grid. The offshore wind farm connects to the AC grid via a high-voltage AC link (HVAC) at the PCC, and the injected active and reactive power is denoted as $P_{wf}$ and $Q_{wf}$. The hydrogen plant, employing thyristor rectifier-controlled electrolyzers, absorbs powers $P_{h2}$ and $Q_{h2}$ from the PCC and converts them into hydrogen. The power-tracking controller uses the active power of the wind farm $P_{wf}$ as a reference to regulate the DC current reference $I_{dc}^*$ of thyristor rectifiers, thus to further adjust the power consumption of hydrogen plant $P_{h2}$, aiming to reduce the required grid capacity, i.e., $P_g$ and $Q_g$.

B. Selection of Small-signal Modeling Method

To reveal the power dynamics of the system directly, the analysis will be based on amplitude-phase models [25] rather than the traditional impedance model. The major reasons are as follows:

Firstly, the stability analysis is mainly focused on the power dynamics. As Fig. 1 shows, this power dynamics is mainly introduced by the power tracking controller, which dynamically matches the power consumption of the hydrogen plant with the generated power of the wind farm. Fast power tracking dynamics help reduce the grid capacity but will deteriorate the system’s stability, and the models should be able to reveal this trade-off directly.

Secondly, the power dynamics are quite different from the voltage and current dynamics, especially the frequency coupling effects induced by asymmetrical outer control loops [26]. Assume there is an oscillation in the system, and the voltage oscillations in the $dq$ frame $v_d$ and $v_q$ would be asymmetrical, which means that its complex vector $V_{dq}$ will contain both positive sequence and negative sequence components that can be denoted as

$$V_{dq} = v_d + jv_q = v_0 + v_+ e^{j\omega_h t} + v_- e^{-j\omega_h t}$$

where $v_0$, $v_+$, $v_-$ are the magnitude of DC, positive sequence, and negative sequence of voltage, respectively. $\omega_h$ is the oscillation frequency. Similarly, the complex vector of current oscillation $I_{dq}$ can be denoted as

$$I_{dq} = i_d + ji_q = i_0 + i_+ e^{j\omega_h t} + i_- e^{-j\omega_h t}$$

where $i_0$, $i_+$, $i_-$ are the magnitude of DC, positive sequence, and negative sequence of current, respectively. Therefore, the instantaneous active and reactive power components can be calculated in (3).

Remarkably, the frequency coupling of power dynamics couples the oscillations at $\omega_h$ and $2\omega_h$, while the well-known frequency coupling of current and voltage dynamics couples oscillations at $\omega_h$ and $2\omega_h - \omega_h$ [26], where $\omega_1$ is the fundamental frequency of the AC grid. Therefore, it is desirable to choose the amplitude-phase (AP) modeling method [25], [27], [28] to capture the system power dynamics directly.

$$P + jQ = (v_d + jv_q) \cdot (i_d + ji_q)^* = \frac{v_0 i_0 + v_+ i_+ + i_- v_-}{DC} + \left(\frac{v_0 i_0 + v_+ i_0 + v_- i_-}{DC}\right) e^{-j\omega_h t} + \left(\frac{v_0 i_0 + i_0 v_- + (v_+ i_0 + v_0 i_-) e^{j\omega_h t}}{DC}\right) + v_+ i_- e^{2\omega_h t} + i_+ v_- e^{-2\omega_h t}$$

Thirdly, the amplitude-phase model can also be easily measured in a black-box way similar to the impedance model. Depending on the controlled variables, there are two types of small-signal AP models [25]. Fig. 2 (a) shows the AP
model of the voltage-controlled subsystem, where the output variable is the small-signal voltage with amplitude \( \Delta U \) and phase angle \( \Delta \theta \), also denoted as the vector \( \Delta \vec{V} \). This voltage is determined by an independent voltage source \( \Delta V_s \) (\( \Delta U_s \) and \( \Delta \theta_s \)) together with the influence from the input power \( \Delta \vec{S} \) (\( \Delta P \) and \( \Delta Q \)) through the AP model \( \mathbf{Z}(s) \), i.e.,
\[
\Delta \vec{V} = \mathbf{Z}(s) \Delta \vec{S} + \Delta \vec{V}_s.
\]

For convenience, this model is referred to as the voltage-controlled amplitude phase (VAP) model in this paper.

