Phasor Data Concentrators Placement in the Colombian Transmission System

R. Rincón
Department of Electrical and Electronics Engineering
Universidad Nacional de Colombia
Bogotá D.C., Colombia
rrinconb@unal.edu.co

R. Céspedes, SM IEEE
Department of Electrical and Electronics Engineering
Universidad Nacional de Colombia
Bogotá D.C., Colombia
rhcespedesg@unal.edu.co

***Abstract* — An assessment of the cost of implementing a Phasor Measurement System (PMS) to be used among other applications for evaluating the state estimation in the Colombian Transmission System (STN) is performed, using the costs associated with PMUs, Phasor Data Concentrators (PDCs) and leasing of existing communications networks. First, the optimized PMS topology is obtained by the optimized placement of PDCs in the STN considering different scenarios, minimizing the approximate cost of communication which is mostly dependent on the length of the communication channels and also dependent on the number of PDCs considered. Based on the results obtained for the PDCs placement, the approximate total cost of a PMS implementation is evaluated including PMUs and PDCs to compare its various components and draw some conclusions about the best implementation approach.**

Keywords— PDC Placement, PMU, Synchronized Phasor Measurement System, Power System.

I. Introduction

Phasor Measurement Systems (PMS) are being implemented worldwide in all continents to complement SCADA technology that has been used for decades for power systems monitoring, supervision and control. The PMS consists of Phasor Measurement Units which gather the data which is transmitted to distant located data processing centers where decisions about the power system operation are taken. Given the normally long distances involved, a complex communication network must be used for data transmission. Commercially available communications may be employed to keep the PMS implementation costs at reasonable levels. The problem that is then formulated is to obtain the best topology of the communication network that links all the substations with the decision making centers.

The several solutions that may be formulated could involve a star configuration that connects the control center PDC with all substations or have another approach considering an intermediate layer of subordinated PDCs that concentrate data at regions, where data may be needed for distributed decisions, and forward this data to the main control centers. The star configuration involves a number of long point to point communication channels that are considered too costly after some preliminary assessments. Besides, reliability considerations do not favor this approach and rather a network of PDCs appropriately configured is considered the base of an optimal solution. In this work the solution with hierarchical PDCs is analyzed and thus a number of scenarios arise to achieve the goal of designing the best possible configuration.

Phasor Measurement Units (PMUs) perform the calculation of positive sequence components of voltage and current measurements. Phasors measured by these devices are obtained by means the Discrete Fourier Transform (DFT) applied to a moving data window, whose width can vary from a fraction of a cycle up to multiples of a cycle. The sampling rate of the PMUs can reach values of 100 samples/cycle or more [1, 2].

An anti-aliasing filter is used to remove existing higher frequencies in the input signal according to the Nyquist criterion. An oscillator converts the signal of one pulse per second (pps) provided by the GPS system in a pulse sequence of high-speed used for the signal sampling. The microprocessor performs the calculations of the phasor by the DFT of the signal. Finally, a time stamp is assigned to the calculated phasor and the measurement is transmitted to the Phasor Data Concentrator (PDC) which correlates the information obtained configuring a useful set of measurements of the power system.

Consequently, the PMUs provide synchronized phasors and frequency of the power system, as well as additional information such as calculations of active and reactive power and element status data. A PMU can be implemented as a physical "stand-alone" device or as part of a multifunction set of devices such as protection relays, Digital Fault Recorders (DFRs) or meters. The information from PMUs can be recorded locally or transmitted in real-time to a central location as shown in Fig 1.

The PDC functions as a node in the communication network where data from different PMUs or other PDCs are correlated and sent in a single "stream" of data to higher levels PDCs to be used by different applications [3]. A typical phasor data collection network is shown in Fig. 1.

Some of the additional features offered by PDCs are:

- Phasor information validation and insertion of appropriate flags in the "stream" message,
- Disturbances flags validation and information recording for subsequent analysis,

- Measuring system monitoring and results display and performance recording,
- Specialized outputs such as direct interfaces with the SCADA/EMS system [3].

