Optimal WAMS Configuration in Nordic Power System

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Abstract

The Smart grids are considered as multi-disciplinary power systems where the communication networks are highly employed. This paper presents optimal wide area measurement system (WAMS) configuration in Nordic power system. The transition from SCADA to WAMS becomes now trend in all power systems to ensure higher reliability and data visibility. The optimization applied in this research considered the geographical regions of the Nordic power system. The research considered all the devices of WAMS namely phasor measurement units (PMUs), phasor data concentrators (PDCs) and communication links. The study also presents two scenarios for optimal WAMS namely base case and N-1 contingency as different operating conditions. The result of this research presents technical and financial results for WAMS configuration in a real power system. The optimization results are performed using MATLAB 2017a software application.

Keywords:

Wide area measurement system; phasor measurement unit; Nordic power system;

1. Introduction

A smart grid may be defined as an electrical grid which consists of variations of operational and energy measures including smart meters, smart appliances, renewable energy resources, and energy efficiency resources [1]. The Smart Grid may be understood as an electric system that uses information, two-way cyber-secure communication technologies, and computational intelligence in an integrated fashion across electricity stages in terms of generation, transmission, substations, distribution and consumption to achieve a system that is clean, safe, secure, reliable, resilient, efficient, and sustainable [2].

Control of the output and distribution of electricity and electronic power conditioning are important facets of the smart grid. The collection of current and proposed responses to the challenges of electricity supply represents the smart grid. Because of the diversity of factors, there are numerous competing nomenclatures and no agreement on a universal definition. The smart grid without the intervention of technicians, will make use of technologies such as state estimation that improve fault detection and allow self-healing of the network. This guarantees a more dependable supply of electricity and reduced vulnerability to natural disasters or attack is ensured. The present study is designed to provide a contemporary understanding on smart grid. It comprises the benefits, concepts and technology of smart grid; business and operations of energy generation; smart grid architecture and implementation; how advanced technologies shall be integrated to enable a modern grid; and how renewable can be integrated more faultlessly using smart grid technologies. Smart grid is considered the broadest, most researched subject in the electrical energy sector since the turn of the millennium. Many researchers tracked the concept and proved it through either simulations or prototypes. WAMS is considered the most significant topic and the most researched topic in smart grids. The Importance of WAMS came from the idea that all the grid data has to be accessible in real-time basis to all stakeholders with permission to follow. In the past century, SCADA was the main tool of measurement in power systems. the main drawbacks of SCADA can be summarized in delay in sending data and point to point data exchange [3].

Researchers tracked the idea of WAMS in a smart grid with 100% renewable energies using wide area measurement system and control in [4]. In [5], the authors tracked the idea of operating voltage control in a multi-region power system using WAMS. The authors applied load frequency control in a microgrid using PMUs and 5G facility in [6]. In [7], the authors presented wide area measurement system full configuration in standard power systems. In [8], the authors presented WAMS full configuration with least cost in the Egyptian grid.

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Table1. Literature review strength and limitation points

Reference	Authors	Year	Strength	Limitation
[3]	Hady H. Fayek	2019	Wide area measurement system is made for the whole Egyptian grid	WAMS is implemented for secondary voltage control only
[8]	H. H. Fayek, K. R. Davis, A. M. A. Ghany and O. H. Abdalla,	2018	Wide area measurement system is made for the whole Egyptian grid	WAMS is implemented to measure the pilot bus voltage for secondary voltage control only
[9]	F. Li, W. Qiao, H. Sun, H. Wan, J. Wang, Y. Xia, Z. Xu, and P. Zhang	2010	Full smart grid vision is presented	Details of implementations isn't clear
[7]	M. B. Mohammadi, R. A. Hooshmand, and F. H. Fesharaki	2016	Full WAMS configuration optimally implemented in standard grids	No consideration for geographical regions as the applied power systems are benchmarks
[10]	Y. Su, and C-W Liu	2013	PMU configuration is implemented for secondary voltage control	No consideration for the rest of WAMS
[11]	L. M. Putranto, R. Hara, H. Kita and E. Tanaka.	2016	WAMS is implemented for voltage control	WAMS is implemented for voltage control only
[12]	Chathura Thilakarathne, Lasantha Meegahapola, Nuwantha Fernando	2018	PMUs are implemented for real-time voltage stability study based on WAMS	WAMS is implemented for voltage stability only
[13]	M. Hasanuzzaman Shawon, S. M. Muyeen, A. Ghosh, S. M. Islam and M. S. Baptista.	2019	Studies on ICT in smart grids	Outlines study without details
[14]	V. K. Agrawal, P. K. Ararwal	2011	Challenges of implementing PMUs in North India	Not implemented for full system and not for whole grid
[4]	O. H. Abdalla, H. H. Fayek, and A. M. Abdel Ghany,	2020	PMUs configuration is applied for secondary voltage control only	Regions are not considered
[5]	O. H. Abdalla, H. H. Fayek, and A. G. M. Abdel Ghany,	2020	PMUs are implemented only in pilot buses	Optimal WAMS configuration isn't implemented for multi-usage.
[6]	H. H. Fayek	2020	WAMS is implemented for frequency control in microgrids.	Not applicable in power grids.

