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► To cite this version:

Artur Henrique dos Santos Heerdt, Alessio Iovine, Guillaume Ganet-Lepage, Sorin Olaru, Antoine Girard. Estimating the Impacts of Topological Changes in Sub-Transmission Areas Using Hybrid Observers. IFAC Workshop on Smart Energy Systems for Efficient and Sustainable Smart Grids and Smart Cities, Jun 2025, Bari, Italy. <hal-05230570>

HAL Id: hal-05230570

<https://centralesupelec.hal.science/hal-05230570v1>

Submitted on 1 Sep 2025

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Estimating the Impacts of Topological Changes in Sub-Transmission Areas using Hybrid Observers

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Abstract: The increasing integration of renewable energy sources presents significant challenges in managing congestion within power transmission networks. Transmission System Operators (TSOs) often tackle these issues by reconfiguring the network or limiting renewable power generation, particularly in complex subtransmission areas. However, strategies like network reconfiguration that alter the topology necessitate to update the underlying dynamic models used for control purposes. The objective of this paper is to accurately identify and estimate these model changes, allowing for the use of suitable models in model-based control. We focus on a subtransmission area that is affected by external topological changes beyond its boundaries. To account for these unknown changes, we model the system as a hybrid system and utilize hybrid observers to estimate the correct model from a predefined set of possibilities, derived from prior data.

Keywords: Power transmission systems, topological changes, hybrid observers, Power Transfer Distribution Factors (PTDFs).

1. INTRODUCTION

The increasing integration of renewable energy sources, particularly wind farms in rural areas, is introducing significant congestion challenges in power transmission networks. These grids, originally designed for lower demand, now face difficulties in managing the higher levels of generation from renewables (Meyer et al. (2020)). The problem is especially acute in regions with concentrated wind energy production, where the infrastructure struggles to deliver electricity effectively. Although expanding the transmission network with new lines might seem like a solution, this approach faces growing opposition due to its high costs and lack of public acceptance.

To address congestion and ensure to satisfy thermal lines limits, Transmission System Operators (TSOs) commonly use strategies such as network reconfiguration (Han and Papavasiliou (2015)) or curtailment of renewable power generation (see Coletta et al. (2020); Dkhili et al. (2023); Liere-Netheler et al. (2020)) particularly in complex subtransmission zones. The curtailment is often implemented through model-based optimal control algorithms (see Almassalkhi and Hiskens (2015a,b)), such as Model Predictive Control (MPC) (Camacho and Alba (2013)), which

depend on accurate knowledge of the system's topology and the associated model of the portion of subtransmission area of interest, named zone. Models for control strategies for managing congestion typically use Power Transfer Distribution Factors (PTDFs) to quantify the impact of shifting power injections on real power flows (see Cheng and Overbye (2005); Dehnavi et al. (2022)). With recent advancements, MPC approaches have moved beyond simple binary curtailment decisions, allowing for partial curtailment and more nuanced local control adjustments in response to congestion (Dkhili et al. (2023)). This evolution has made it increasingly important to ensure that the models used accurately reflect the current state of the network. However, reconfiguring the network can lead to topological changes that significantly alter the dynamics of power flows, necessitating updates to the models used in control strategies. While local topological changes inside the zone of interest can be accounted for by updating the system's model, modifications occurring outside the area present a greater challenge, as these external changes are not directly communicated or observable.

To address these challenges, this paper focuses on the detection and estimation of model changes needed to maintain effective control strategies under varying network conditions. We focus on a subtransmission zone described by PTFD-based models impacted by topological changes occurring outside its boundaries, which are not directly observable. To address this uncertainty, we model the system as a hybrid system (Lygeros et al. (2008)) that combines discrete-time linear dynamics with discrete topological shifts. In this approach, we leverage prior knowledge of po-

* This project follows the PEPR TASE call "Technological solutions for the digitalisation of intelligent energy systems". It has received funding from "France 2030" program through the TASTING grant (ANR-22-PETA-0012).

