Dual Inertia-Emulation Control for Interlinking Converters in Grid-Tying Applications

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***Abstract*—Electric grids are undergoing several changes, mostly driven by the replacement of classical highly-inertial generators by converter-interfaced generation and storage systems. This entails the reduction of inherent inertia levels and might lead to instability issues. In a future scenario formed by grids of different natures and characteristics, power electronic converters will play a key role on grid tying applications. These converters are known as interlinking converters (ICs), and they enable total control over the power flow between interconnected grids. Therefore, they are envisioned to take part not only tying hybrid ac/dc systems but also in ac/ac connections. This paper presents a novel control strategy for ICs named dual inertia-emulation (DIE), that improves the dynamic response of tied grids by emulating inertia at both sides of the converter, and which can be employed at any IC regardless of the interconnected grid type (ac or dc). The proposed control is tested by means of time-domain simulations of WSCC 9-bus and IEEE 14-bus benchmark systems. The obtained results demonstrate that the proposed technique increases the equivalent inertial response of the interconnected grids, hence reducing frequency oscillations and the rate of change of frequency (RoCoF), and improving the frequency nadir.**

***Index Terms*—Dual Inertia-Emulation, Dual Droop, Power Systems, Virtual Inertia, Interlinking Converter, Ancillary services, Grid Tying, Decentralised Control.**

I. INTRODUCTION

CLASSICALLY, the energy generation has been carried out using synchronous machines (SM) at big generation plants. This energy is transported to consumption areas by means of power transformers and long transmission and distribution lines, completing a so-called top-down topology [1]. Thanks to their high inertia, these synchronous generators are capable of keeping the voltage and the frequency of the grid under tight boundaries, making the system very stable under power variations.

On the other hand, power systems with a significant penetration of electronic power converters become more susceptible under transients, since converters do not inherently respond under frequency or voltage variations [2], [3]. This is specially challenging when some parts of the grid are completely isolated from the main grid—such as microgrids—when they are interconnected through an interlinking converter (IC) or when they are based on dc current, since they are completely decoupled in terms of inertial response [4]. The result is a poorly regulated system suffering from severe rates of change of frequency (RoCoF) and voltage (RoCoV) under power variations [5].

A recent trend to overcome these challenges is to control power converters to support the grid frequency and voltage, e.g. by carrying out the primary regulation [6] or by emulating the inertial behaviour of classical SGs [7], [8]. A large number of these techniques are designed for converters interfacing distributed generation (DG) units [9]–[11], as the ones compared in [12]. Most of these controls are hence designed based on the assumption that there is a constant or nearly constant dc power source, so they do not consider the dynamics of the dc bus. Some studies such as [13] also make this assumption for controlling ICs that interconnect different parts of the grid and they emulate inertia for the ac grid. However, depending on the type and scale of the interconnected grids, this assumption might not be valid for such cases, since both sides of the converter fluctuate under power variations.

This paper focuses on how to control ICs to support the interconnected power systems, in this case by considering both sides of the converter. Some previous works have already proposed alternatives to carry out the primary regulation with ICs, and an extensive review can be found in [14]. Some of these techniques include e.g. *dual droop* (DD) or *e-Droop*, which compensate steady-state frequency and voltage deviations of the interconnected grids. However, there are very few proposals where ICs are employed to improve the inertial response of both interconnected grids.

Among the different control strategies to preserve grid stability in interlinked systems by emulating inertia using ICs, grid-forming and grid-supporting approaches can be found. In the case of grid-forming control techniques, the inertia-emulation is only achieved for one of the tied systems which typically corresponds to the ac subsystem as authors propose in [15], [13] and [16], although it can also be performed for dc systems [17]. However, if the inertia-emulation is to be performed for both of the interconnected grids, the controller needs to employ a grid-supporting control philosophy due to the fact that an IC cannot set the voltage at both sides of the converter. Employing grid-supporting control philosophy, [18] and [19] perform inertia-emulation only for an ac system linked by HVDC systems. With regard to the employment of ICs on microgrids for the emulation of inertia, authors in [19] propose a control strategy for ICs to enhance the inertial response of both grids. However, the behaviour of the cited technique does not correspond to an inertial device (i.e. a SG for ac grids or a capacitor for dc ones) because it aims to make equal the frequency and voltage deviation of the hybrid ac/dc microgrid, and obtains the power reference according to that premise. He *et al.* in [20] and [21], propose two similar strategies employing an improved droop control together with a "cross-grid" and local inertial support in hybrid ac/dc microgrids and they take into account variables and devices from both interconnected grids with the IC. The results in these papers show how the transient response of interconnected systems is improved. However, the strategy is based on a central controller specifically designed to coordinate the different grid-connected units of the studied system and the IC(s). Therefore, the strategy might not be suitable for other scenarios in which energetic resources are physically spread, and the use of a communication network might deteriorate the reliability of the system.