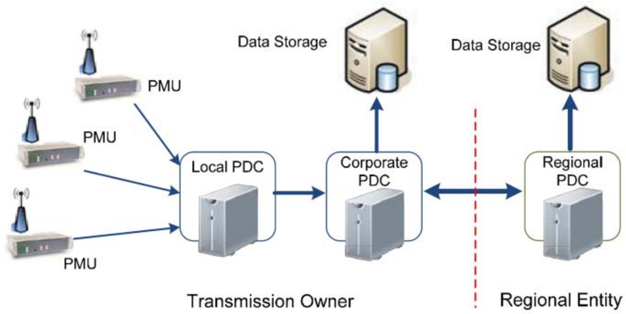

Fig. 1. Phasor Data Collection Network [3]

Local PDCs incorporate and align in time the phasor information coming from different PMUs feeding applications. The medium level PDCs collect phasor information from other PDCs, perform data quality validations and feed applications. The high level PDCs or "SuperPDCs" incorporate and archive the phasor information. The PDCs can be recognized more as a function instead as a "stand-alone" hardware and/or software device and they can be integrated with other systems and devices. A structured hierarchy of PDCs may be implemented to be used at substations, utilities, control areas and reliability coordination interconnection levels. Each layer of this hierarchy may have different latency[1], quality[2] and resolution[3] requirements, which are determined by the applications fed by the phasor information. Since local PDCs represent a potential local failure point for the information stream, backup options or network reconfigurations are needed to mitigate these failures and maintain a high system reliability, with availability figures of normally 99,9% or more.

One of the main components of a synchronized phasor measurement system is the communications system which must exist to link the substations equipped with PMUs to the data processing centers. A Phasor Measurement System will thus include all the implemented PMUs, which data is normally concentrated in a hierarchical set of data concentrators (PDCs) using a communication network. Phasor data is transmitted to the PDCs, using several means such as dedicated phone lines or Wide Area Network (WAN), fiber optics, microwave links, Power Line Carrier over transmission lines, etc. The speed of the communication system must be adequate to support the high amount of data from the PMUs. This can impose a strong limitation on the number of PMUs installed in the system if there are no adequate communication channels, but the benefits obtained by having an optimized synchronized phasor measurement system can justify the installation of an appropriate communications infrastructure.

[1] Time delay introduced by the elements of the layer corresponding to the period of time required to process and transmit the received data.
[2] The state of completeness, validity, consistency, timeliness and accuracy of the data.
[3] Sample time at which data from the electric system is captured.

This paper is organized as follows: in section II the methodology proposed for the optimal PDCs placement in the Colombian Transmission System (STN) from the economic viewpoint, is presented under the assumption of a gradual implementation of PMUs in the STN. In section III, the total annual cost of phasor measurement system implementation is calculated taking into account the investment, maintenance and the communication costs in order to determine the optimal amount of PDCs to be implemented in the STN. Finally, some conclusions regarding the optimal PDCs placement are presented in section IV.

II. PDCs Placement in the Colombian Transmission System (STN)

Taking into account the equipment and communications costs of a phasor measurement system to be implemented in a power system, an optimal PDCs placement was performed in the STN from the economic viewpoint, assuming the plan is to gradually increase the number of PMUs installed in the STN and considering the communication system required to accomplish this goal. The central PDC should be close to the national control center. For the Colombian case, this is accomplished considering a substation where the alternate national control center is located.

The cost of leasing communication channels is assumed to be proportional to the length of the channel and is given by:

$$C_i = k_i \cdot \ell_i \tag{1}$$

Where k_i mainly depends on the bandwidth required to transmit data from the PMU installed in the node *i* to the data concentrator, it is expressed in monetary units per kilometer ($/km) and ℓ_i is the distance from the node *i* to the data concentrator, given in kilometers (km).

Assuming that the bandwidth is constant and adequate for the amount of data to be transmitted and other costs are fixed, to minimize the cost of leasing a particular communication channel, the channel distance must be minimized:

$$min\ C_i = k_i \cdot min\ \ell_i \tag{2}$$

Therefore, to minimize the cost of using the communication channel, is equivalent to find the shortest path from node *i* to the data concentrator. To perform this, MATLAB® was used, which features a tool based on the shortest path algorithm of Dijkstra [4]. The topology of the STN and the length of each of the transmission lines were taking into account to build a matrix containing elements at ℓ_{kl} and ℓ_{lk}, the shortest distance between any pair of nodes *k* and *l*.

To determine which system substation might implement a data concentrator, the fact that data must be transmitted to the alternate control center, where the access to the National System Operator data network is granted, was taken as a criterion. Another important consideration is that if a PDC must be installed in a substation for a set of PMUs, the owner of this substation should be the National Transmission Company, since it has the service of a WAN communications network that can provide the service to other transmission companies that may require it.