Artur Henrique dos Santos Heerdt received funding from the BRAFITEC program through the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

tential topological changes and their corresponding models, which are stored as the set of matrices associated with different scenarios. These matrices are constructed based on the PTDF values, representing various configurations of the linear dynamical system. The hybrid model allows us to capture the evolution of the system over time by considering possible combinations of these configurations. Hybrid observers, implemented as a set of Luenberger observers, are here suggested to identify the most suitable model for the current dynamics (see Alessandri and Coletta (2001); Balluchi et al. (2002)). The observers assess which model best aligns with the actual system behavior by minimizing the error according to selected criteria.

Since network reconfigurations do not happen frequently, we assume that there is sufficient time to estimate any changes in topology before the next reconfiguration occurs. It is important to note that our goal is not to precisely identify the specific topological change, since different changes could lead to similar dynamical evolutions; rather, it is to adapt the dynamic model to one that accurately reflects the current reality of the power flow behavior. By employing hybrid observers, we can select the most appropriate model from a predefined set, ensuring that the control strategy remains effective despite changes in the network's external conditions. This approach allows TSOs to dynamically adjust the control model, improving the reliability and performance of model-based congestion management techniques like MPC.

The organization of the paper is described as follows. Section II reviews the process of modeling transmission zones by PTDFs and explains what should be considered in the hybrid model when topological changes are accounted. Section III details the design of the blocks that compose the hybrid system observer. Section IV approaches the methodology used to validate the observer and the results obtained, while section VI concludes the study and indicates the future work on the topic.

2. MODELING TRANSMISSION ZONES VIA PTDF

2.1 No topological changes: linear system

The model we consider here has been developed in previous works as Iovine et al. (2021), Hoang et al. (2021), Dkhili et al. (2023). It consists in a linear model of a sub-transmission zone of the electrical grid, which is composed by few nodes and edges similarly to Fig. 1, suited for control purposes. The particular goal is to use it in the design of a model predictive controller for power flow congestion management. However, the computation of the (optimal) control values is out of the scope of the present paper. The modeling is based on PTDFs, a methodology that computes, for a given power transaction between two buses, the fraction that flows in each line of the system (Cheng and Overbye (2005)). In the following, we recall the notation and the linear model introduced in Iovine et al. (2021) that considers a direct current approximation of the actual alternate current system.

Notations:

- \mathbb{Z}^N is the set of nodes in the considered zone; n^N is its cardinality. P_n^T is the power generated in the trans-

mission network flowing from the external network to the node $n \in \mathbb{Z}^N$ of the zone of interest.

- $\mathbb{Z}^C \subset \mathbb{Z}^N$ is the set of nodes where the curtailment of the generated power is allowed; n^C is its cardinality. P_n^G is the generated power, while P_n^C is the curtailed one at node $n \in \mathbb{Z}^C$. P_n^A is the available renewable power that can be generated each sampling time.
- $\mathbb{Z}^B \subset \mathbb{Z}^N$ is the set of nodes with a battery; n^B is its cardinality. P_n^B is the power injected from the battery on node $n \in \mathbb{Z}^C$, while E_n^B describes the battery energy at the same node.
- $\mathbb{Z}^L \subset \{(i, j) \mid \{1, \dots, n^N\} \times \{1, \dots, n^N\}\}$ is the set of power lines in the zone; n^L is its cardinality. F_{ij} represents the power flow on the line ij .