Similarly, Fig. 2 (b) shows the AP model of the power-controlled subsystem, where the output variable is power \( \Delta \vec{S} \) (\( \Delta P \) and \( \Delta Q \)). This power is determined by an independent power source \( \Delta \vec{S}_s \) (\( \Delta P_s \) and \( \Delta Q_s \)) together with the influence from the input voltage source \( \Delta \vec{V} \) (\( \Delta U \) and \( \Delta \theta \)) through the AP model \( \mathbf{Y}(s) \), i.e.,
\[
\Delta \vec{S} = \mathbf{Y}(s) \Delta \vec{V} + \Delta \vec{S}_s.
\]

For convenience, this model is referred to as the power-controlled amplitude phase (PAP) model.

C. Amplitude-phase Model of the System

Based on the circuit diagram in Fig. 1, its corresponding AP model is derived in Fig. 3(a), where the wind farm and hydrogen plant are linearized as small-signal PAP models \( \mathbf{Y}_w(s) \) and \( \mathbf{Y}_h(s) \), and the AC grid is represented as VAP model \( \mathbf{Z}_g(s) \). The minus sign of \( \mathbf{Y}_w(s) \) in Fig. 3(a) is intentionally introduced to reflect the non-associated reference directions of power flow defined for the wind farm. It is assumed that the power of the wind farm and hydrogen plant can be controlled stably under ideal grid conditions, thus there will be no right-half-plane (RHP) poles in \( \mathbf{Y}_w(s) \) and \( \mathbf{Y}_h(s) \) [24]. Moreover, it is also expected that AC grid voltage is stable at PCC when the wind farm and hydrogen plant are disconnected, thus, there are no RHP poles in \( \mathbf{Z}_g(s) \), either.

The power tracking controller uses the active power of the wind farm \( \Delta P_w \) as the reference and the power consumption of the hydrogen plant \( \Delta P_h \) as the feedback. Then the output of \( G_{PT}(s) \) further regulates the internal DC current reference \( I_{dc}^* \) of the hydrogen electrolyzers within the hydrogen plant to ensure that \( \Delta P_h \) can closely track \( \Delta P_w \). The transfer functions between the DC current reference \( I_{dc} \) and hydrogen active and reactive powers \( \Delta P_{h,dc} \), \( \Delta Q_{h,dc} \) are represented by \( G_{PT,dc}(s) \) and \( G_{PT,eq}(s) \), respectively.

D. Equivalent Transformation of System Block Diagram

Fig. 3 (a) shows that the power tracking control introduces cross-plant feedback, which brings significant obstacles for stability and power tracking performance analysis. Thus, an equivalent block diagram transformation of the power tracking control will be implemented, with the aim of removing the cross-couplings of power tracking control away from wind farm and hydrogen plant. To simplify the expression of the transfer function, \( s \) is omitted in the following analysis.

The equivalent transformation mainly contains three steps:
1) Moving the point of the power feedback signal from \( \Delta P_h \) to \( \Delta P_{h,dc} \):
2) Moving the point of the power reference signal from \( \Delta P_w \) to PCC voltage variables \( \Delta \theta \) and \( \Delta U \); 3) Moving the point of input signal of \( G_{PT,eq}(s) \) from DC current reference signal \( I_{dc}^* \) to \( \Delta P_{h,eq} \).

(1) Moving the Point of Power Feedback Signal
The original feedback signal \( \Delta P_h \) can be expressed as
\[
\Delta P_h = \Delta P_{h,dc} + \Delta P_{h,eq}
\]
Therefore, when moving the point of the feedback signal...
from $\Delta P_h$ to $\Delta P_{s,h}$, the missing part of the feedback signal $\Delta P_{h}'$ should be added back, as the dashed line is shown in Fig. 3 (b). This additional feedback signal will first pass through the dashed line, then $G_{PT}$, and $G_{PT-p}$, $G_{PT-q}$, and are finally added to the outputs of hydrogen plant $\mathbf{Y}_h$.

These additional signal paths can be simplified as $G_{h1}$ and $G_{h2}$, as indicated in Fig. 3 (b), which use $\Delta P_{h}'$ as input, and directly add their outputs to the outputs of $\mathbf{Y}_h$. The expressions can be derived as

$$G_{h1} = \frac{1}{1 + G_{PT}G_{PT-p}}$$

(5)

$$G_{h2} = -\frac{G_{PT}G_{PT-q}}{1 + G_{PT}G_{PT-p}}$$

(6)

Therefore, the PAP model for the hydrogen plant considering the closed-loop control of power tracking can be given by:

$$\mathbf{Y}_{h,cl} = \begin{bmatrix} G_{h1} & 0 \\ G_{h2} & 1 \end{bmatrix} \cdot \mathbf{Y}_h$$

(7)

(2) Moving the Point of Power Reference Signal

The relationship between $\Delta P_{w}$ to PCC voltage variables $\Delta \theta$ and $\Delta U$ is given by

$$\Delta P_{w} = -\mathbf{Y}_w (1,:) \cdot \begin{bmatrix} \Delta \theta \\ \Delta U \end{bmatrix}$$

(8)

where $\mathbf{Y}_w (1,:)$ represents the first row of the matrix $\mathbf{Y}_w$.