The purpose of this paper is to demonstrate the improved operation of a novel control technique for ICs, named *dual inertia-emulation* (DIE). Comparing to the aforementioned techniques for ICs that perform the inertia-emulation, this technique enables to achieve the inertia-emulation for both sides of the IC in a decentralised and communication-less manner. Besides, the DIE control always supports the most damaged grid by extracting power from the contrary grid in order to perform the emulation of inertia and supporting the transient response of tied grids. The conceptual form of this technique was first introduced in [22] and in this paper we go a step further by demonstrating that the DIE technique does indeed improve the transient behaviour of the interconnected grids as predicted in [22]. The DIE technique supports both sides of the converter to improve the rate of change of the interconnected grids (RoCoF or RoCoV) under transients and one of the main advantages of this control is that, since it is based in a per unit notation [23], it can be equally employed for ICs interconnecting ac or dc grids. Moreover, the controller parameters can be adjusted independently based on the type and strength of the interconnected grids to prioritise the support of the most weak side. As we demonstrate in the paper, this technique can be easily incorporated to a classical controller. Furthermore, the presented technique is completely autonomous and communication-less, while many of the employed techniques for ICs use complex communication links to operate as gathered in [14]. This feature makes the IC operation more reliable and besides, ICs can be connected in parallel autonomously.

The rest of the paper is organised as follows: in Section II, the proposed control technique for ICs is explained in detail. In Section III, the simulation scenario that has been chosen for the validation of the proposed technique is shown together with the simulation results that prove the effectiveness of the presented control strategy. Finally, Section IV concludes the paper with most important remarks of the presented work.

II. DUAL INERTIA-EMULATION CONTROL

A. Operation Principle

Most of the existing techniques for the emulation of inertia on ac systems are based on the well known swing equation of rotational masses (1), as explained in [1]:

$$2H\frac{d\omega}{dt} = T_m - T_e - K_d\Delta\omega \tag{1}$$

where H is the per unit inertia constant, ω is the per unit frequency, T_m and T_e are the mechanical and the electrical torques and K_d is the damping factor.

This equation can be also written in terms of mechanical and electrical power (P_m and P_e, respectively) as follows:

$$2H\frac{d\omega}{dt} = \frac{P_m}{\omega} - \frac{P_e}{\omega} - K_d\Delta\omega \tag{2}$$

Several grid-forming controllers such as virtual synchronous machines (VSM), synchronverters or synchronous power controllers (SPC) incorporate this equation into the controller to emulate the inertial behaviour of a SG with a converter [8], [24], [25]. Recently, this approach has been also extended to converters connected to dc systems by considering that the frequency of ac systems is analogous to the voltage of dc ones [22]. From this analogy, various articles such as [26]–[28] propose *virtual-capacitor* or *virtual dc machine* techniques to improve the RoCoV of the dc system under power perturbations.

The DIE technique is based on this ac/dc analogy [22], and it might be included in parallel to a primary regulation loop like the ones gathered by the authors in [14]. For instance, it can be set up in parallel to a DD loop and then cascaded to a current reference calculation (CRC) stage and a classical current controller (CC) as shown in Figure 1.

The inertia-emulation of the proposed technique is built on the swing equation in (2). The purpose is to generate a power reference from a grid voltage or frequency variation, similar to the response of a SG in an ac grid or a bus-connected capacitor in a dc one by employing the grid derivative *df/dt* like in [29]. Since most of the times such techniques include a droop gain for power-sharing purposes, equation (2) can be simplified by

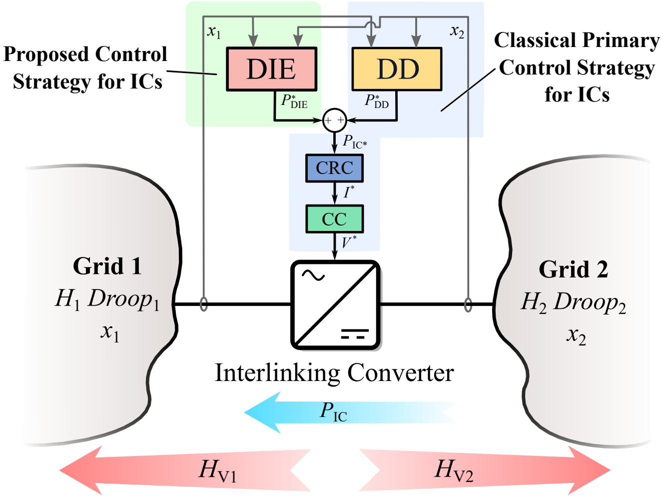

Fig. 1. Representation of the IC with the proposed dual inertia-emulation technique and classical control approach.

neglecting the damping term (which is almost equivalent to the droop), leading to:

$$-2H_V\omega\frac{d\omega}{dt} = P^* \tag{3}$$

where H_V is the virtual inertia in per unit and P^* is the power reference. The $(-)$ sign is introduced because for a negative grid evolution, the control strategy needs to respond with a positive power to the system and vice versa.

Basically, this technique observes the grid derivative (frequency on ac grids and voltage at dc ones) and provides a power reference which is proportional to the emulated inertia H_V. Implementing this technique, different ICs can be connected in parallel to perform the inertia-emulation. The provided power by each IC will depend on the H_V control parameter and the grid derivative that each IC controller senses, achieving the power sharing in a communication-less and autonomous manner. By providing a transient response under frequency or voltage variations, we provide more time for other devices (generators, energy storage systems, etc.) to carry out the primary regulation of the system.