The main contributions of this paper are:

- Optimal configuration of WAMS in the Nordic power system as a real power system considering regional boarders
- Presenting two scenarios for the optimal configuration of WAMS which are base case where each bus bar should be measured by at least one PMU while the second scenario is N-1 contingency where each bus bar should be measured by at least two PMUs.

The paper is organized as follows. Section 2 describes WAMS. Section 3 presents the Nordic power system. Section 4 presents the proposed technique in this research. Section 5 explains the programming of the proposed technique. Finally, section 6 presents the main results and section 7 summarizes the concluding points.

2. WAMS

Deregulating the power system has resulted in more complexity in planning, operation, control and protection. The SCADA system in power grids should be upgraded to achieve the most favorable operation. As the global inclination to achieve near optimum performance, the SCADA could be supplanted by WAMS (wide area measurement system). Time synchronized and time aligned phasor data from WAMS allows the following [8]:

- To see dynamics not detectible in conventional SCADA measurement systems.
- Enables real event analysis by precise comparison.
- Like traffic cameras monitoring transmission highways.
- Visualize traffic density as well as pattern.
- Provides early warning of trend in beginning of dynamic interaction.
- Provides root cause analysis of the events.
- Improve situational awareness.

A device that benefits from digital signal microprocessors that can measure 50/60Hz AC voltage waves and current waves typically at a rate of 48 samples per cycle is known as the phasor measurement unit as shown in Figure 1 [15]. A phase-locked oscillator aligned with a GPS reference source, provides the required high speed synchronized sampling with 1μs accuracy. Each site of the Phasor Measurement Unit (PMU) is calculated by the transmission frequency. This mode of phasor measurement takes place with a highly marked resolution and accuracy. The resultant time tagged phasors can be transmitted to a local or remote receiver at rates up to 0-60 samples per second based on the country code. PMUs have various sizes. Some of the larger ones can measure up to 10 phasors plus frequency while others only measure from one to three phasors plus frequency. The PMUs are integrated to the power grid through current and voltage transformers as shown in Figure 2 [3].

Problems that may occur in using WAMS according to previous experiences [14];

- Problem in some places due to limitation of cable length of GPS antenna.
- Unavailability of clearest possible view of the sky.
- GPS sometimes lose synchronization due to bad weather conditions.
- Non-availability of communication links/channels.
- Non-availability of protection core or restriction of load on protection core of current transformer.