Therefore, to equivalently move the power reference signal from $\Delta P_{w}$ to PCC voltage variables $\Delta \theta$ and $\Delta U$, an additional gain $\mathbf{Y}_w (1,:)$ is added in the path of the reference signal, as shown in Fig. 3 (c).

(3) Moving the Point of Input Signal of $G_{PT-q}(s)$

Moving the point of the input signal of $G_{PT-q}(s)$ from $I_{dc}$ to $\Delta P_{s,h}$ will introduce additional gain $G_{PT-q}(s)$ in the original signal path, which should be removed to make the transformation equivalent. The obtained new gain is denoted $G'_{PT-q}$ in Fig. 3 (c), which is expressed as:

$$G'_{PT-q} = G_{PT-q} \cdot (G_{PT-q})^{-1}$$

(9)

Based on the three steps of equivalent transformation mentioned above, the final PAP model of the power tracking control $\mathbf{Y}_{PT}$ can be expressed as

$$\mathbf{Y}_{PT} = \begin{bmatrix} 1 \\ G'_{PT-q} \end{bmatrix} \cdot G_{PT-cl} \cdot (-\mathbf{Y}_w (1,:))$$

(10)

where $G_{PT-cl}$ is the closed-loop transfer function of the ideal power tracking control, which can be expressed as:

$$G_{PT-cl} = G_{PT}(1 + G_{PT}G_{PT-p})^{-1}$$

(11)

To facilitate analysis of different partition methods below, the block diagram in Fig. 3 (c) is further simplified to the vector-based single-line block diagram shown in Fig. 4, where Consequently, the input vectors of the system are grid side voltage reference $\Delta V_{sg}$ and wind farm side power reference $\Delta S_{sw}$, the output vectors are grid side voltage $\Delta V$.

III. DIFFERENT PARTITION METHODS AND STABILITY EQUIVALENCE

There are five feasible partition methods for the stability analysis, as shown in Fig. 4. Since partition methods 3, 4, and 5 are similar to each other, only partition method 3 is analyzed below due to the focus of this paper on power tracking control. The physical meanings of partition methods 1 and 2 are to separate the circuit in Fig. 1 at the locations 1 and 2, respectively, while partition method 3 has a virtual partition location not visible in Fig. 1 but is equivalently disconnected from the power reference signal at location 3.

The minor-loop gains of three different partition methods have different expressions and even different dimensions. Therefore, it is important to know which partition method gives accurate stability analysis results and provides clear insight into power tracking performance to enable the trade-off between these two aspects.

Below, it will be mathematically proved that stability analysis with three different partition methods has the same closed-loop stability conditions and the proof contains three steps:

1) Derive minor loop gains of different partition methods;
2) Calculate characteristic polynomials of minor-loop gains;
3) Prove characteristics of polynomials having the same roots.

A. Minor Loop Gains of Different Partition Methods

According to Fig. 4, the minor loop gains obtained by partitioning the system at locations 1, 2, and 3, can be obtained as $G_1$, $G_2$, and $G_3$, respectively.

$$G_1 = \mathbf{Z}_g (\mathbf{Y}_w + \mathbf{Y}_{PT} + \mathbf{Y}_{h,cl})$$

(12)

$$G_2 = \begin{bmatrix} \mathbf{Y}_w & -\mathbf{Y}_{PT} & -\mathbf{Y}_w \end{bmatrix}$$

(13)

$$G_3 = (\mathbf{I} + \mathbf{Z}_g (\mathbf{Y}_w + \mathbf{Y}_{h,cl}))^{-1} \mathbf{Z}_g \mathbf{Y}_{PT}$$

(14)

As seen, the dimension of $G_1$ and $G_3$ is 2 by 2, while the dimension of $G_2$ is 6 by 6.

Meanwhile, the complexities of the three minor loop gains are also significantly different from each other, which may lead to different stability implications.

B. Characteristics Polynomials

The system stability condition is ultimately determined by the closed-loop poles of the minor loop gain, which can be calculated by solving the roots of the characteristic polynomial [29]. The characteristics of polynomials for different minor
loops will be derived and simplified individually in the following sections.