The dynamical model is depicted as

$$\left\{ \begin{array}{l} F_{ij}(k+1) = F_{ij}(k) + \sum_{n \in \mathbb{Z}^B} b_{ij}^n \Delta P_n^B(k - \tau_B) \\ \quad + \sum_{n \in \mathbb{Z}^C} b_{ij}^n [\Delta P_n^G(k) - \Delta P_n^C(k - \tau_C)] \\ \quad + \sum_{n \in \mathbb{Z}^N} b_{ij}^n \Delta P_n^T(k), \forall (ij) \in \mathbb{Z}^L \\ P_n^C(k+1) = P_n^C(k) + \Delta P_n^C(k - \tau_C), \forall n \in \mathbb{Z}^C \\ P_n^B(k+1) = P_n^B(k) + \Delta P_n^B(k - \tau_B), \forall n \in \mathbb{Z}^B \\ E_n^B(k+1) = E_n^B(k) - T c_n^B [P_n^B(k) + \Delta P_n^B(k - \tau_B)], \\ \quad \forall n \in \mathbb{Z}^B \\ P_n^G(k+1) = P_n^G(k) + \Delta P_n^G(k) - \Delta P_n^C(k - \tau_C), \\ \quad \forall n \in \mathbb{Z}^C \end{array} \right. \quad (1)$$

where:

State Variables: Power flows on the lines F_{ij} , curtailed power P_n^C and battery power output P_n^B , respectively, the battery energy E_n^B , and generated power P_n^G .

Control Inputs: Power variation of the ΔP_n^B and of curtailment ΔP_n^C .

Disturbances: The unknown disturbance ΔP_n^T represents the power variations on the nodes outside the operated zone. The power variation ΔP_n^G of the generated power P_n^G is a filtered disturbance acting on the system.

It is supposed that the available power P_n^A is communicated to the TSO at each sampling time, together with the power variation ΔP_n^A . Consequently, the value of ΔP_n^G is implicitly defined with respect to the communicated values of P_n^A , ΔP_n^A , and the stored value of P_n^G with respect to P_n^C . The parameter T describes the sampling time, b_{ij}^n are the parameters given by the PTDF computation and c_n^B are constant power reduction factors for the batteries. The delays are expressed by τ_C (curtailment) and τ_B (battery).

The aim of this paper is to identify topological changes that affect power flow dynamics via the PTDFs, and therefore we specifically focus on the dynamics F_{ij} . As we do not target specific control actions, the control input u over time is treated simply as a known sequence of values. These values, communicated in advance due to actuation delays, are considered inputs that excite the system.

For this reason, we do not need to take into account the actuation delays; we just consider the values to be known at the time k when the observation is performed. Clearly, at this sampling, the curtailment value will have been

decided at $u_C(k - \tau_C)$, while for the battery at $u_B(k - \tau_B)$. Therefore, with respect to the model in (1), we can write the following discrete-time linear system in matrix form:

$$x(k+1) = Ax(k) + Bu(k) + Dd(k). \quad (2)$$

According to the dynamics in (1), the matrix A is the identity matrix, while B and D depends on the PTDFs, particularly in the columns impacting the dynamics F_{ij} (see Iovine et al. (2021) for more details).

2.2 Topological changes: hybrid system modeling

Efficient control approaches, as the considered MPC one, require accurate knowledge of the model, i.e., of the PTDF values since they define the matrices in the model and determine how the system responds to control inputs and disturbances. Changes in grid topology can significantly alter PTDFs, impacting the model's accuracy and thus the effectiveness of control strategies. To address this issue, we model the possibility for the model to change over time as a switching system, where changes in PTDF coefficients correspond to discrete events affecting the topology and changing the B and D matrices. Therefore, the hybrid model with switching behaviour we consider is:

$$x(k+1) = Ax(k) + B_{\sigma(k)}u(k) + D_{\sigma(k)}d(k) \quad (3)$$

where $\sigma(k)$ is the variable that changes according to the current topology configuration of the grid, representing then the possible dynamics that the model can have. Since network reconfigurations do not happen frequently, we consider the switching to take place slowly enough to allow to estimate the change in topology before the next reconfiguration occurs. Moreover, due to this slow switching time, we suppose the switching not to impact the stability of the closed loop system once the correct modeling is considered.

The possible switching events, such as line openings or closings, that affect the signal $\sigma(k)$ depend on the number of lines in the interconnected network, which is usually large. However, we can reduce the number of cases by focusing on the impact of each line with respect to the zone of interest. To do this, we first establish a threshold γ , which defines the minimum variation in PTDF coefficients necessary to be considered significant. This threshold could be based, for instance, on the impact such variations have on the outcomes of control inputs.

