A Decentralized Observer for Electrical Power Systems:

Implementation and Experimental Validation

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Abstract – In the last few years the growing in complexity of the electrical power networks, mainly due to the increased use of electronic converters together with the requirements of higher level of reliability and security, pushed the development of new techniques for the state estimation of the power systems. In this paper, the author focus their attention on the implementation and experimental validation of a decentralized observer for the state estimation in an electric ship, whose power network is characterized by fast dynamics and by the presence of many electronic devices. The proposed solution implements a Decentralized Information Filter (DIF).

Keywords – Decentralized observer, Decentralized Information Filter, State estimation.

I. INTRODUCTION

State estimators have a critical role in power systems allowing the implementation of all the necessary controls for the safe and reliable operation of the network.

Traditional electric grids are characterized by a centralized control system that acquires and processes all the data collected from the grid. Usually, the state estimation of this system is based on a static model [1, 2]. Because of this, the estimator can be used only if the system is considered quasi-static.

In the last few years, due to the introduction of electronic power converters, the network can no longer be assumed to be quasi-static, and the implementation of a dynamic model has become necessary. Moreover, the use of converters has introduced a significant increase in the complexity of the network. Given this complexity, a centralized system becomes difficult to deploy and manage. These problems have required the development of new solutions; one of these solutions is the use of distributed systems [3,4] and decentralized systems [5,6]. Distributed systems are composed of several estimators, each of which supervises a portion of the network. The process of distribution and decentralization in the state estimation is also coherent with a similar process that is also happening for the control architecture more in general.[7]

In the paper we will present a first implementation of a Decentralized Information Filter (DIF) [8] for the state estimation on board of an electric ship, whose power network is characterized by fast dynamics and by the presence of many electronic devices. The proposed solution involves the use of several estimators distributed along the network, each of which makes an estimate for the sub-network and communicates with all the others. In this type of approach, the estimation is not based only on the measurements but also on a dynamic model of the network.

The main characteristics of this solution are:

• increased computational efficiency, due to the distribution of the computational burden among the estimators;
• increased reliability of the estimator, due to the distribution of the resources; and
• scalability of the estimation system.

In the following the results obtained from a physical implementation of this system are also shown. The experimental activity has been design to analyze in particular the following problems:

• implementation of real-time software,
• target synchronization, and
• communication.

II. THEORETICAL BASIS OF THE DIF

For the DIF each observer uses a dynamic model of the system (as well as for the Decentralized Kalman Filter). The forecasts of each observer are corrected based on measurements performed locally and information exchanged with other areas.

As outlined in [8], given the state vector $\mathbf{x}(k)$ and the covariance matrix of its estimate $\mathbf{P}^A(k)$, the DIF requires the introduction of two new variables denoted as the information matrix $\mathbf{Y}(k)$ and the information state $\mathbf{y}(k)$:

$$\mathbf{Y}(k) = [\mathbf{P}^A(k)]^{-1}$$
$$\mathbf{y}(k) = [\mathbf{P}^A(k)]^{-1} \mathbf{x}(k)$$
The implementation of the DIF is based on three fundamental steps:

A. Prediction

In this phase, the information matrix and state are predicted by the power system model from their estimates \(Y^T\) and \(y^T\) at the previous time step:

\[
Y^T(k) = [A_k][Y^T(k-1)] + Q_e:(k-1)
\]

\[
y^T(k) = L_c(k)y^T(k-1) + Y^T(k)B_c: e(k-1)
\]

\[
L_c(k) = Y^T(k)C_c: Y^T(k-1)
\]

The state space power system model is in the form:

\[
x_i(k) = A_i(k)x_i(k-1) + B_i(k)e(k-1)
\]

being \(e(k)\) the forcing input from the generators of the power system.

It is important to underline that the variations of \(A(k)\) and \(B(k)\) are due to variations of the Breaker-status vector, which describes the topology of the power system. The index \(i\) refers to the \(i\)th partition (zone) of the power system considered.