In the case of the DIE technique, (3) is implemented twice (hence the use of the term “dual”), one for each of the interconnected grids. Figure 2 represents the main structure of the DIE loop, where the two normalised inertia-emulation branches can be observed. The DIE control concept has been proposed for a single stage IC. However, if a multiple stage IC is employed, each stage can be treated as an independent IC that interconnects two systems. In any case, a power converter cannot work as a grid-forming unit for both sides of the converter so it needs to have an externally fixed voltage in one side in order to set the voltage of the other side. Therefore, the dual inertia-emulation loop cannot be implemented as two classical PLL-free (or measurement-free) VSM grid-forming loops, and it has been proposed as a grid-supporting technique for both grids transferring active power between them in order to support the inertial response.

The main difference between the proposed control technique and previous approaches is that the DIE control considers not only one, but both sides of the converter by implementing the swing equation twice in order to support the frequency and/or voltage of the grid under perturbations. The power references for each grid are calculated based on (3) as follows:

$$P^*_{\mathrm{DIE}_1} = -2H_{V_1}x_1\frac{dx_1}{dt} \quad P^*_{\mathrm{DIE}_2} = -2H_{V_2}x_2\frac{dx_2}{dt} \tag{4}$$

where the subscript on parameters from Equation (4) represents the number of the grid (i.e. grid 1 or 2), x represents the frequency (for ac grids) or the voltage (for dc grids) of the grid and H_V is the emulated inertia. Since this control loop is carried out using per unit values, the control strategy can be implemented regardless of the nature of the grid (ac or dc) and the rated frequency and voltage.

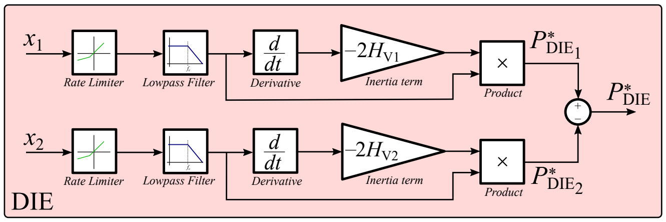

Fig. 2. Detailed Dual Inertia-Emulation control loop for ICs.

The two power references from (4) are then subtracted to obtain the final power reference for the converter:

$$P^*_{\mathrm{DIE}} = P^*_{\mathrm{DIE}_1} - P^*_{\mathrm{DIE}_2} \tag{5}$$

By observing Equation (5), it can be deducted that the inertia-emulation will be performed for the most damaged subgrid, extracting power from the contrary one. If a simultaneous load variation occurs in both grids, the power reference will tend to be cancelled.

In most cases the measured grid signals (voltage and frequency) exhibit electric noise, spikes or oscillations. Since the proposed DIE technique relies on the derivative of these signals the controller inherently responds under such perturbations, which might lead to disproportionate power references. This is specially critical when the IC is connected to ac grids, inasmuch as the frequency cannot be directly measured and needs to be estimated using a phase locked loop (PLL). A great deal of research is currently being conducted in this path regarding the frequency estimation under non ideal grid conditions or voltage dips and although authors are conscious of this fact, this study is out of the scope of this research. Therefore, we have considered that the grid position can be correctly estimated for the proposition of the DIE control strategy.

In order to avoid issues with grid frequency estimations and voltage measurements (for ac and dc subgrids respectively), we first filter the grid voltage or frequency by means of a rate limiter and a low-pass filter (Figure 2). As in the case of the PLL, it is worth noting that the selection of the parameters of these blocks will strongly depend on the environment where the IC is implemented, keeping the commitment between the grid dynamic measurement (which relies on the robustness of the grids) and the filtering of undesired electric noise.

Regarding the virtual inertia coefficients H_{V_1} and H_{V_2}, we must choose them according to the capacity and robustness of each grid, as will be explained in Section III.

B. *Supporting the transient response of grids*

By including two independent inertia-emulation loops in the controller it is possible to decouple the extent to which we want to support each of the grids in terms of inertial response. This is an interesting feature when one of the grids is much stronger than the other one, or when we want to transfer the inertial response between two grids.

Lets assume for instance that an IC is interconnecting two grids with an equivalent inertia H_1 and H_2 as shown in Figure 1. The power variations in each grid are considered as an aggregated power variation named ΔP_1 and ΔP_2 (considering load as negative power), and the power of the IC is considered to be positive when flowing from grid 2 to grid 1. Then, the differential equations that model the dynamic response of the grid frequency or voltage can be written down as follows:

$$x_1 \frac{dx_1}{dt} = \frac{1}{2H_1}\left(\Delta P_1 + P_{\mathrm{IC}}\right) \qquad x_2 \frac{dx_2}{dt} = \frac{1}{2H_2}\left(\Delta P_2 - P_{\mathrm{IC}}\right) \tag{6}$$

Assuming that x_1 and x_2 will be close to their rated values, from (6) it is clear that if the IC does not provide any power—i.e. $P_{\mathrm{IC}} = 0$—the rate of change of the voltage or frequency depends on the inertia of the grid and the amplitude of the power perturbation.