We begin by examining the PTDF changes caused by opening lines that connect a node within the zone to a node outside it. We then expand this analysis iteratively to include lines connected to the first-degree neighbors of the zone, and continue this process outward. The investigation stops once no further line opening or closing results in a PTDF variation that exceeds the established threshold γ .

Moreover, it is possible the different switching events lead to similar variations in the PTDF coefficients. In this case, the different events would fall under the same description, thus still reducing the number of possible matrices $B_{\sigma(k)}$ and the curse of complexity of the possible switching paths.

3. DESIGN OF THE HYBRID SYSTEM OBSERVER

Once we have defined the hybrid system describing the set of possible switching describing the change of topology

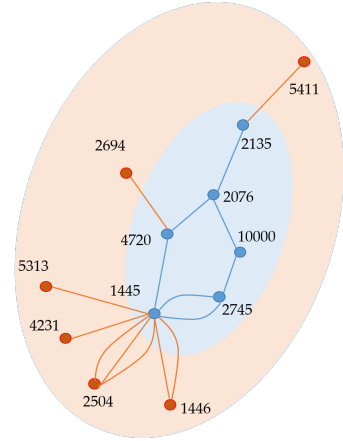


Fig. 1. Sub-Transmission Area

of interest, we here leverage previous results on hybrid observers (Balluchi et al. (2002)) to manage to estimate which model to consider to match reality. The considered hybrid observer is split in two parts; it consists of a location observer, which identifies the current location of the system (in this case, indicating if the PTDFs and consequently the B matrix of the model need to be updated), and a bank of Luenberger observers that tracks the discrete-time dynamics of the system.

3.1 Location Observer

As there is no discrete output of the system available to indicate its current location, it is necessary to estimate it according to discrete-time dynamics evolution. To this purpose, we consider the approach developed in Balluchi et al. (2002), consisting of three blocks: the residuals generator, the decision function, and the fault decision logic:

- the residuals generator is a bank of Luenberger observers that tracks the system dynamics according to the model of each location;
- the decision function indicates when the fault decision logic must be activated;
- the fault decision logic indicates when a location transition occurs.

The error (residual) between the measurement and each observer's output serves as the input to the decision function, which determines when to activate the fault decision logic. Specifically, the decision function calculates the norm of the residual and compares it to a design threshold, ε , to produce a binary output. If the residual exceeds the threshold, the fault decision logic is triggered, prompting a transition to the location associated with the smallest residual at the current step:

$$r_i(k) = \begin{cases} true, & \text{if } \|\tilde{r}_i(k)\| \leq \varepsilon \\ false, & \text{if } \|\tilde{r}_i(k)\| > \varepsilon. \end{cases} \quad (4)$$

3.2 Luenberger Observers

For the identification of the discrete-time dynamics, a Luenberger observer for each location is implemented. In this case, all states of the system are measured, and the

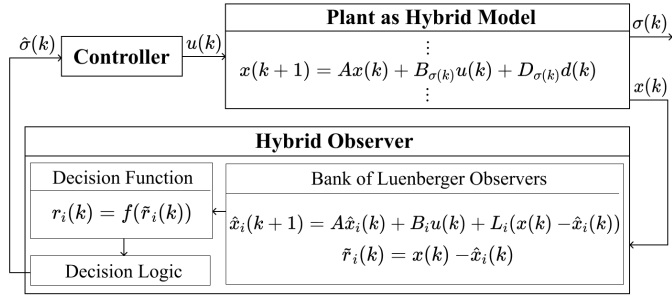


Fig. 2. Closed loop system representation considering the hybrid observer.

purpose of this identification is only to generate the error that is used by the location observer. Its expression is defined as:

$$\hat{x}_i(k+1) = A\hat{x}_i(k) + B_i u(k) + L_i(y(k) - \hat{y}_i(k)) \quad (5)$$

with i being the index of each observer and L_i the respective gain, defining the convergence velocity in each location (Balluchi et al. (2002)). In the sequel, we consider

$$\hat{y}_i(k) = \hat{x}_i(k) \quad (6)$$

and

$$y_i(k) = x_i(k) + w_i(k), \quad (7)$$

where $w_i(k)$ represents measurement noise. The stability of the observers clearly hinges on the selection of the L_i gains, which must ensure that the dynamics of $(A - L_i C)$ is stable (Alessandri and Coletta (2001)), where here C is the identity matrix. Notably, the choice of L_i gains is inherently influenced by the quality of the measurements.