B. Communication

At this stage, the observer of each area \(j\) communicates with the others, exchanging the matrix \(I\) and the vector \(l\) obtained using the given formulas

\[
i_j(k) = C_j^T R_j(k)^{-1}[z_j(k)-D_j: e(j-1)]
\]

\[
I_j(k) = C_j^T R_j(k)^{-1} C_j
\]

\[
z_j(k) = C_j(k)x_j(k)+D_j(k)e_j(k).
\]

C. Measurement Assimilation

In this phase each observer assimilates the data obtained from other areas with the data calculated during the prediction and the measurements made locally, in order to obtain the new values of \(Y\) and \(y\).

\[
Y^T(k) = Y^T(k) + \sum_{j \in i} l_j(k)
\]

\[
y^T(k) = y^T(k) + \sum_{j \in i} l_j(k)
\]

To implement the information filter on the grid of a ship, the \(A\) and \(B\) matrices must be obtained by describing the network using state-space model. A criterion for the definition of the sub-grids of the system must be identified, together with the selection of the quantities \(y\) to be measured for each zone. The relation among the measurements and the state and input variables is expressed by means of the \(C\) and \(D\) matrices.

The topology discussed in this paper is a slightly simplified version of what has been previously proposed in [8]. This network is a reasonable notional power system for an electric ship application. The power system is composed of a three-phase distribution line and three zones, each composed of an AC-DC converter and an RC load in which \(R\) is variable (Fig. 1). The two inductors \(L_1\) and \(L_2\) are three-phase inductors which simulate the inductances of the AC lines of the ship.

The three-phase line represents the distribution system of the ship, and each zone models the structure of an area of the ship. Each zone is connected to the main AC grid by an AC-DC converter. The main simplifications of our approach concern with the realization of only three areas (a real ship will contain many more zones) and the choice of RC loads as shown in figure 2 (the loads on a ship are obviously expected to be more complex). The main idea is to introduce some significant equivalent dynamic to be analyzed with the DIF.

The modular structure of the chosen network has many similarities with the grid on board of a ship and facilitates the implementation of a decentralized estimator. The energy buffer created by the capacitors of each converter decouples the DC area from the AC area. This decoupling represents a natural separation among the three zones. The process of
partitioning a complex power system is discussed in [9,10, 11, 12].

Even if these converters are beneficial in their creation of a natural separation between zones, they represent an interesting challenge from the modeling standpoint. For example, for the implementation of the information filter, a linear model of the power system needs to be formulated in terms of state variables. A linear time-variant model approach is adopted for the converters. The model of the converter (Fig. 3) is based on controlled-voltage and controlled-current sources in the Park domain [13].

$$\begin{align*}
V_{di} &= \sqrt{2} I_d \sin \left( k \frac{\pi}{3} \right) \\
V_{d2} &= \sqrt{2} v_d \cos \left( k \frac{\pi}{3} \right)
\end{align*}$$

$\text{Fig. 3. Modeling of AC-DC converter using Park transformation.}$

As result, the network is composed of only linear components, and a state-space formulation can be adopted.

The model of the converter is time-variant because its variables are dependent on which diodes are in conduction at a given time. The time-variacy is reflected in the coefficient $k$. The choice of the correct value for $k$, is performed determining which diodes are conducting at every given time. This evaluation required for the hardware implementation the design of a custom hardware to keep the simulation synchronized with the network operation.

### III. IMPLEMENTATION OF THE EXPERIMENTAL TESTBENCH

#### A. Hardware

A power system replica of the model in Fig. 1 has been built. Each zone is made of an AC/DC converter connected to a variable load, as previously shown in Fig. 2.

The system has been equipped with a distributed data acquisition with local elaboration capabilities. The hardware used for the experiment can be divided into two blocks: the power section equipped with sensor and measurement processing and the intelligent module for the software implementation (Fig. 4).

The measurement system returns both the measurement-data vector, composed of the measurements of voltage and current on the DC side of the converter, as well as the breaker-status vector, composed of logic signals. These signals reveal the status of the load and the synchronization signal, i.e. the transition to zero of the phase chosen as reference for the system.

The components of the hardware are as follows:

- Uncontrolled AC/DC converter with $I_{\text{out,max}}=15$ A.
- Variable loads with absorption switching between 1.5A and 3A at a frequency of 1Hz, and,
- Variac which models the line inductors L1 and L2.

Two transducers are used for the measurement on the DC side: LA 55-P [14] for the current and LV 20-P [15] for the voltage. The signals of the transducers are conditioned and filtered at 250 Hz. The whole system has been designed for a bandwidth of 100 Hz. The synchronization signal used to determine $k$, is obtained by using a voltage transformer and a comparator. The signal is then filtered at 60Hz to remove any spikes due to switching. The phase error introduced by the filter and transformer is tabulated for frequencies between 58 and 62Hz and is corrected in the software.