To perform this analysis, the following STN operative areas were considered: "Antioquia/Chocó", "Caribe", "Nordeste", "Oriental" and "Suroccidental" as shown in Fig. 2. To locate a PDC, the sum of the distances from the nodes which have PMUs to the node where the PDC is implemented shall be minimum:

$$min\ L = \sum_{i=1}^{p} \ell_i \qquad (3)$$

Where p is the number of PMUs considered in an operative area or in the whole STN, according to the selected scenario.

Twenty-four scenarios for PDCs placement were considered. For scenarios 1 to 12, the starting point is a PDC in the substation where it is considered the Alternate control center (Base Case 1), increasing the number of PDCs in each operative area e.g. to have two PDCs in each area for scenario 12. For scenarios 13 to 24, an additional PDC is considered in San Carlos node (Base Case 2) due to the sum of minimum distances from the remaining nodes to this node is minimum and then the number of PDCs is increased in each operative area.

TABLE I. COMUNICATION CHANNELS DISTANCE CHANGE WITH 35 PMUS

35 PMUs			
Scenario	***Placement PDCs***	***$\Delta\ell$ (relative to the base case) [km]***	***Number of measurements concentrated***
1 (Base Case 1)	Ancón Sur	0,00	304
8	Ancón Sur	-7.906,89	48
	Sabanalarga		62
	Guatigurá		76
	La Mesa		40
	San Marcos		78
12	Ancón Sur	-8.307,35	48
	Sabanalarga		50
	Bolivar		12
	Guatigurá		46
	Comuneros		30
	La Mesa		20
	Noroeste		20
	San Marcos		64
	Páez		14
13 (Base Case 2)	Ancón Sur	0,00	48
	San Carlos		256
20	Ancón Sur	-6.334,12	48
	Sabanalarga		62
	Guatigurá		76
	La Mesa		40
	San Marcos		78
	San Carlos		256
24	Ancón Sur	-6.774,58	48
	Sabanalarga		50
	Bolivar		12
	Guatigurá		46
	Comuneros		30
	La Mesa		20
	Noroeste		20
	San Marcos		64
	Páez		14
	San Carlos		256

Distance differences ($\Delta\ell$) were determined for the total distance of the communication channels for each scenario relative to the base cases 1 and 2, this information was used for the calculation of the cost of using the communications service. This was performed for the case that consider 35 PMUs belonging to the optimal set [5] of the STN, Table I, and for the case that consider 101 PMUs, which includes all of the nodes of the analyzed system, Table II.

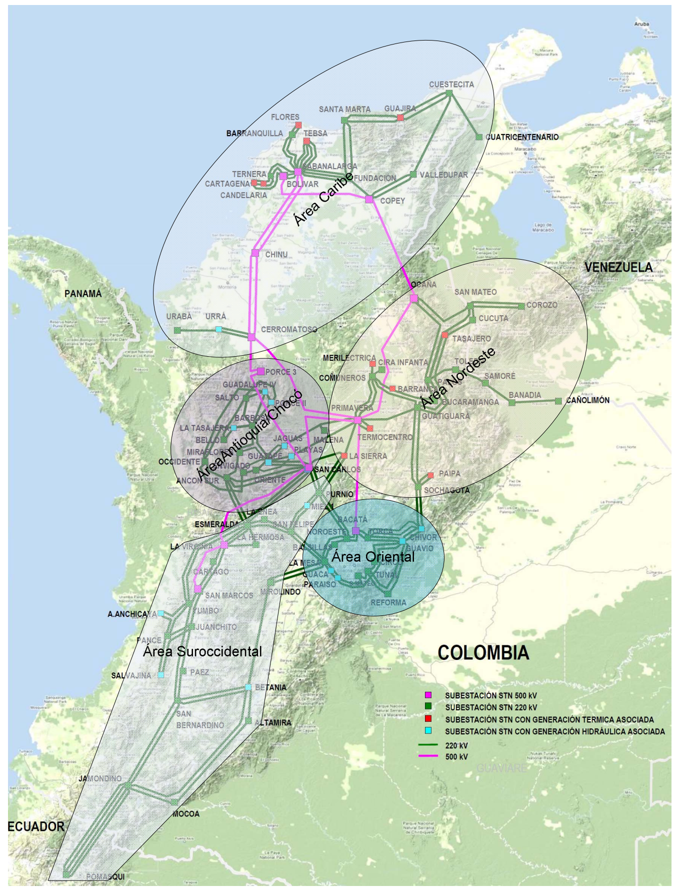

Fig. 2. Transmission System (STN) Operative Areas [6]

From Tables I and II, it is clear that when considering a larger number of PDCs in operative area, the total distance of the communication channels decreases. Also the PDCs to be implemented and the number of phasor measurements concentrated by each PDC are shown. For better illustration only 6 of the 24 scenarios are presented, while the complete results for each of the 24 scenarios considered are shown in [7].