As for the minor loop $G_1$, its characteristic polynomial can be expressed as:

$$|I + G_1| = |I + Z_g (Y_w + Y_{PT} + Y_{h,cl})| \quad (15)$$

As for $G_2$, its characteristic polynomial can be calculated as

$$|I + G_2| = \left| \begin{array}{ccc}
1 & 0 & 0 \\
-
Y_{PT} Z_g & I & 0 \\
\end{array} \right| = |I + (Y_w + Y_{PT} + Y_{h,cl}) Z_g| \quad (16)$$

By subtracting rows two and three from row one, the polynomial $|I + (Y_w + Y_{PT} + Y_{h,cl}) Z_g|$ can be extracted from the determinant. Then, adding column one to columns two and three, the characteristic polynomial can be equivalently rewritten as

$$|I + G_2| = |I + (Y_w + Y_{PT} + Y_{h,cl}) Z_g| \quad (17)$$

As for $G_3$, its characteristic polynomial can be given by

$$|I + G_3| = |I + (I + Z_g (Y_w + Y_{h,cl}))^{-1} Z_g Y_{PT}| \quad (18)$$

By first extracting matrix $(I + Z_g (Y_w + Y_{h,cl}))^{-1}$ and then applying the determinant multiplication rule, the characteristic polynomial can be equivalently rewritten as

$$|I + G_3| = |I + Z_g (Y_w + Y_{h,cl})|^{-1} \cdot |I + Z_g (Y_w + Y_{h,cl})| \quad (19)$$

Since the determinant of the inverse of the matrix is the inverse of the determinant, thus the characteristic polynomial can be further rewritten as

$$|I + G_3| = \frac{|I + Z_g (Y_w + Y_{PT} + Y_{h,cl})|}{|I + Z_g (Y_w + Y_{h,cl})|} \quad (20)$$

C. Roots of Characteristics Polynomials

The closed-loop poles of the different minor loops can be obtained by solving the roots of the characteristics polynomials, i.e.,:

$$|I + G_x| = 0 \quad (21)$$

where $x$ can be 1, 2, or 3.

(1) Stability Equivalence of $G_1$ and $G_2$

According to the Aronszajn–Weinstein identity [30], the determinant $|I + AB| = |I + BA|$. Therefore, the characteristic polynomials for minor loops $G_1$ and $G_2$ are the same, which means that minor loops $G_1$ and $G_2$ have the same closed-loop poles.

(2) Stability Equivalence of $G_1$ and $G_3$

As for $G_3$, the closed-loop poles can be categorized into two groups: 1) zeros of the determinant in the numerator of (21) and 2) poles of the determinant in the denominator of (21). The first groups are the same as that of $G_1$. Since $Z_g (Y_w + Y_{h,cl})$ is part of the transfer function matrix $Z_g (Y_w + Y_{PT} + Y_{h,cl})$, the poles of the determinant in the denominator will be completely canceled out by the poles of the determinant in the numerator. As a result, the closed-loop poles of $G_3$ are also the same as those of $G_1$.

To sum up, the three partition methods are equivalence in terms of closed-loop stability conditions, even though their minor loop gains are significantly different from each other.

IV. PERFORMANCE AND STABILITY ANALYSIS WITH OPTIMAL PARTITION METHOD

A. The Definition of the Optimal Partition Method

Despite equivalence in closed-loop stability conditions for different partition methods, their insights into power tracking performance and root causes of the stability issues are significantly different from each other. It is desirable to select an optimal partition method that meets three criterion, i.e., can provide clear insight into:

1) the power tracking performance of the hydrogen plant;
2) impact of the power tracking control on system stability;
3) the stability issue caused by system interactions.

The partition method 1 treats the wind farm and hydrogen plant as a whole, as partition location 1 indicated in Fig. 1, so the power tracking control is embedded in the wind-hydrogen system, and its tracking performance and stability impact cannot be investigated separately. As a result, the partition method 1 cannot meet criterion 1, and 2.

The partition method 2 separates wind farm, and hydrogen plant with power tracking control from the AC power grid, as partition location 2 indicated in Fig. 1. In this case, it is difficult to analyze the actual power tracking performance accurately considering the dynamics of the wind farm and AC power grid. Thus, it cannot meet criterion 1.

Only partition method 3 can provide all three criterion and is proposed as the optimal partition method, which will be analyzed in detail below. To better reveal the insights of the partition method 3, Fig. 3 (c) is redrawn as shown in Fig. 5, which can clearly reflect the ideal and non-ideal power tracking performances and stability issues of different loops.