If we neglect the effect of the DD loop (or any other present primary regulator) to simplify the analysis and consider that the current controller is fast compared to the inertial response (i.e. $P_{\mathrm{IC}} = P^{*}_{\mathrm{DIE}}$), when we control the IC with the proposed DIE technique we get the following expressions by introducing (5) into (6):

$$\begin{aligned} x_1 \frac{dx_1}{dt} &= \frac{1}{2(H_1 + H_{V_1})}\left(\Delta P_1 + 2H_{V_2}\frac{dx_2}{dt}x_2\right) \\ x_2 \frac{dx_2}{dt} &= \frac{1}{2(H_2 + H_{V_2})}\left(\Delta P_2 + 2H_{V_1}\frac{dx_1}{dt}x_1\right) \end{aligned} \tag{7}$$

These expressions show that, for the same power perturbations, the dynamic transients of the frequency or voltage now also depend on the virtual inertia introduced by the DIE loop. This means that we are capable of improving the transient response of the grid by emulating a certain inertia H_{V_1} and H_{V_2}.

As one would expect, unlike in a converter interfacing an ESS with classical inertia-emulation control, in this case the power to support the load variation on one of the grid comes from the other one. Therefore, the second grid will also suffer a perturbation according to P_{DIE} and its own inertia. However, as it will be demonstrated in the upcoming section, in the case that two neighboring grids are tied using a tie line or a power transformer, the power disturbance happening in one grid is completely coupled to the neighbouring grid. Therefore, by employing the DIE technique we can choose the coupling level of the disturbance by properly setting virtual inertia control terms according to the robustness of the interconnected grids by the IC. In a sense, we can say that the DIE enables to transfer the inertial response of the interconnected grids in a controllable manner, thus extending the benefits of using ICs to interconnect different power systems.

The transfer of this inertial response allows to optimise the usage of energy generation and storage resources of tied systems, since they will support all the grids under perturbations. In the case of a simultaneous power variation in both grids, the DIE technique will always support the most damaged one by emulating more inertia to this side.

III. DIE CONTROL VALIDATION

A. DIE Testing Scenario

We propose a testing scenario comprised by two standard distribution systems to validate the proposed control strategy. The first system corresponds to a modified 9-node WSCC system [30] (referred from now on as System 1), and the second one is a modified 14-node IEEE system [31] (System 2). Figure 3 shows the single-line diagram of these two systems interconnected via an IC. The employed parameters, IC control strategy or grid-tying elements are detailed on each test case.

Even though the proposed control concept can be employed for the interconnection of different types of grids (ac grids with different frequencies, dc grids with different voltage levels), in this case both tied grids are ac. The reason for choosing two ac grids is that, in addition to comparing the DIE technique to other control approaches, it also enables to compare the performance to a classical power transformer or a tie line.

Regarding the simulation, this scenario has been implemented in a MATLAB/Simulink® environment. In classical power-flow studies such as [32], only the steady-state operation of the system is studied. However, in this case we carry out a simulation that also considers the voltage and frequency dynamics to study the inertial response of the proposed controller. This is done by taking into account the dynamic behaviour of all the grid-connected devices.

The line data from Figure 3 has been gathered from [30] and [31] for Systems 1 and 2, respectively, and the same base power and voltage magnitudes have been employed for the per unit conversion in both systems (230 kV and 100 MVA). The specific generated/consumed power and controller parameters

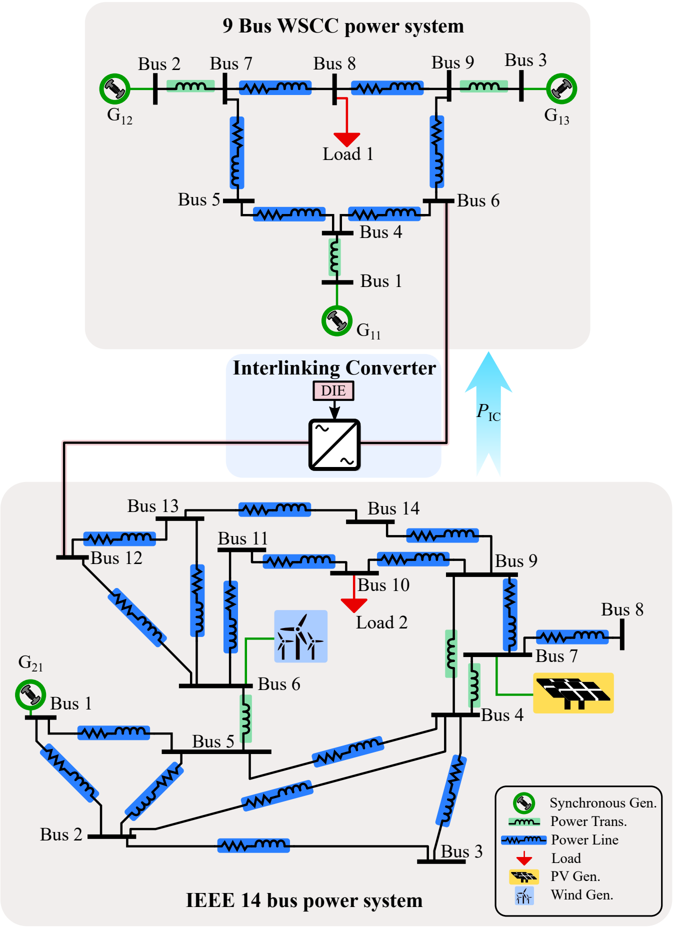

Fig. 3. Proposed simulation scenario for testing the DIE technique on an IC tying two electric grids.

are detailed in each test case.

