Dynamic Average Consensus with Anti-windup applied to Interlinking Converters in AC/DC Microgrids under Economic Dispatch and Delays

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***Abstract*—This work proposes an application of dynamic average consensus in interlinking converters of AC/DC microgrids with a distributed anti-windup for dealing with steady-state errors from communication delays. The proposed controller consists of a PI control that looks after the power-sharing between interlinking converters while achieving a global incremental cost consensus. The controller uses an observer (by dynamic average consensus) for estimating the average power of the interlinking converter cluster; this method represents an alternative formulation to conventional single-integrator consensus. An anti-windup with reset scheme is proposed to reduce steady-state errors in presence of fixed time delays. Stability analyses are also presented as well as simulations. Both show that the proposed controller successfully balances the power between interlinking converters being comparable with similar approaches in the literature.**

***Index Terms*—AC/DC microgrids, distributed control, dynamic average consensus, fixed delays, interlinking converters.**

I. INTRODUCTION

THE theory behind the distributed coordination of multi-agent systems has found an interesting field of application in the control of Microgrid (MG) systems [1], [2]. The concept of MG refers to a group of loads and local generation capable of autonomously deciding its power management. Recently, hybrid AC/DC MGs topologies (combined AC and DC MGs, from now on AC/DC MGs) have been proposed to improve the energy efficiency of traditional AC systems [1], [3], [4].

The control over AC/DC MGs involves Distributed Generators (DGs), which are generally defined as converter-based and dispatchable agents inside the system [2], and new entities, named Interlinking Converters (ILCs) [3], which are high-power bidirectional AC/DC converters. Conventionally, the control of ILCs is made by decentralized droop curves, producing that the MG's power dispatch relies on the controllers (centralized or distributed) of DGs [2], [4]. For real world implementations, instead of a single ILC, clusters of ILCs are getting attention due to their scalability in power capacity.

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Distributed control has been proposed for the coordination of ILCs [5]–[8], improving resiliency compared with centralized approaches and accuracy compared with droop control. Concerning the consensus algorithms, [7] uses single-integrator dynamics with a proportional controller whereas [5], [6] and [8] modify the dynamics by including proportional-integral (PI) gains. Moreover, [8] explored the use of a distributed observer for adjusting droop gains inside the ILC cluster.

To the best of the authors' knowledge, dynamic average consensus algorithms can be applied as an alternative to conventional consensus, improving the trade-off management (see observers in secondary control [2]). Also, this would give each ILC access to a local measurement estimation during transient states, facilitating the development of cyber-attack detection methods, like the Kalman filter in [9]. However, dynamic average consensus suffers small steady-state errors when communication delays are present. In [10], a division scheme is proposed to eliminate the effects of delays in secondary control, but adding consensus variables. In [8], authors proposed a low-pass filter to reduce but not eliminate the effects of delays in ILCs. In addition, all of the reported works in distributed ILC power-sharing look after the global power-sharing of the AC/DC MG. Thus, interactions with global economic dispatch performed distributedly have not been sufficiently explored.

Motivated by this, this paper introduces a power observer (by dynamic average consensus) with a PI control that uses a novel anti-windup algorithm that reduces the effects of time-delays. The ILCs perform the power balancing inside the cluster by comparing the local power measurement against the observed average power. In addition, the ILCs also perform a control action related to the economic dispatch between AC and DC subgrids and a local power constraint. This approach looks after the simultaneous convergence of both control goals giving a robust access to the average power of the ILC cluster. The contributions of this work are summarized as follows:

- A distributed control for the coordination of a cluster of ILCs is proposed using a power observer. The control is jointly implemented with an economic dispatch protocol. Large-signal stability is provided.
- A novel anti-windup with reset scheme is proposed to reduce steady-state errors when communication delays exist in the dynamic average consensus.

- A case study of hybrid AC/DC MG with a cluster of ILCs is simulated and evaluated under different conditions.