B. Power Tracking Performance of the Hydrogen Plant

Power tracking performance of the hydrogen plant is essential to reduce the required grid connection capacity, which can avoid expensive grid expansion. According to Fig. 5, the tracking performance can be characterized by the closed-loop gain from power reference $\Delta P_w$ to the output power of the hydrogen plant $\Delta P_h$, of which the gain can be divided into two parts: 1) gain from $\Delta P_w$ to $\Delta P_{s,h}$, which reflect the power tracking performance under the ideal grid condition; 2) gain from $\Delta P_{s,h}$ to $\Delta P_h$, which reflect the impact of the system interactions on the tracking performance.
(1) Ideal Power Tracking Performance
The ideal power tracking performance is determined by open-loop gain as $G_{PT,o}$ in Fig. 5, which can be expressed as

$$G_{PT,o} = G_{PT}G_{PT,p}$$  \hfill (22)

The whole control process is as follows: the output active power of the wind farm $\Delta P_w$ is taken as a reference and compared with the active power consumption of the hydrogen plant $\Delta P_{wh}$. Then the error is fed to a PI controller ($G_{PT}$), and its output is used to adjust the setting point of the DC current of the thyristor-rectifier in the hydrogen power plant $I_{dc}^*$, to regulate its active power consumption $\Delta P_{wh}$ following the output active power of wind farm $\Delta P_w$.

The ideal power tracking performance is determined by the cut-off frequency of $G_{PT,o}$, i.e., a higher cut-off frequency $f_c$ indicates faster tracking performance.

As a result, the closed-loop gain from $\Delta P_w$ to $\Delta P_{wh}$ is given by $G_{PT,cl}$ in (11), which behaves as a low-pass filter of which the corner frequency approximates to $f_c$.

(2) Impact of System Interactions on the Actual Power Tracking Performance
As seen in Fig. 5, the actual performance of the power tracking control is also influenced by the additional loop $G_{si,o}$, which represents the impacts of the system interactions between the wind farm $\mathcal{Y}_w$, the hydrogen plant $\mathcal{Y}_h,cl$ and the AC power grid $Z_g$. The expression of $G_{si,o}$ is given by

$$G_{si,o} = \mathcal{Y}_h,cl(I + Z_g\mathcal{Y}_w)^{-1}Z_g$$  \hfill (23)

And the corresponding closed-loop gain can be expressed as:

$$G_{si,cl} = (I + \mathcal{Y}_h,cl(I + Z_g\mathcal{Y}_w)^{-1}Z_g)^{-1}$$
$$= (Z_g)^{-1}(I + Z_g\mathcal{Y}_w) \cdot (I + Z_g(\mathcal{Y}_w + \mathcal{Y}_h,cl))^{-1}Z_g$$  \hfill (24)

As a result, the additional gain from $\Delta P_{wh}$ to $\Delta P_{wh}$ introduced by the system interactions is given by the element in the first row, the first column of $G_{si,cl}$, which is denoted as $G_{si,cl}(1,1)$. $G_{si,cl}(1,1)$ also exhibits the characteristics of a low-pass filter with corner frequency $f_L$. When $f_L$ approaches the cut-off frequency of $G_{PT,o}$, $f_c$, this low-pass filter will further slow down the power tracking speed.

C. Stability Analysis
In the context of a complex grid-connected wind-to-hydrogen system, it is important to eliminate all the hidden instability hazards to ensure the robust operation of the system.

Theoretically, the overall system can be stabilized even if the minor loop gain $G_3$ contains RHP poles. However, those RHP poles will make the system unstable when the reference signal $\Delta P_w$ for the power tracking control is lost due to the plant-level communication fault. Therefore, it is imperative to ensure not only the stability of the overall system but also the stability of its internal loops.

Different from the other minor loops $G_1$ in (12) and $G_2$ in (13), the sub-gains that multiplied with each other in $G_3$ in (14) have clear physical meanings, and can explicitly reveal different stability issues caused by ideal power tracking and different-level system interactions respectively, which helps to eliminate all the possible instability hazards.

(1) Stability of the Ideal Power Tracking Control
The stability of the ideal power tracking control is determined by the open loop gain $G_{PT,o}$, which represents the stability of the power tracking control when the hydrogen plant is connected to an ideal grid.

Since this open-loop gain $G_{PT,o}$ in (8) is a single input single output system (SISO), this stability can easily be assessed using the Nyquist criterion.

When this loop is stable, $G_{PT,cl}$ and $\mathcal{Y}_h,cl$ in $G_3$ will not contain any RHP poles.