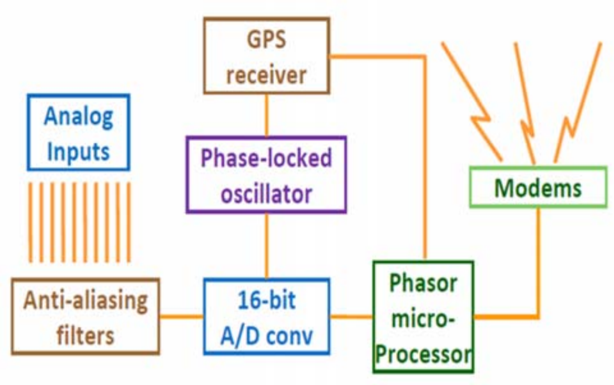

Figure 1 PMU block diagram

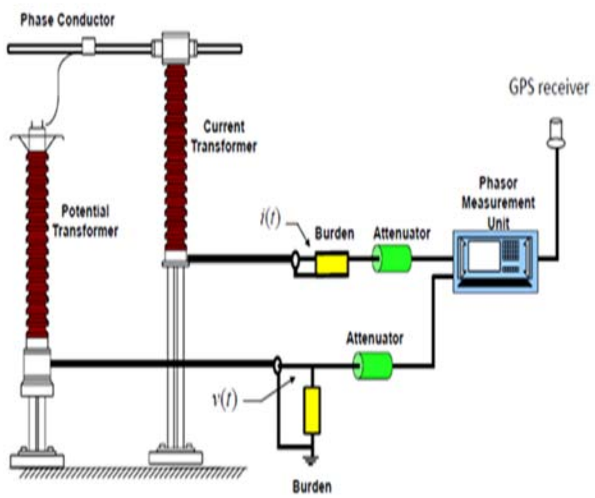

Figure 2 Integration of PMU to power grid

2.2. WAMS components

As shown in Figure 3, the WAMS consist of the following devices:

- Phasor measurement unit
- Phasor Data Concentrator (PDC) which can be applied as a stand-alone unit that collect data and reallocate it to other applications. The PDC functions can also be incorporated into other systems, for example monitoring/control platforms.
- Communication links that transmit data among PDCs and PMUs
- Operator console which is responsible for monitoring the operation in control center either regional or national scale
- Data storage which stores the data for future and evaluation

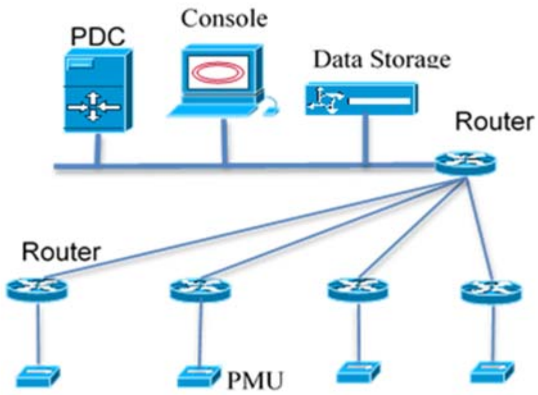

Figure 3 WAMS components

3. Nordic Power System

The Nordic power system consists of 17 generators, and it represents Finland transmission power grid with Sweden, Norway and Eastern Denmark. The power grid is shown in Figure 4.

The power system is consisiting geographically of 4 regions namely

1. External region
2. North region
3. Center region
4. South region

Many studies were applied in Nordic power system such as open dispatch [15], modelling and simulation of Hydro power plants in Nordic area [16].