II. Proposed Control of a Cluster of Interlinking Converters in a Hybrid AC/DC Microgrid

For the distributed control design, a communication network is required. A communicated AC/DC MG involves agents which may be DGs or ILCs [6], [7], [11]. Then, the communications allow the AC/DC MG to be viewed and analyzed as a multi-agent system with a graph $\mathcal{G}_{\text{sys}} := \mathcal{G}_{\text{AC}} \cup \mathcal{G}_{\text{DC}} \cup \mathcal{G}_{\text{ILC}}$ [11]. The subgraphs $\mathcal{G}_{\text{AC}}$ and $\mathcal{G}_{\text{DC}}$ can operate independently when the ILC cluster ($\mathcal{G}_{\text{ILC}}$) is disconnected, or when one side stops communicating to the ILC cluster. It is defined $\mathcal{G}_{\text{ILC}} := (\mathcal{N}^*, A^{\text{ILC}})$ with $\mathcal{N}^* \subset (\mathcal{N}_{\text{AC}} \cup \mathcal{N}_{\text{DC}} \cup \mathcal{N}_{\text{ILC}})$; it represents communications between the side MGs and the ILCs. Also, $\boldsymbol{a}^{\text{ILC}}_{\text{AC}i}$ and $\boldsymbol{a}^{\text{ILC}}_{\text{DC}i}$ are vectors that represent the communication of the i-th ILC with the DGs in the AC and DC subgrids, and $A^{\text{ILC}} = [a^{\text{ILC}}_{\text{ILC}ij}]$ is the matrix with the links between the system's ILCs.

A. Distributed control using dynamic average consensus

For economic dispatch, the control over the power flow of an ILC can be described as compensation of average received incremental costs (ICs), supporting the IC consensus implemented by the subgrids [11]. When multiple ILCs are considered, a balancing control should be added. Then, inspired by [6], [7] and [11], the following protocol is proposed:

$$P^*_{\text{ILC}i} = (u_{\text{L}i} + u_{\text{C}i} + u_{\text{R}i}) G^P_{\text{PI}}(s), \quad (1)$$

$$u_{\text{L}i} = c_L \left(\sum_{i=1}^{N_{\text{AC}}} \frac{\boldsymbol{a}^{\text{ILC}}_{\text{AC}i}}{N^{\text{ILC}}_{\text{AC}}} \lambda_i - \sum_{j=1}^{N_{\text{DC}}} \frac{\boldsymbol{a}^{\text{ILC}}_{\text{DC}i}}{N^{\text{ILC}}_{\text{DC}}} \lambda_j \right), \quad (2)$$

$$u_{\text{C}i} = c_C \left(\overline{P}_{\text{ILC}i} - \frac{P_{\text{ILC}i}}{P^{\max}_{\text{ILC}i}} \right), \quad (3a)$$

$$\overline{P}_{\text{ILC}i} = \frac{P_{\text{ILC}i}}{P^{\max}_{\text{ILC}i}} + c_P \frac{1}{s} \sum_{j=1}^{N_{\text{ILC}}} a^{\text{ILC}}_{\text{ILC}ij} (\overline{P}_{\text{ILC}j} - \overline{P}_{\text{ILC}i}), \quad (3b)$$

$$u_{\text{R}i} = c_{Ri} \left(P^{\text{ref}}_{\text{ILC}i} - \frac{P_{\text{ILC}i}}{P^{\max}_{\text{ILC}i}} \right), \quad (4)$$

where $P^*_{\text{ILC}i}$ is the power reference for the internal control loop ($P_{\text{ILC}i} \approx P^*_{\text{ILC}i}$ is used here), $P^{\text{ref}}_{\text{ILC}i}$ is a hard constraint of desired power (e.g. from a network operator), u_{L} is the local error estimation for power transfer, u_{C} is the error from the balancing of the cluster of ILCs, u_{R} is the local error from the hard constraint, $G^P_{\text{PI}}(s) = k^P_p + k^P_i/s$ is a PI controller. k^P_p and k^P_i can be determine according to the hierarchical control in both subgrids [11]. The parameters c_L, c_C, c_P, c_{Ri} regulate the convergence speed of their corresponding compensation loop. Also, $N^{\text{ILC}}_x = a^{\text{ILC}}_{xi} (\mathbf{1}_{N_x})^{\text{T}}$, with x representing the AC or DC side, and $\mathbf{1}_{N_x}$ being a vector of ones with length, N_x, equals to the active nodes sending information to the ILC.

The proposed protocol in (1)-(3) gives the following result.

Theorem 1. *Consider the control protocol described in* (1)-(3) *implemented by the ILCs of an AC/DC MG. Under a balanced set of subgraphs $\mathcal{G}_{AC}, \mathcal{G}_{DC}, \mathcal{G}_{ILC}$ with spanning trees, all the DGs synchronizes their ICs while the ILCs synchronizes their power asymptotically.*

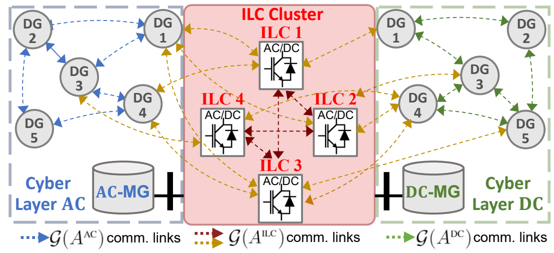

Fig. 1. Simulated MG topology with communications.