As an example, in Fig. 3 the distances to be considered for scenario 8 with 35 PMUs are shown. For this scenario, a PDC in each of the operative area is considered and they are connected with the alternate control center PDC, which besides being the link with the national control center, it is also used as PDC of the "Antioquia/Chocó" area. The total distance of the communication channels for this scenario is 6.686 km, achieving a reduction of 7.906 km relative to the base case 1, as shown in Table I.

TABLE II. COMUNICATION CHANNELS DISTANCE CHANGE WITH 101 PMUS

101 PMUs			
Scenario	***Placement PDCs***	***Δℓ (relative to the base case) [km]***	***Number of measurements concentrated***
1 (Base Case 1)	Ancón Sur	0,00	821
8	Ancón Sur	-22.073,55	159
	Sabanalarga		154
	Guatigurá		174
	La Mesa		114
	San Marcos		220
12	Ancón Sur	-23.193,81	159
	Sabanalarga		118
	Bolivar		36
	Guatigurá		96
	Comuneros		78
	La Mesa		44
	Noroeste		70
	San Marcos		190
	Páez		30
13 (Base Case 2)	Ancón Sur	0,00	159
	San Carlos		662
20	Ancón Sur	-17.993,66	159
	Sabanalarga		154
	Guatigurá		174
	La Mesa		114
	San Marcos		220
	San Carlos		662
24	Ancón Sur	-19.113,92	159
	Sabanalarga		118
	Bolivar		36
	Guatigurá		96
	Comuneros		78
	La Mesa		44
	Noroeste		70
	San Marcos		190
	Páez		30
	San Carlos		662

III. PDCS AND PMUS COSTS

To obtain the PMUs and PDCs costs, a comparison of the main features of a dedicated PMU and a protection relay that in addition to its protection and control functions can perform PMU functionalities was performed. The functionalities of a PMU ABB RES670 [8] and SEL411L [9] relay with PMU capabilities were compared.

The functionalities of the available equipment are comprehensive and not very different from one manufacturer to another, but the main difference is the price of the equipment. Given that a relay with PMU capabilities may have similar characteristics to a dedicated PMU, a relay can be used as part of the synchronized measurement system.

The PDCs cost must be taken into account, in [10] several models of PDCs from different manufacturers are listed, including some reference prices. The costs shown in Table III for PMUs and PDCs are used. To obtain the annualized cost of PMUs and PDCs, a lifespan of 20 years, an interest rate of 10% and annual maintenance cost of 10% of the initial investment were assumed.

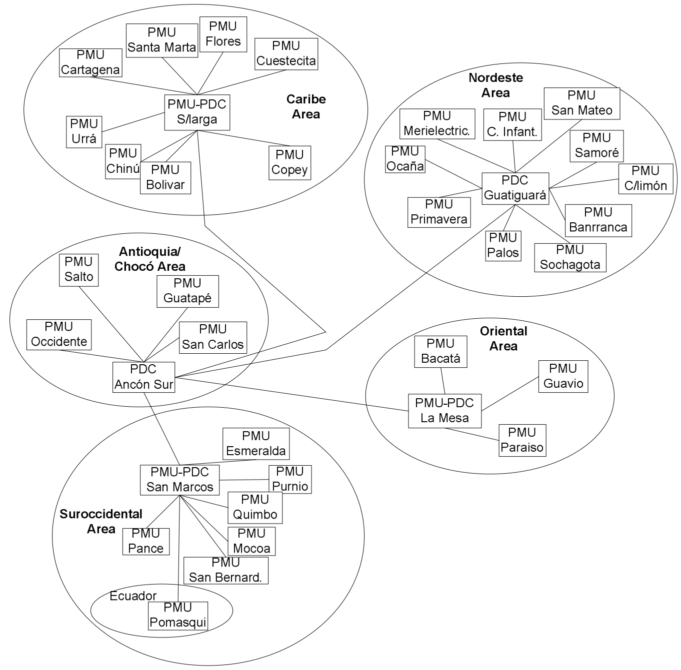

Fig. 3. Schematic Diagram for PDCs Placement – Scenario 8 (35 PMUs)

TABLE III. PMUS AND PDCS COSTS

	Investment [USD]	***Maintenance Cost [USD/year]***	***Annual Cost [USD/year]***
PMU	8.515	851,50	1.851,67
PDC	80.000,00	8.000,00	17.396,77

The estimated Total Annual Cost (TAC) of the phasor measurement system implementation is given by the following expression:

$$TAC = N_{PMU} \cdot Cost_{annualPMU} + N_{PDC} \cdot Cost_{annualPDC} + k_{\ell} \cdot \ell_{total} \quad (4)$$

Where, N_{PMU} is the number of PMUs implemented, N_{PDC} is the number of PDCs implemented, k_{ℓ} is the cost of hiring or utilization of a communication channel given in (USD/ (km•year) and ℓ_{total} is the total length of the communication channels. From expression (4), it is observed that total annual cost of implementing a phasor measurement system depends on the scenario under consideration. These scenarios were defined in Section II.