4. SIMULATIONS

Similarly to Dkhili et al. (2023); Iovine et al. (2021), the simulations are performed in MATPOWER (Zimmerman et al. (2011)): to represent the grid, the function *runpf* of MATPOWER is employed at each time step to compute the active power in the branches using an AC power flow. This provides measurements of the system states and disturbances originating from the grid. Since this paper focuses solely on developing the hybrid system observer, the system is simulated in open loop and without delays ($\tau_C = \tau_B = 0$), without any loss of generality.

To facilitate understanding of the proposed mechanism, we focus on the sub-transmission area described in Hoang et al. (2021) and illustrated in Fig. 1 with only two possible lines opening. In this example, either the branch between buses 5411 and 2135 or the branch between buses 4720 and 2694 can be disconnected. This simplification reduces the number of possible scenarios to a hybrid state with three possible discrete states and highlights the effectiveness of the proposed method.

4.1 Case Study

The proposed case study considers the event of the disconnection of the branch between buses 5411 and 2135, which induces a considerable impact on the power flow distribution of the grid. This event happens at time $t = 300s$ over a simulation time of 600s. Moreover, we consider a relevant

presence of measurement noise (V_i) in each branch, even if with different magnitude, where V_i is a Gaussian noise:

$$V_i \sim \mathcal{N}(\mu_i, \sigma_i^2).$$

Fig. 3, 4, 5, 6, 7, 8 and 9 show the power flow (generated via the command *runpf* of MATPOWER) on the branches of the zone and the considered noise for each of them/. Accordingly to the presence of noise, we select the values of the chosen parameter ϵ in (4) and of the considered L_i gains in (5). Because of the possible high uncertainties shown in Fig. 6 and 9, we consider $\epsilon = 30MW$ and privilege lower gains for the observers.

The generated power ΔP_n^G reflects real data of the wind power profiles considered in Hoang et al. (2021). Since the goal of this paper is merely estimation rather than control, as already mentioned we consider here the system to be open loop with a sequence of control inputs as exogenous inputs already predefined that play the role of exciting the system. This is done without loss of generality, as usually when a topological change takes place excitation signals are available, as power variation due to the neighborhood and consequent control decisions. Fig. 11 shows the considered excitation signals for $\Delta P_n^G(k) - \Delta P_n^C(k - \tau_C)$ in (1).

To better illustrate the considered approach and its possible advantages, the performance of the hybrid observer shown in the Figures of the branches is compared with a discrete-time Luenberger observer (indicated as "Discrete-Time Observer" in the Figures) that only takes into consideration the full grid model throughout the whole simulation (therefore, not considering the topological change), i.e., the model in (2).