(2) Stability of System Interactions without Cross-Plant Feedback
When the cross-plant feedback is disconnected, that is, the reference signal $\Delta P_w$ for the power tracking control is replaced by a constant reference signal, the wind farm, the hydrogen plant and the AC power grid will interact with each other through the PCC voltage.

This stability can be obtained by using the Generalized Nyquist Criterion (GNC) to assess the open-loop gain in (23).

According to (24), if this interaction is stable, there will be no RHP poles in $(I + Z_g(\mathcal{Y}_w + \mathcal{Y}_h,cl))^{-1}$, which means no RHP poles in the first inversion term of $G_3$, neither.

(3) Stability of System Interactions with Cross-Plant Feedback
When the cross-plant feedback is enabled, i.e., the output active power of wind farm $\Delta P_w$ is used as the power tracking reference, the equivalent PAP model of power tracking control $\mathcal{Y}_{PT}$ participates in the system-level interaction together with
A. System Description

To validate the power tracking performance and stability analysis using the optimal partition method, a 180 MW wind farm and hydrogen plant with power tracking control are built in the PSCAD/EMTDC v4.6.3 simulation software. To demonstrate the applicability of the proposed method, the wind farm and hydrogen plant are modeled in detail which is close to the complexity of real-life projects.

As shown in Fig. 6, two strings of 90 MW wind turbine generators (WTGs) are firstly connected to the 66 kV buses. The voltage is then stepped up to 230 kV through the transformer TR2. After that, the wind power is transported through a 30 km offshore cable section and a 10 km onshore cable section and fed into the PCC point at the 380 kV busbar. The detailed EMT models of wind turbines, cables, and transformers can be found in [24].

The hydrogen plant is also connected to the PCC point, and its design follows the industrial practice. The voltage is first stepped down from 380 kV to 150 kV through a three-winding transformer TR3 and then further to 33 kV through TR4. The autotransformers TR5 are then used to control the 22 kV busbar to the nominal value against the load variations. To better eliminate the harmonic emissions in the system, 12-pulse thyristor rectifiers are used. Moreover, to compensate the reactive power of the hydrogen plant dynamically at different load conditions, an 80 Mvar STATCOM is added to the tertiary winding of the TR3.

B. Black-box Modeling

The whole renewable energy system is built in PSCAD/EMTDC, and then the developed advanced frequency-scanning toolbox automates the measurement of required AP models individually in a black-box way, which includes the PAP model of the wind farm (\( \mathbf{Y}_w \)), the hydrogen plant (\( \mathbf{Y}_h \)), VAP model of AC grid \( \mathbf{Z}_g \), and the transfer function inside the power tracking control (\( G_{PT,P} \) and \( G_{PT,Q} \)). Moreover, the PAP model introduced by power tracking control \( \mathbf{Y}_{PT} \) and \( \mathbf{Y}_{h,el} \) can be calculated according to different PI controller parameters.

Frequency scanning is carried out from 1 Hz to 300 Hz with 100 equal-distance points on the log scale to capture the power dynamics in this paper. All the subsystems except the AC grid are operating-point-dependent; therefore, they are all measured at the selected operating point. The measured frequency responses of \( G_{PT,P} \), \( G_{PT,Q} \), \( \mathbf{Y}_h \), \( \mathbf{Y}_w \), and \( \mathbf{Z}_g \) are shown in Fig. 7 (a), (b), (c), and (d), respectively. In this case, sweeping a single model takes several hours.

C. Stability Analysis with the Optimal Partition Method

The optimal partition method is partitioning the system at the virtual power tracking input signal, indicated as partition position three in Fig. 6. In addition to assessing the stability of the overall system, the optimal method can also provide insight into the stability of important internal ideal power tracking loop \( G_{PT,el} \) and the additional interaction loop \( \mathbf{G}_{si,E} \). This level of insight into the hidden instability hazards is unattainable when partitioning at either the grid side or the wind-to-hydrogen system output ports (positions one and two in Fig. 6).
By applying NC and GNC to its minor loop gains \( G_{PT,\omega} \), \( G_{si,\omega} \), and \( G_3 \), the stability of the wind-to-hydrogen system can be assessed. The proportional gain \( k_p \) and integral gain \( k_i \) in the power tracking controller are 0.5 and 200, respectively.

1) As Fig. 8 (a) shows the frequency response of \( G_{PT,\omega} \), its phase margin is 110 degrees, indicating the internal ideal power tracking loop is inherently stable.