The reference values for k_{ℓ} may vary from 65 USD/(km•year) for channels with a bandwidth of 50 Mbps to 84 USD/(km•year) for a bandwidth of 100 Mbps, but it is possible to take a lower value when a large number of transactions are considered collectively. A value for k_{ℓ} of 50 USD/(km•year) was used to calculate the total annual cost of the synchronized phasor measurement system given by expression (4).

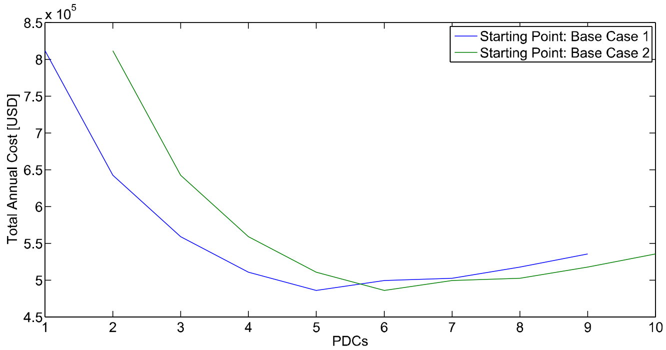

Fig. 4. Total Annual Cost vs. Number of PDCs (35 PMUs)

As shown in Fig. 4, when the implementation of 35 PMUs is considered, the total annual cost decreases as a PDC is implemented in each operative area, once the minimum cost point is reached, the total annual cost starts to increase again. Starting from base case 1, the minimum cost is reached when there are 5 PDCs i.e. for scenario 8. Starting from base case 2, the minimum cost is reached when there are 6 PDCs installed, which corresponds to scenario 20.

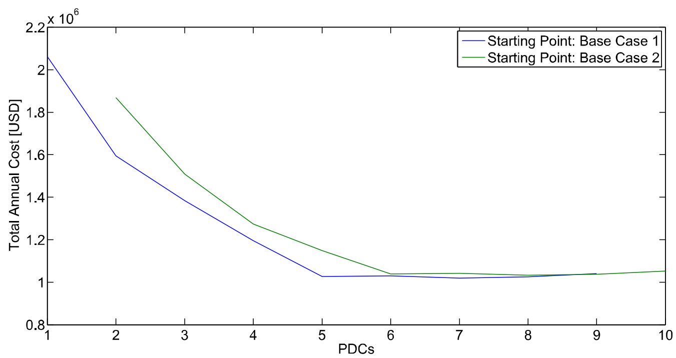

Fig. 5. Total Annual Cost vs. Number of PDCs (101 PMUs)

As shown in Fig. 5, when the implementation of 101 PMUs is considered, the total annual cost decreases as a PDC is implemented in each operative area, once the minimum cost point is reached, the total annual cost starts to increase again, but this increase is not significant. Starting from base case 1, the minimum cost is reached when there are 5 PDCs i.e. for scenario 8. Starting from base case 2, the minimum cost is reached when there are 6 PDCs, which corresponds to scenario 20.

In Both cases 35 PMUs and 101 PMUs implemented in the STN, the scenario 8 has the lowest cost of phasor measurement system implementation due that for this scenario fewer communication channels are needed, reducing the overall cost considerably when considering a PDC in each operative area of the STN.

IV. CONCLUSIONS

When implementing a synchronized phasor measurement system, it is important to consider the cost of the communication services required which according to this analysis correspond to the highest costs of the system.

The installation of more than one PDC per operative area for the case of Colombia implies an increase in the total annual cost of the synchronized phasor measurement system. Therefore, due to the high costs in implementing a synchronized phasor measurement system, it is important to optimize the location of the PDCs to have a better communication topology to minimize its impact on the cost of the communications service.

Although the cost of PMUs has declined significantly in recent years, it is important to optimize their placement to keep the total system investment reasonable considering also operation and maintenance costs of the phasor measurement system to justify its implementation.

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