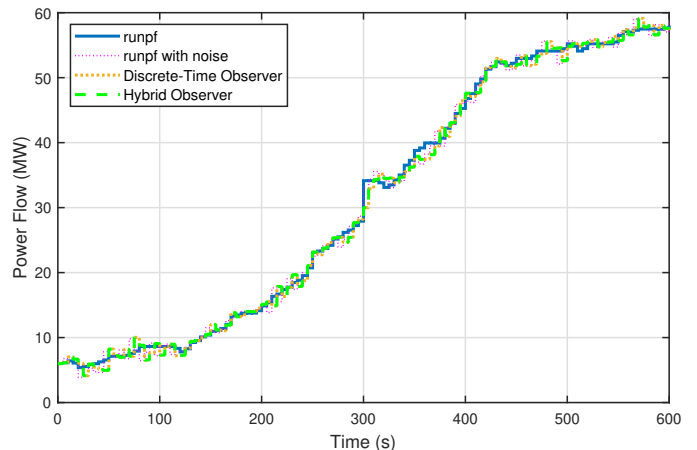


Fig. 3. Branch between buses 2745 and 1445

The results show the effectiveness of the hybrid observer to identify the correct model representing the current topology of the grid, as clearly shown in Fig. 6 and 9 when comparing the two observers performance after the topological change at $t = 300s$. Indeed, the hybrid observer is shown to converge faster to the correct state, thus implying a fast selection of the discrete mode representing the correct topological configuration. Clearly, the higher the noise, as common in real applications, the more effective the utilization of the hybrid observer. More in detail, Fig. 10 shows the dynamical evolution of each \hat{x}_i representing the output of a single observer (and so, one grid configuration)