2) Then, using the GNC to evaluate the stability of the internal additional interaction loop. Since the ideal power tracking loop is stable, the calculated AP models \( Y_{PT} \) and \( Y_{h,cl} \) are all RHP poles free. Then, submitting all the measured AP models into (23), the eigenvalues of \( G_{si,\omega} \) can be calculated in Fig. 9 (a), its gain margin is -2 dB, and the phase margin is 10 degrees. The eigenvalue of \( G_{si,\omega} \) has a negative crossing, which means the internal additional interaction loop has two RHP poles. The internal additional interaction loop shown in Fig. 5 is unstable.

3) Finally, the stability of the overall loop \( G_3 \) can be evaluated according to GNC by plotting its no-zero eigenvalue shown in Fig. 9 (b). \( G_3 \) has two RHP poles, but its no-zero eigenvalue has no crossing. Consequently, the phase margin of \( G_3 \) at 16 Hz is -18 degrees, which means an oscillation at 16 Hz is expected at the PCC. Compared with the internal additional interaction loop, the overall loop includes the impact of the power tracking \( Y_{PT} \), which increases the gain margin of \( G_{si,\omega} \) but decreases its phase margin.

Similarly, submitting the measured results of \( Y_w \), \( Y_{PT} \), \( Y_{h,cl} \), and \( Z_s \), which are all RHP poles free, into (12) and (13), then the eigenvalues of \( G_1 \) and \( G_2 \) can be calculated as shown in Fig. 10(a) and (b). Since \( G_2 \) has six eigenvalues with two no-zero eigenvalues, only the non-zero eigenvalues are shown here.

1) The open-loop gains \( G_1 \) and \( G_2 \) are all RHP poles free.

2) The no-zero eigenvalue has one negative crossing at 16 Hz, which means an oscillation at 16 Hz is expected at the PCC [24].

Figs. 11 (a) and (c) show the EMT simulation waveform of the active power of the hydrogen plant, and the corresponding FFT analysis result, respectively. A primary oscillation at 16 Hz is prominently observed, which confirms the correctness of the stability analysis results.

As seen, the non-zero eigenvalues of the \( G_1 \) and \( G_2 \) have the same frequency responses. Even though all three partition methods give the same stability conditions, the unstable inner loop \( G_{si,cl} \) can only be directly located by the open-loop gain \( G_3 \) of the third partition method.

Then, decreasing \( k_i \) to 30, the frequency response of \( G_{PT,\omega} \) is shown in Fig. 8 (b), and its phase margin increased to 120 degrees. The eigenvalues of the open-loop gain of the internal additional loop \( G_{si,\omega} \) can be reshaped into Fig. 12(a). Since all the AP models have no RHP poles and the \( G_{si,\omega} \)'s eigenvalue has no crossing, which means the closed-loop gain \( G_{si,cl} \) is redesigned to be stable. The gain margin and phase margin of \( G_{si,\omega} \) are 5.4 dB and 15 degrees respectively. As Fig. 12(b) shows the no-zero eigenvalue of \( G_3 \) has no crossing, thus, the system is redesigned to be stable. With the impact of \( Y_{PT} \), the gain margin and phase margin of \( G_3 \) are all increased, which are 14
dBi and more than 90 degrees respectively. 12(c) and (d) show the EMT simulation waveforms of active power waveforms of the wind farm and hydrogen plant respectively, and it can be observed that the system is stable obviously.

D. Frequency Coupling Effects in Power Dynamics

Due to the frequency coupling effects caused by asymmetrical control loops, such as power control loop, PLL, etc, a sub-synchronous oscillation also occurs at 32 Hz besides the dominated oscillation frequency of 16 Hz, which confirms the analysis result in (3).

These power dynamics resulting from the frequency coupling effects significantly differ from those of voltages and currents. Figs. 11(b) and (d) show the EMT simulation waveforms of the current of the PCC and its corresponding FFT analysis result, respectively; the oscillations occur at 34 Hz and 66 Hz, which are symmetrical to the fundamental frequency 50Hz, which is the typical frequency coupling dynamics in voltage and currents.

In sum, AP models are more effective in revealing the power dynamics directly.

E. Power Tracking Performance

![Fig. 13. The frequency responses of closed-loop gain of (a) ideal power tracking control and actual power tracking performance; the step response of (b) the ideal power tracking, and (c) the actual power tracking performance.](image)

The insights of the power tracking performance will be analyzed, including the ideal power tracking performance $G_{PT-cl}$ and the impact of the additional internal loop $G_{si-cl}(1, 1)$ given in Eqs. (11) and (24). The additional loop reflects the impact of system interactions and behaves as a low-pass filter. The actual power tracking performance needs to consider the impact of the additional loop on the ideal power tracking loop, which has a much lower bandwidth than the ideal power tracking performance.