B. DIE Operation Concept

In this test we show the effectiveness of the proposed technique in a simplified scenario. Both grids are modelled with a single synchronous generator at the first node. The parameters are represented as N_{ij}, where N denotes the name of the parameter (inertia, damping, reactance, etc.), subscript i represents the system and j represents the generator number. For this test case, G_{11} and G_{21} are the only operative generators on Figure 3 and they are configured with equal inertia (H_{11} and H_{21}), droop coefficients (D_{11} and D_{21}) and synchronous reactances (X_{s11} and X_{s21}). In order to show the operation concept of the DIE technique in a clearer way, we have modelled the droop of both grids as an instantaneous gain—i.e. as a first order filter with zero time constant ($\tau_{11} = \tau_{21} = 0$). The parameter values for this test are gathered in Table I.

TABLE I
SYSTEM AND IC PARAMETER VALUES FOR THE SIMPLIFIED SIMULATION SCENARIO.

Device	Parameter	Value [p.u.]
System 1 G_{11}	H_{11}	1
	D_{11}	10
	X_{s11}	0.1
	τ_{11}	0
System 2 G_{21}	H_{21}	1
	D_{21}	10
	X_{s21}	0.05917
	τ_{21}	0
IC - DIE	H_{V_1}	1
	H_{V_2}	1

To illustrate the operation concept of the proposed DIE technique we have carried out two tests. On the first one we simulate both systems decoupled from each other, and on the second one we repeat the same test by interconnecting them via a DIE-controlled IC. In both simulations, a 0.2 p.u. step-shaped load power is introduced, first in System 1 (at $t = 1$s) and then in System 2 (at $t = 11$s). The DIE technique is tested using equal virtual inertia values ($H_{V_1} = H_{V_2} = 1$)

Figure 4a and b show the frequency of each grid for both tests. When a power step occurs on any of the two grids, the RoCoF of the perturbed grid is improved thanks to the DIE-controlled IC. The IC improves this dynamic response by transferring power from the opposite grid. Therefore, the frequency of the opposite grid also suffers a small transient because of the load variation.

This can be also seen in Figure 4c, where the power references for each grid on the DIE technique are illustrated. The transferred power by the IC, calculated from these two references, is shown in Figure 4d. When the 0.2 p.u. load is introduced at System 1, power flows transiently from System 2 to System 1. Similarly, when power is demanded in System 2, power flows from System 1 to System 2 via the IC. Since both systems have equal inertia, we are emulating the same inertia at both sides of the IC (i.e. $H_{V_1} = H_{V_2}$) and the load perturbations have the same amplitude, the power transferred by the IC is very similar but with opposite sign for each load variation. The small differences are caused by the topologies employed at System 1 and 2.

From these results, we can say that the IC is capable of transferring the inertial response of the interconnected grids so that all the devices supporting (or forming) the grid contribute under power perturbations.

C. DIE Test Cases

In this case we test the performance of the proposed control under more realistic conditions and compare it not only with other IC control approaches, but also with other grid-tying devices such as power transformers.

In order to consider the dynamic response of generators in the following simulations, we have applied a time delay to the droop controllers of the generators of both grids. Besides, we will analyse the DIE technique for the case in which the IC is tying one strong grid and a relatively weak grid. System 1 is a robust grid with high equivalent inertia and droop coefficients ($H_1 = 6$ and $D_1 = 30$), representing a classical power system. On the other hand, System 2 represents a weaker grid in terms of inertial and primary response (with $H_2 = 1$ and $D_2 = 10$), which could be the case of a power system with a higher penetration of renewable energy sources and electronic power converters. The DIE and DD technique parameters have been designed to support more the weaker System 2. We have defined the emulated inertia of the DIE as $H_{V_1} = 0.33$ and $H_{V_2} = 2$.

Table II summarises the rest of parameters that have been used to carry out the set of tests under this section.

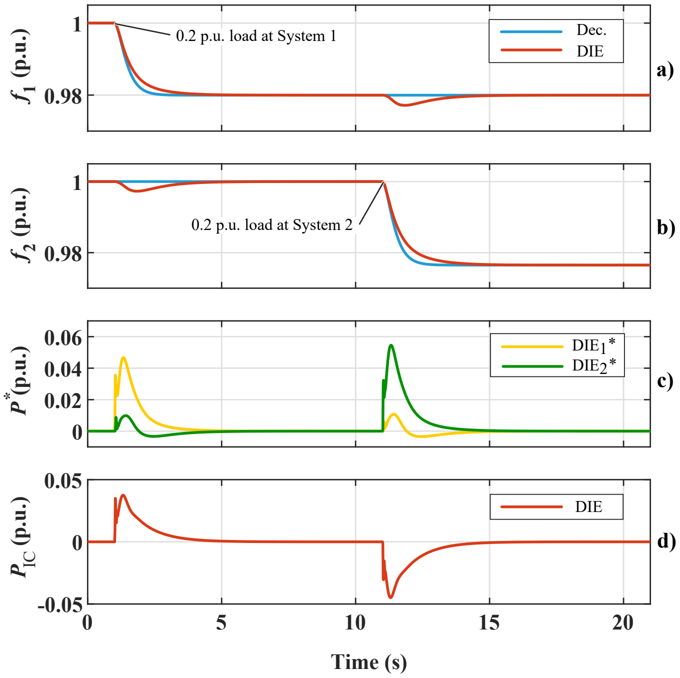

Fig. 4. DIE operation concept test: a) Frequency of System 1, b) Frequency of System 2, c) Power references of the DIE control branches, and d) Power transferred by the IC

TABLE II
SYSTEM AND IC PARAMETER VALUES FOR THE TEST CASES.