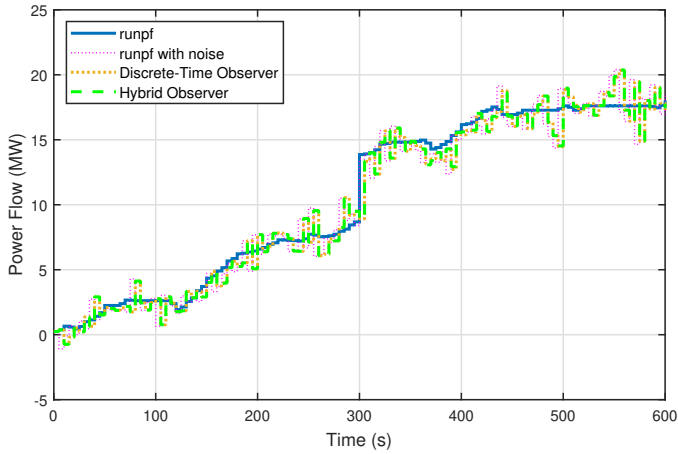


Fig. 4. Branch between buses 4720 and 1445

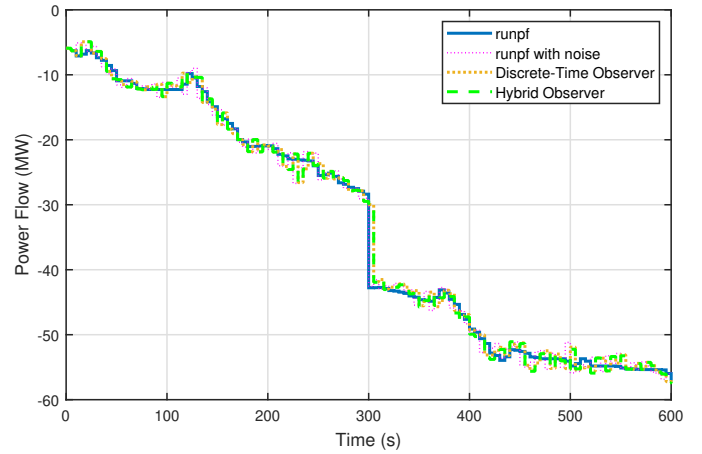


Fig. 7. Branch between buses 4720 and 2076

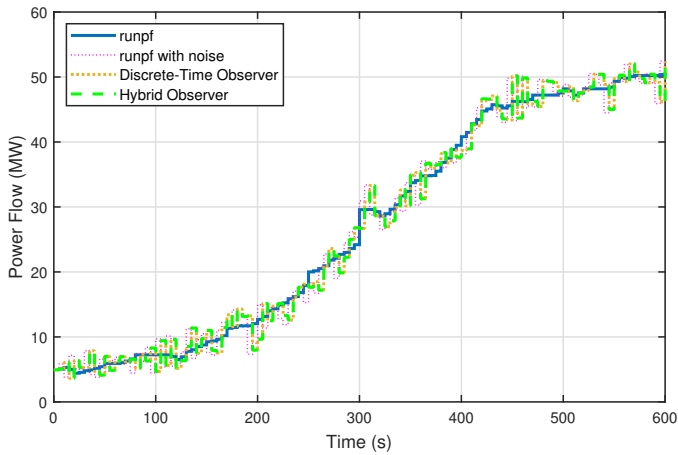


Fig. 5. Branch between buses 2745 and 1445

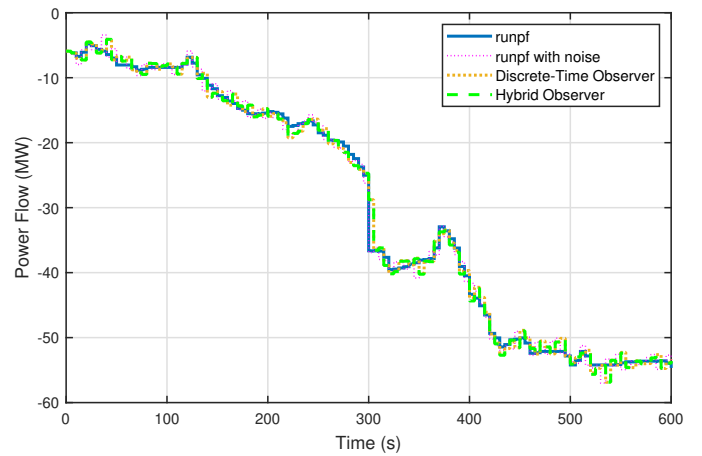


Fig. 8. Branch between buses 2745 and 10000

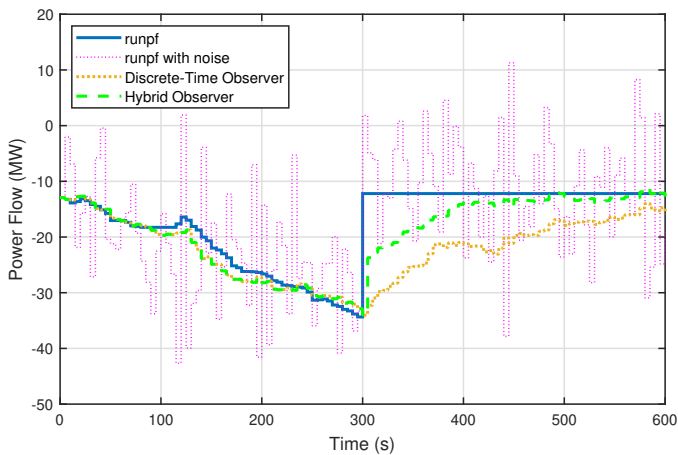


Fig. 6. Branch between buses 2135 and 2076

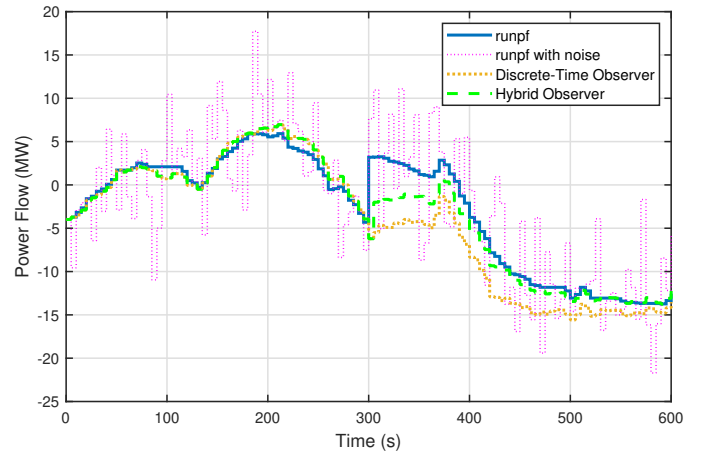


Fig. 9. Branch between buses 2076 and 10000

that is used in the formulation of the hybrid observer. As it is possible to see, the observer \hat{x}_3 (depicted in the dotted black line) which considers the model without topological changes, greatly fits the dynamical evolution of the system before the branch opening at $t = 300s$. Afterwards, the observer \hat{x}_1 (depicted in the red line), which refers to the correct topological change, it the one closer to the real power flow evolution.