1) Ideal Power Tracking Control When $k_i = 30$, the corresponding frequency response of the ideal power tracking performance is shown in Fig. 13(a). Then, it can be observed the bandwidth of the ideal power tracking is 4.6 Hz. The ideal power-tracking performance can be assessed by measuring the response speed of the ideal grid-connected hydrogen plant to a fixed power reference. Figs. 13(b) shows a 10MW small-step response, and the response time is around 0.2s.

2) Impact of System Interactions on Power Tracking Control

The additional loop gain $G_{si-cl}(1, 1)$ all acts as a low-pass filter under different PI controller parameters, which reduces the bandwidth of the ideal power tracking controller greatly. Then, considering the impact of system interactions, the actual power-tracking performance can be calculated as $G_{h,2} = G_{si-cl}(1, 1) G_{PT-cl}$, and its frequency response is shown in Fig. 13(a), which is lower than 1 Hz. Figs. 13 (c) shows a 10MW small-step response of the grid-connected wind-to-hydrogen system with the $k_p = 0.5$ and $k_i = 30$ respectively. The responding time is about 5s, thus, compared with the ideal power tracking response of about 2s, the effective bandwidth is reduced from 4.6 Hz to 0.2 Hz by the internal additional loop $G_{si-cl}(1, 1)$.

F. The trade-off between Tracking Performance and Stability

![Fig. 14. The gain margin and phase margin of (a) $G_{PT-o}$ (b) $G_{si-o}$ (c) $G_3$.](image)

Based on equations (7) and (10), the influence of power tracking control on AP models $\mathcal{YP}_T$ and $\mathcal{Y}_{h-cl}$ can be analytically calculated, which avoids the repetitive and time-consuming black-box measurement when tuning the power tracking controller for the trade-off between the tracking performance and stability. The optimal partition method can achieve a good trade-off between power-tracking performance and system stability by revealing the relationship between the bandwidth of power-tracking performance and the amplitude margin and phase angle margin of important loops involving $G_{PT-o}$, $G_{si-o}$, and $G_3$. Fig. 14 (a), (b), and (c) give the corresponding frequency response respectively. Since the gain margin and phase margin of $G_{si-o}$ are always smaller than $G_{PT-o}$ and $G_3$ under different ideal power tracking bandwidths, the system’s margin is decided by the additional loop $G_{si-o}$. In this case, the ideal power tracking controller can maximize tracking performance and ensure system stability with a bandwidth of 15.9 Hz.

According to the equation (13), it is crucial not only to consider the ideal power tracking performance bandwidth but also to ensure the stability of additional loops caused by external subsystems and the system-level open loop gain to ensure system stability.

VI. CONCLUSION

The co-location of a wind-to-hydrogen system, when employed with an accurate power tracking controller, requires
only limited grid connection yet offers both temporal (i.e., energy balancing) and spatial (i.e., congestion management) flexibility when it comes to power system integration. However, to achieve high performance (e.g., fast and accurate tracking) for the power tracking controller, the cross-plant feedback of the power tracking control in an integrated wind-to-hydrogen system challenges the design-oriented stability analysis. Based on the amplitude-phase modeling, equivalent transformation of system model, and proof of stability equivalence, an optimal partition method is proposed in this paper, which can not only provide clear insight into the power tracking performance but also can characterize the stability conditions of different loops individually.

Based on this optimal partition method, the major insights can be obtained as follows:

1) The dynamics of the system interactions among the wind farm, hydrogen plant, and AC grid will equivalently introduce a low-pass filter that cascades after the ideal power tracking control, which will reduce the actual power tracking speed.

2) The root causes of instabilities are identified, including the ideal power tracking control loop and system interactions without and with the cross-plant feedback, and they can be characterized by the corresponding loop gains respectively.

3) To ensure robust system operation even under the communication fault at the plant level, it is vital to eliminate all the ideal power tracking control, which will reduce the actual power tracking speed.

4) Using the equivalent transformation, the computing speed of the trade-off between power tracking speed and system stability can be greatly improved, which can be readily used for real-life large-scale wind-to-hydrogen systems to determine the minimum grid connection capability.

Besides these insights, this paper also analytically proves the unique frequency-coupling feature of the power dynamics, i.e., the power oscillations couples at $\omega_h$ and $2\omega_h$, which is significantly different from the well-known frequency-coupling in current and voltage dynamics that usually couples the oscillations at $\omega_h$ and $(2\omega_1 - \omega_h)$, where $\omega_1$ is the grid fundamental frequency.

REFERENCES