Device	Variable	Value [p.u.]
System 1 G_{11},G_{12},G_{13}	H_{11},H_{12},H_{13}	2
	D_{11}, D_{12}, D_{13}	10
	$X_{s11}, X_{s12}, X_{s13}$	0.1
	$\tau_{11}, \tau_{12}, \tau_{13}$	0.5
System 2 G_{21}	H_{21}	1
	D_{21}	10
	X_{s21}	0.05917
	τ_{21}	0.5
IC - DIE	H_{V_1}	0.33
	H_{V_2}	2
IC - DD	D_{d_1}	3.33
	D_{d_2}	10

1) Case 1 – Decoupled grids vs tied grids with a DIE-controlled IC: Grids that are weak in terms of equivalent inertia are prone to oscillate when there is a sudden power perturbation in the grid. This is mainly caused by the time delays of the generators that are carrying out the primary regulation of the frequency. The purpose of this test is to show how, by interconnecting two grids with an IC controlled with the proposed technique, we are capable of transferring the inertial behaviour to damp the frequency oscillations caused by a power variation.

Figure 5a and b illustrate the frequency response of System 1 and System 2, respectively. Since System 1 is strong and the inertia emulated at this grid with the DIE technique is relatively small, there is no difference in the frequency when a load step is applied in that system (at $t = 1$s). This can be also observed in Figure 5c, where it can be seen that the IC provides almost no power during this transient. This means that System 2, which is much weaker than System 1, is very slightly affected by a perturbation in System 1.

On the other hand, when there is a sudden power variation in System 2 (at $t = 11$s), the frequency response is significantly improved when the two systems are connected via the DIE-controlled IC. In this case, the IC transmits power transiently to decrease the RoCoF, to damp the frequency oscillation and to improve the frequency nadir. As explained in previous sections, this improvement is achieved by extracting power from System 1, which suffers a small frequency perturbation at that instant.

2) Case 2 – Tied Grids using DIE Technique vs Power Transformer: When a power transformer or a tie line is used to connect two power systems, all the devices participating in the regulation of the grid share the power perturbations occurring at any point of the system. This means that the droop coefficients and inertia are aggregated. The main drawback of these classical interconnections is that there is no control over the power that flows between the two systems, since it directly depends on the phase (voltage for dc) difference on the device terminals and its impedance. ICs are an interesting solution to increase the degrees of freedom of the system operator, since the power flow can be actively controlled. Moreover, in this section we show that by controlling the IC with the proposed DIE technique, we can damp the frequency oscillations after a sudden power variation.

The results of this test are illustrated in Figure 6. In these curves we can see how the inertia and droop values of both systems are aggregated for both cases (with the transformer and a DIE-controlled IC). When a power variation occurs at any of the grids, both systems respond to it, improving the RoCoF and the steady-state deviation compared to the decoupled scenario.

One of the main differences between interconnecting two systems with a transformer or a DIE-controlled IC is that the steady-state value of the frequency is not equal for the same power perturbation. This is because, in the first case, the frequency deviation is dependent on the droops of all grid-connected devices. As the transformer tightly couples both systems, their frequency deviations are equal in steady-state.

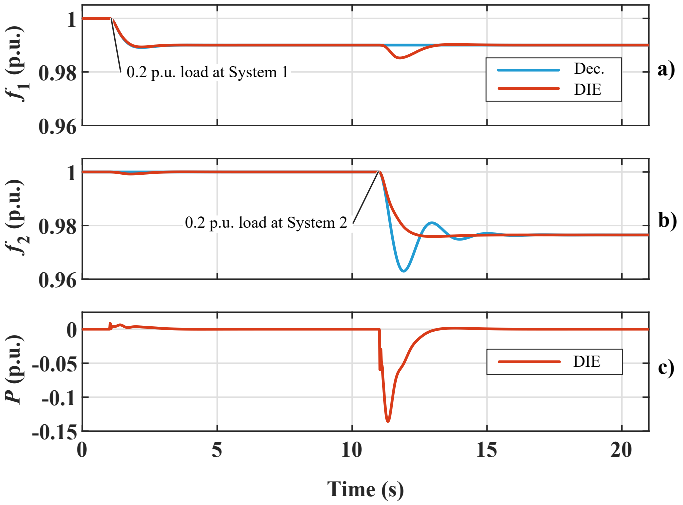

Fig. 5. Case 1: a) Frequency of System 1, b) Frequency of System 2, and c) Power transferred by the DIE-controlled IC.