**Power section: two zones and one variac**

**Control section**

**Fig. 4. Experiment hardware.**

The main specification for the elaboration and acquisition system of each area are summarized in the following.
The sampling frequency of 200 Hz with a resolution of 12 bits has been defined for the Analog to Digital Conversion. For the communication purpose an Ethernet interface has been selected. We chose to use standard ethernet communication instead to be aligned with the current trends in the automation of power systems. This choice in effect enables a future implementation of the IEC61850 standard, which is based on Ethernet physical layer [16]. These requirements were fixed also having in mind the equipment already available from our laboratory.

The acquisition-elaboration systems of each area are organized as follows:

- **Zone 1:** National Instrument CompactRio-9002
  - Digital Input-Output: Ni9401
  - Analog Input-Output: Ni9215
- **Zone 2:** National Instrument CompactRio-9002
  - Digital Input-Output: Ni9401
  - Analog Input-Output: Ni9201
- **Zone 3:** National Instrument PXI 8176
  - Analog and Digital Input-Output: Ni PXI 7831R

### B. Software

In a physical implementation of the DIF two main issues arise:

- role of the communication protocols
- synchronization of the execution.

Last but not least, the overall system has to be designed according to the requirement of being a hard real-time system. With this goal in mind, all functions were timed and particular attention was paid to communication.

The final structure of the software is reported in Fig. 4. A first step in the execution is the initialization during which the matrices $\mathbf{Y}$ and $\mathbf{y}$ are calculated and the ports for communication are opened. When this first phase is completed, the software enters an infinite timed loop.

The equations described above in the prediction and measurement assimilation stages are calculated in the local filter and in the global assimilation steps (see Fig. 5). The steps of synchronization, communication, and transmission-to-host are described below.

**Synchronization**

For synchronization, we used an external shared clock. With this solution, the error between two different observers is less than 200 µs. This synchronization technique is easy to implement and produces good results. However, it results in strong limitations for the distribution of the system: this is not a limiting factor for this experimental validation, but it may be a problem in future applications in systems characterized by long distance between the observers. In these applications, the synchronization must be replaced with a technique of synchronization based on ethernet communication: this issue has already been analyzed and resolved in many publications, such as in [16].

**Communication**

During the execution of this block each observer transmits to the others the values of $\mathbf{I}$ and $\mathbf{i}$, calculated in the local filter, as well as the values of the breaker-status vector, for the elements in each observer’s area. UDP (User Datagram Protocol) was used as communication protocol. Even though it does not possess the control-of-errors capabilities that TCP (Transmission Control Protocol) has, it was chosen because of its execution speed. The broadcast technique was used for transmission. Using the UDP protocol with broadcast transmission, a complete exchange of information among the three areas can be achieved in 6 ms.

**Transmission-to-host**

During the execution of this step, each observer transmits the values of $\mathbf{Y}$ and $\mathbf{y}$, calculated during global assimilation, to the host. Though the communication with the host is essential to monitor the operation of each observer, it is not necessary for the operation of the filter. Therefore, the transmission-to-host is not a critical point in the implementation of the software and does not have to be timed like the communication between one target and another. The transmission-to-host is executed in background, and the execution time of the program is reduced by 2ms. All the software was written using Labview 8.0.

### IV. EXPERIMENTAL RESULTS

Fig. 6 and Fig. 7 represent the comparison between the voltage directly measured on the capacitor $C_b$ (see Fig. 2) on zone 1 and the trend calculated by the software.

**Fig. 6.** Comparison between voltage measured and voltage estimated on capacitor $C_b$ of zone 1.
V. CONCLUSIONS

As shown in Fig. 6, 7 and 8, estimates are very close to the real trend of the voltage across the capacitor Cb: this result gives a confirmation of the theoretical work described in previous publications.

The performances of this system are conditioned only by the execution speed of the filter, which depends on the characteristic of the hardware and software: the performances of the system can be improved using more sophisticated hardware. The communication and synchronization steps influence the speed of the system, but not its accuracy.

A problem that arises from the analysis of this system is about the duration of the communication step: in fact, each communication needs 2 ms. In future applications with multiple observers, it will be necessary to develop an algorithm in which the observers communicate only with those nearest, to limit to overall computational burden deriving from the communication protocols.

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