Proof. Lets assume $N = N_{\text{AC}} = N_{\text{DC}}$ and $a^{\text{ILC}}_{\text{AC}} = a^{\text{ILC}}_{\text{DC}}$ for the sake of simplicity. Then, the IC dynamics can be expressed as $u_{\text{L}i} \approx \dot{e}^\lambda_i = c_L \sum_{j=1}^{N} a_{ij} \left(e^\lambda_j - e^\lambda_i \right)$ [11], with $e^\lambda_j = \lambda_l - \lambda_k \ \forall (l,k) \in (\mathcal{N}_{\text{AC}}, \mathcal{N}_{\text{DC}})$. For the ILC power-sharing, we define $e^C_i = \overline{P}_{\text{ILC}i} - \frac{P_{\text{ILC}i}}{P^{\max}_{\text{ILC}i}} \equiv \sum_{j=1}^{N_{\text{ILC}}} \frac{P_{\text{ILC}j}}{N_{\text{ILC}} P^{\max}_{\text{ILC}j}} - \overline{P}_{\text{ILC}i}$. Then, $\dot{e}^C_i = c_P \sum_{j=1}^{N_{\text{ILC}}} a^{\text{ILC}}_{\text{ILC}ij} \left(e^C_j - e^C_i \right)$. For the power constraint, a proper selection of c_{Ri} ensures local decoupling, so $e^R_i = 0$. Also, let $V = V_L + V_C = 1/2 \left(\boldsymbol{e}^\lambda R (\boldsymbol{e}^\lambda)^{\text{T}} + \boldsymbol{e}^C Y (\boldsymbol{e}^C)^{\text{T}} \right)$ be a Lyapunov candidate function, with R and Y positive-definite matrices, $\boldsymbol{e}^\lambda = (e^\lambda_1, \ldots, e^\lambda_N)$, and $\boldsymbol{e}^C = (e^C_1, \ldots, e^C_{N_{\text{ILC}}})$. Following similar steps than *Theorem 1* [12], the components $\dot{V}_L$ and $\dot{V}_C$ can be proved non-increasing provided $c_L, c_P > 0$ and that there is a spanning tree in the communication matrices. Therefore, $\dot{V} < M \in \mathbb{R}$, i.e., $\boldsymbol{e}^\lambda$ and $\boldsymbol{e}^C$ converge to zero asymptotically, which completes the proof. ∎

B. Robustness of controller under fixed communication delays

As demonstrated in [13] and [10], the dynamic average consensus has bounded errors in steady-state due to delays. To overcome this, (3) is adjusted according to Algorithm 1.

Algorithm 1 Selective Anti-windup with Reset (i-th ILC).

INITIALIZATION $T = 0,\ S = 0,\ st = 0,\ \overline{\boldsymbol{P}}_{\text{ILC}} = \mathbf{0}_{N_{\text{ILC}}}$
STEP 1 Simultaneously execute the functions:
TIMER(T , S , st)
  if $S == 1$, $T \leftarrow 0$, $st \leftarrow 0$, **end if**
  while $T < T_{st}$, $T \leftarrow T + T_{\text{sample}}$, **end while**
  $st \leftarrow 1$
  return st , T
ANTIWIND($\boldsymbol{a}^{\text{ILC}}_{\text{ILC}i}$, $\overline{\boldsymbol{P}}_{\text{ILC}}(t-\tau)$, st)
  for $j = 1, \ldots, \mathcal{N}^{\text{ILC}}_i$
    if $\left\| \overline{P}_{\text{ILC}j}(t-\tau) - \overline{P}_{\text{ILC}j}(t-\tau-T_k) \right\| > \epsilon$, $ss_{ij} \leftarrow 1$
    else $ss_{ij} \leftarrow 0$, **end if**
    $a^{\text{ILC}}_{\text{ILC}ij} \leftarrow a^{\text{ILC}}_{\text{ILC}ij} \cdot ss_{ij}$
  end for
  $S \leftarrow \prod_{j=1}^{\mathcal{N}^{\text{ILC}}_i} a_{ij} \cdot st$
  return $\boldsymbol{a}^{\text{ILC}}_{\text{ILC}i}$, S
STEP 2 Reset the integrator of (3) with the rising of S, and multiply u_C by NOT(S) and NOT($\sum_{j=1}^{\mathcal{N}^{\text{ILC}}_i} a^{\text{ILC}}_{\text{ILC}ij} == 0$).
STEP 3 Return to STEP 1.