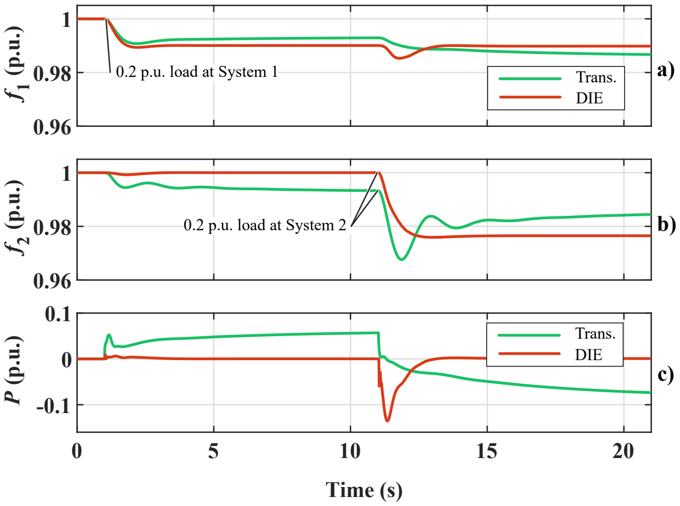

Fig. 6. Case 2: a) Frequency of System 1, b) Frequency of System 2, and c) Power transferred by the interlinking device (transformer or DIE-controlled IC).

However, when we replace the transformer by an IC, the frequency deviation of the system will be dependent on the droops of the devices connected to that system and the droop of the IC. Since in this case we are only observing the effect of the DIE loop and the IC does not have any droop or primary controller, the frequency deviations are higher compared to the scenario in which the systems are connected through the transformer. The incorporation of a droop regulator is studied in the next section.

On the other hand, the transient response of the frequency is significantly improved thanks to the inertial response transmitted by the DIE-controlled IC. When the power perturbation occurs in System 2—which is weaker than System 1—we can clearly see how the frequency oscillations are damped and the frequency nadir is improved. From this analysis we can conclude that, in addition to enabling the control of the power flow, ICs can be a potential solution to improve the sudden frequency variations occurring in the grid by tuning the virtual inertia terms (H_{V_1} and H_{V_2}) of the DIE technique.

3) Case 3 – Tied Grids using dual inertia-emulation + dual droop (DIE-DD) Technique vs Power Transformer: The previous tests have shown the benefits of using a DIE-controlled IC over a power transformer in terms of damping, frequency nadir and oscillatory response. However, we could also see that from the point of view of primary regulation the proposed DIE technique is not as effective as connecting the systems with a transformer.

As we have mentioned at the beginning of the paper, the proposed DIE technique can be easily implemented along with a primary regulation control technique such as the ones reviewed in [14]. Therefore, in this test we repeat the simulations of the previous section but considering that the IC also includes a dual droop controller, in the configuration shown in Figure 1.

The IC will therefore run two power controllers in parallel. The DIE loop will provide the power reference under a transient power perturbation. On the other hand, the steady-state power response—and the power shared with other devices—will be determined by the DD loop.

For this test we have maintained the parameter values related to the grid and the IC controller gathered in Table II, and the simulation results are shown in Figure 7.

As in the previous test, when grids are tied using a power transformer, the frequencies of both grids converge to the same value. However, when we incorporate the DD loop to the IC controller, we can see that the steady-state frequency deviations are reduced compared to the case in which we only have a DIE loop. This reduction is more significant in the case of System 2, which is an expected outcome considering that we are trying to support more the weakest system. This phenomenon can be clearly observed in Figure 7c; when the power load step is introduced at $t = 1$ s, a small quantity of power is transferred by the IC, while at $t = 11$s a notable power spike is transferred to actively damp the frequency response at System 2.

At this point we should also highlight that, if opposite sign power disturbances occurred at both sides of the IC at the same time, the DIE-DD-controlled IC would support both systems at the same time by compensating the generation excess from one system with the demand of the other system.

4) Case 4 – DIE-DD vs DD Technique on a real test case: The last test consists of evaluating the proposed DIE technique under a more realistic scenario in terms of the generated and consumed power. For that purpose we have integrated different renewable energy-based generation systems and loads at both grids, which are placed as shown in Figure 3. The 20 minute dynamic profiles of these elements can be observed in Figure 8. Moreover, since our purpose is to study the effect of the proposed DIE loop, the comparison is based on a DD-controlled IC with and without that DIE loop.

The controller values and grid conditions remain as shown in Table II. Figure 8a and b show the wind and solar photovoltaic (PV) generation profiles at System 2, while Figure 8c and d show the aggregated loads applied at Systems 1 and 2, respectively. Lastly, Figure 8e and f illustrate the evolution of grid frequencies of Systems 1 and 2 for the DD and DD-DIE-controlled IC cases.

From these results we can see that the frequency of System 1 is similar for both IC control approaches. This is because, as in test case 3, we have configured the DIE loop to support more System 2, since it is weaker than System 1. The main difference in both controllers can be observed in Figure 8f, where the evolution of the frequency is much smoother with the DIE loop than without it. This illustration clearly shows how the frequency overshoot (and hence the nadir) are improved by employing the DIE technique. As an example, if the the second zoom of Figure 8f is observed, the RoCoF is decreased from -1.077 Hz/s to -0.82 Hz/s and the frequency nadir level is improved a 64% when the DIE technique is employed (being 100% the frequency gap on steady-state before and after the load variation). Moreover, the frequency oscillations of that grid are significantly damped, improving the frequency transient behaviour.