5. CONCLUSION

The paper explores the application of a hybrid observer to identify the impact that topological changes might cause in the PTDF's of sub-transmission zones, which are extremely relevant for power congestion management. The results show that, in the case of a severe change in the power flow distribution and the presence of high measurement noise, this methodology clearly outperforms a standard observer, with only one system model taken

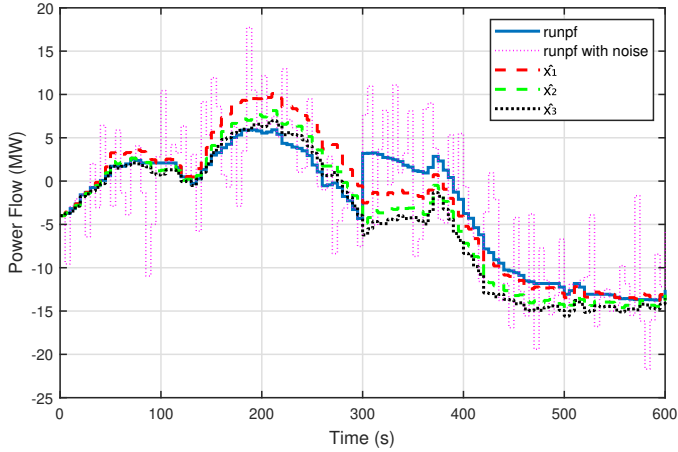


Fig. 10. Evolution of the Bank of Observers for Branch between buses 2076 and 10000.

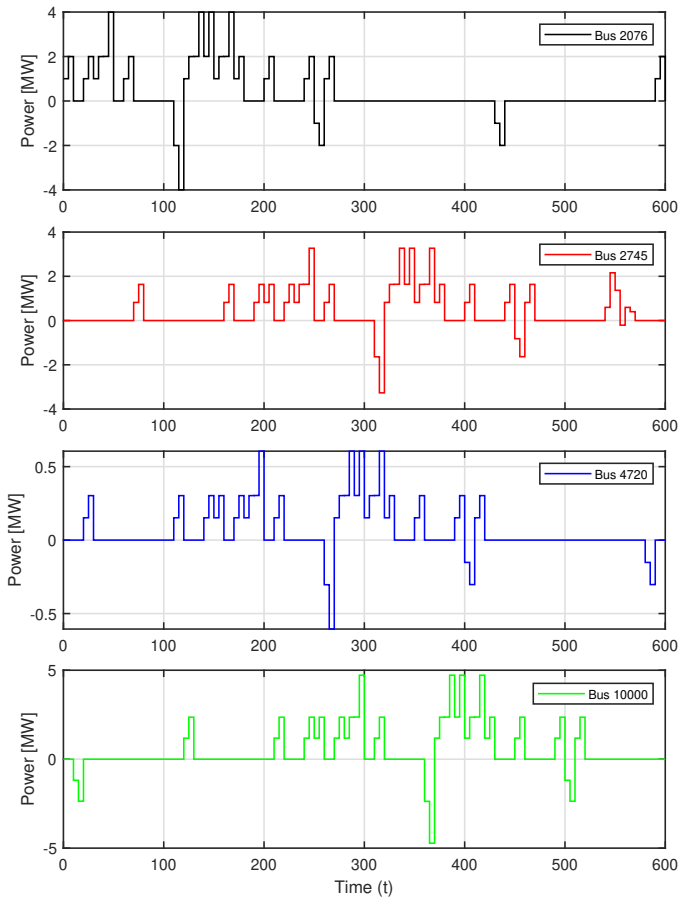


Fig. 11. Evolution of $\Delta P_n^G(k) - \Delta P_n^C(k - \tau_C)$ in (1).

into account, converging considerably faster to the new state of the power flow. Future work might investigate the application of this methodology in closed loop MPC formulations.

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