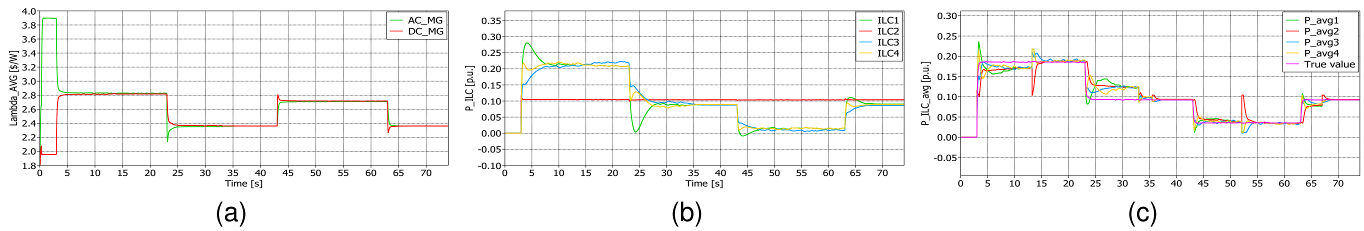

Fig. 2. Simulation results for Case 1. (a) Subgrids' IC curves, averaged from DGs data. (b) ILCs' power curves. (c) ILCs' average power curves.

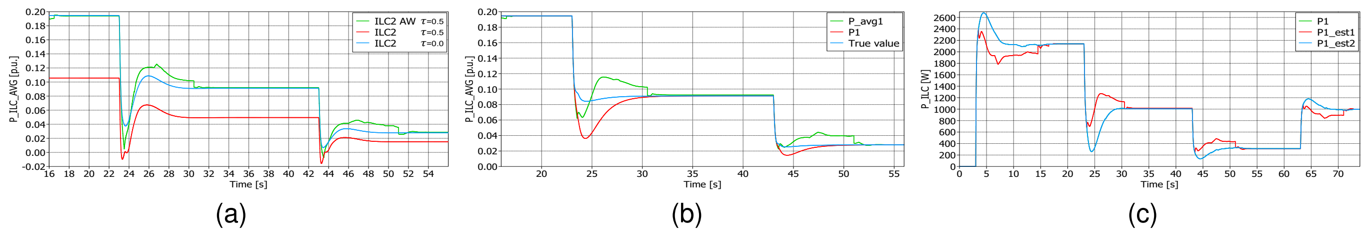

Fig. 3. Simulation results for Case 2. (a) Comparison of the ILC #2's estimation of ILC average power using the proposed controller with and without anti-windup and delays. (b) Comparison of the ILC #1's estimation of ILC average power using the proposed controller and conventional consensus with $\tau = 0.5$[s]. (c) Comparison of the ILC #1's estimation of local power with estimators (i) and (ii) and $\tau = 0.5$[s].

Algorithm 1 clamps to zero the invariant inputs regarding a sampling time $T_k \in [\tau, \infty)$, where τ is the delay; this reduces the error induced during $t < \tau$. Also, a reset signal is generated to refresh the cumulative steady-state error after multiple load changes; this signal is activated with a Boolean flag signal from a periodic timer (with period $T_{st} >> \tau$). T_k should be close (20-120% tolerance) to τ. T_{st} can be determined according to the knowledge of load variability of the AC/DC MG.

III. Case Studies

The proposed controller is tested in a simulated AC/DC MG in PLECS. The MG is based on [11] and depicted in Fig. 1. The control parameters are k_p^P = 0.25, k_i^P= 1.57, c_L= 1400, c_C= 560, c_P= 0.8, c_{Ri}= 0, ϵ= 10^{-3}, T_k= 0.5[s] and T_{st}= 13[s]. The rest of the electrical and control parameters of the system are listed in [11] (Tables I-II). Also, $P^{\max}_{\text{ILC4}}$ = 10 [kW], $P^{\max}_{\text{ILC3}} = 1.3P^{\max}_{\text{ILC4}}$, $P^{\max}_{\text{ILC2}} = 0.7P^{\max}_{\text{ILC4}}$, and $P^{\max}_{\text{ILC1}} = 1.1P^{\max}_{\text{ILC4}}$.

Case 1: The MG is subdued to load impacts; first, on the AC side by changing Z3 from 7.69 to 4.69[Ω], then, on the DC side by changing Z6 from 12.63 to 8.47[Ω] and vice versa. Time delays are tested throughout the ILC Cluster graph, using 330 [ms] (tests with small delays are omitted for briefness). Also, in ILC #2, c_{R2}=20 and $P^{\text{ref}}_{\text{ILC2}}$=800[W].