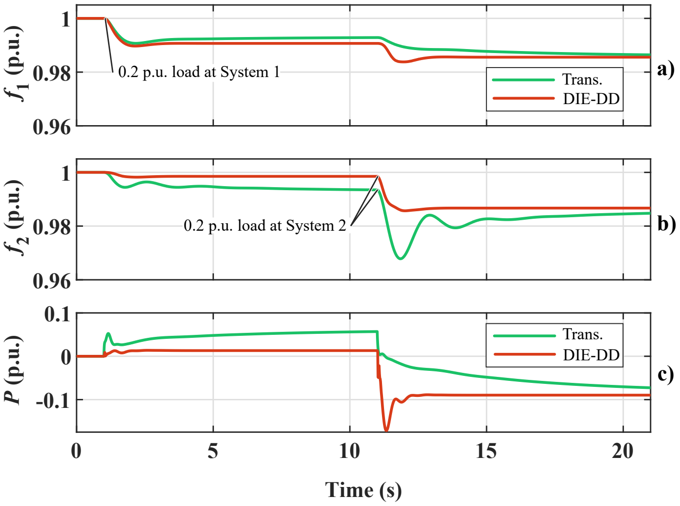

Fig. 7. Case 3: a) Frequency of System 1, b) Frequency of System 2, and c) Power transferred by the interlinking device (transformer or DIE-DD-controlled IC).

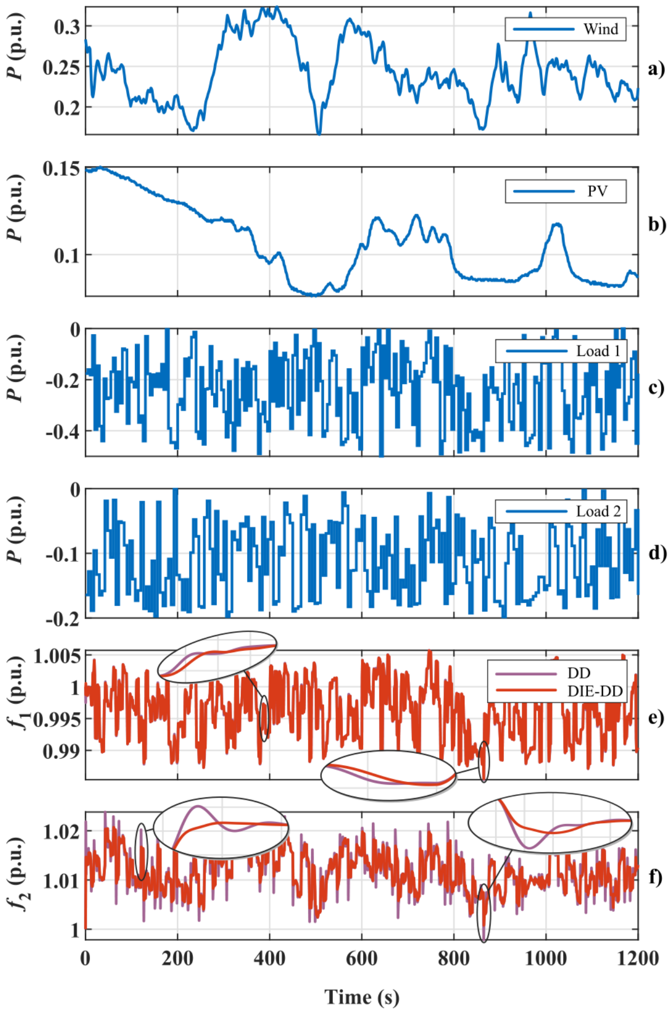

Fig. 8. Test case 4: a) Wind Power generation at System 2, b) PV generation at System 2, c) Power load profile at system 1, d) Power load profile at System 2, e) Frequency of system 1, and f) Frequency of System 2.

IV. CONCLUSIONS

The massive penetration of converter-interfaced energy storage and renewable-energy-based generation is causing a significant decrease of the inherent rotating inertia in modern power systems, causing a deterioration in the quality of the voltage and frequency. In this context, the use of ICs to tie different electric grids or parts of the grid is arising as one of the most promising solutions to provide different ancillary services to the interconnected grids.

This paper presents a derivative-based dual inertia-emulation (DIE) control strategy for ICs, which enables to provide inertial support to both interconnected grids without any communication network. In addition to improving the transient response of tied grids under power variations, the proposed technique enables to adjust the response of each side of the converter independently. Moreover, since the controller is normalised with per unit variables, it can be employed to interconnect any type of electric grid (ac or dc, different voltage levels, frequency values, etc.) and can be easily incorporated to more classical power controllers.

The simulation results have shown how, when a power variation occurs in one grid, the DIE technique supports it by interchanging power transiently from the grid on the other side. Therefore, we can say that this technique transfers the inertial response of the interconnected grids, so that all the devices participating in the regulation of the grids share the power variations occurring at any part of the system. Although the transient stability of the proposed technique has not been directly analysed, simulation results have shown that it is improved by employing the DIE technique. Besides, the improvement of the RoCoF, frequency nadir and oscillation damping has been demonstrated by means of a simplified scenario and a more realistic scenario with time-varying generation systems and loads, where one grid was stronger than the other in terms of inertia and primary reserve.

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