Case 2: A test is conducted showing the performance of $\overline{P}_{\text{ILC}i}$ estimation using both conventional (with a gain of 5) and dynamic consensus without hard constraints, and for 0 and 500 [ms] of delays. Also, $P_{\text{ILC}i}$ is compared with: (i) $\widehat{P}^1_{\text{ILC}i} = P^{\max}_{\text{ILC}i}\overline{P}_{\text{ILC}i}$, (ii) $\widehat{P}^2_{\text{ILC}i} = P^{\max}_{\text{ILC}i}\left(\overline{P}_{\text{ILC}i} - \frac{c_P}{s}\sum a^{\text{ILC}}_{\text{ILC}ij}(\overline{P}_{\text{ILC}j} - \overline{P}_{\text{ILC}i})\right)$.

IV. Results and Discussions

From the simulation tests, it can be seen in Fig. 2a that the average ICs of each subgrid converge asymptotically. Small errors can be observed in the presence of time-delays, $\approx 6\times10^{-3}$[%] at τ=0.5[s], which is negligible when compared with other real-world sources of error, like noise. Similarly, Fig. 2b depicts an appropriate power balancing inside the ILC cluster with small steady-state error due to time-delays ($\approx 1.2\times10^{-1}$[%] at τ=0.5[s]). The latter exempts the ILC's #2 power, which remains restricted to a fixed amount. From Fig. 2c, the balance of average powers can be seen. Here, it is possible to advert small oscillations that Algorithm 1 creates, especially at the beginning of the simulation. One can note that even with $\overline{P}_{\text{ILC2}} \neq P_{\text{ILC2}}$ the controller allows the convergence in average power and economic dispatch.

A deep performance analysis of Algorithm 1 can be obtained from Fig. 3a. Here, the proposed controller without anti-windup (red) suffers large steady-state errors, ≈51[%] with τ=0.5[s], when compared with the delay-free case (blue). The controller with anti-windup (green) greatly reduces the gap between the ILC's cluster average power estimations concerning the true average value, with an error of ≈11[%] after the load impact, and ≈1[%] after the reset produced at t=30.5[s]. This result differs from the solution shown in [14] where a delay-robust algorithm achieves consensus between the local estimates $\overline{P}_{\text{ILC}i}$ but with constant deviations proportional to the delays, which are undesirable in this application.

A comparison of average power estimation is given in Fig. 3b. It can be seen a similar dynamic performance for both controllers. The proposed controller (green) uses the observer in (3) and presents less damping, in general, when compared to single-integrator consensus (red) that only relies on the local power measurement. Overall, the conventional consensus is barely affected by the delays due to its slow convergence speed (≈7[s]). In the case of the proposed controller, the anti-windup algorithm successfully worked to compensate for steady-state errors and maintain the quality of the response. Fig. 3c shows how effective the dynamic consensus can be to estimate the local power. The estimation $\widehat{P}^1_{\mathrm{ILC}i}$ (red) is not accurate during the transients states. However, estimation $\widehat{P}^2_{\mathrm{ILC}i}$ has a perfect fit with the true value of $P_{\mathrm{ILC}i}$ at almost any time. The anti-windup helps the dynamic consensus to provide an accurate measurement of $\overline{P}_{\mathrm{ILC}i}$ and, consequently, $P_{\mathrm{ILC}i}$ (steady-state error $<2[\%]$). This estimation can be used for further reliability purposes beyond the scope of this paper.

Due to space limitations, analyses concerning the controller robustness against time-varying delays are regarded as future work. However, previous developments, such as [10], allow us to anticipate the convergence of the proposed algorithm given a bounded magnitude of the time delay and its derivative.

V. Conclusions

This paper validated the feasibility of dynamic average consensus for power balancing in an ILC cluster of an AC/DC MG. It can be seen that the power balancing using the observer does not adversely affect the economic dispatch, even though communication delay exists. Moreover, steady-state errors are small and bounded, and they are greatly reduced by the proposed anti-windup algorithm. The latter allows the deployment of the proposed controller without compromising the operation costs of the MG. The proposed controller makes the average power utilization of the ILC cluster available from each ILC, which can be used for further decision-making or cyber-attack resilient algorithms.

Limitations of the work are related to the selection of parameters. There must be some prior knowledge about the range of time-delays magnitude (especially for selecting T_K and T_{st}). Also, the control design has not included robustness against time-varying delays since it is regarded as a line of future work.

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