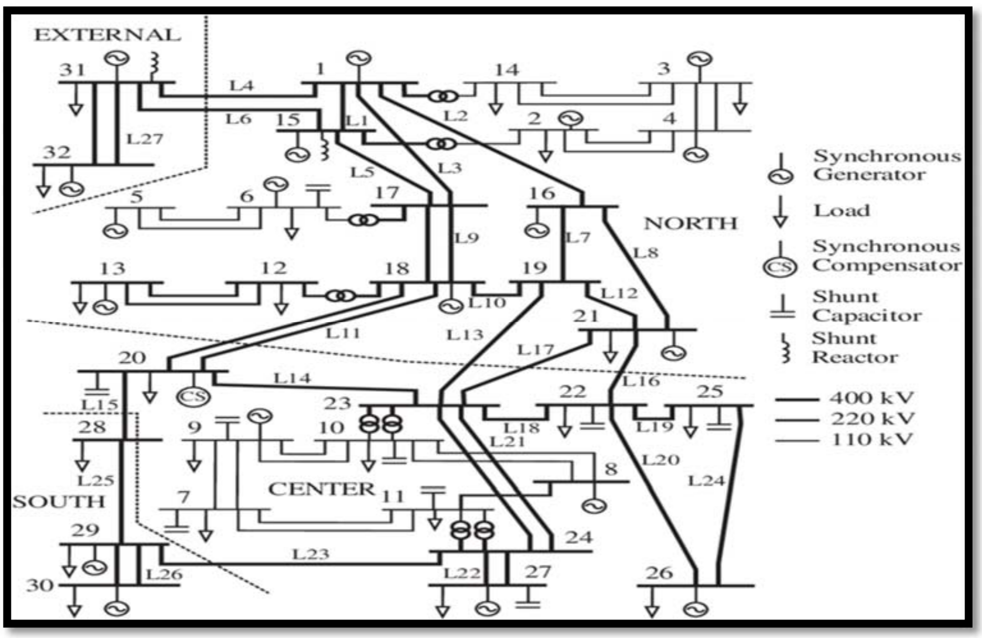

Figure 4 Nordic power system

4. Proposed method for optimal configuration of WAMS

The flowchart for the proposed method to optimally configure WAMS in a power system is shown in Figure 5

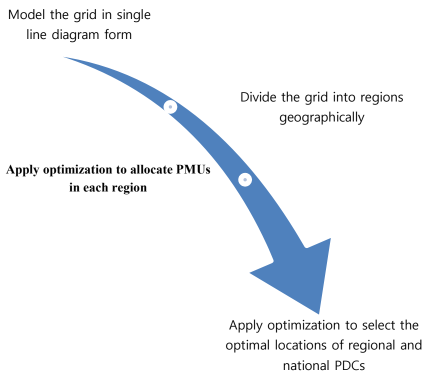

Figure 5 Proposed method for optimal WAMS configuration flowchart

To allocate PMUs optimally in each region the following optimization is applied using integer programming:

Objective Function: minimization of total cost

$$min \sum_{i=1}^{n} C_i x_i \qquad (1)$$

Variables: Buses include PMUs

Constraints: variables at each bus should be measured by at least one PMU (K = 1) at base case or two PMUs in N-1 contingency (K = 2). K is the minimum number of PMUs that can measure the voltage at each busbar.

$$\boldsymbol{f}(X) \geq \boldsymbol{K} \qquad (2)$$

In the constraint (2), $f(X)$ implies that at least K PMU(s) can measure each busbar in the power system. $\boldsymbol{K}$ is a vector whose entries are all of the same value K. The PMU can measure the voltage at its own bus and the buses which are directly connected through a transmission line or a transformer to that bus. The cost of the PMU includes costs of many components like channels, routers and communication facilities in addition to the transportation and installation costs. Despite all of that it can be assumed that all PMUs have the same cost except for the channels.

To allocate the PDCs optimally, the objective function in (3) is applied

$$min\left\{\sum_{i=1}^{n}(C_i X_i) + C_{fb} \sum_{i=1}^{m}(l_i) + C_{Sw} \sum CI\right\} \qquad (3)$$

Where C_{fb} is the installation cost of 1 km of the optic fiber links and l_i is the total length of the optic fiber links between the i^{th} PMU and the PDC. Also, m is the number of PMUs installed in the network and C_{Sw} is the cost of a switch. Every CI node is one of the system buses appearing in the communication path from a PMU to the PDC. After allocating the PMU, the optimization program assumes that the PDC is allocated at each bus and the total cost of the communication will be calculated. Finally, the lowest cost indicates the optimal location of the PDC.

5. MATLAB coding for optimal configuration of WAMS

The following lines are the code for optimal allocation of PMUs in a power system clc;

```
f=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1];

A=[1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0;

 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0;

 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0;

 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0;

 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0;

 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;

 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0;
```

0 0 0 0 0 0 1 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;

1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0;

0 0 1 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 1 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0;

0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0;

0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0;

```
  0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0;
  1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0;
  1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0;
  0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0;
  0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0;
  0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0];
 b=[1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1];
Aeq=[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1];
beq=1;
lb=[0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0];
ub=[1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1];
[x ,fopt]=bintprog(f,-A,-b,Aeq,beq,lb,ub);
k=0;
for i=1:length(x(:,1))
if x(i,1)==1
k=k+1;
pmu_location(k)=i;
end
end
```

6. Optimization Results

After applying the proposed method to the Nordic power system considering the condition that at least one PMU can reach the voltage measurement of each busbar, Table 2 shows the results.

Table 2. Optimal configuration of WAMS in base case

Region	PMUs at Buses	Regional PDCs	National PDC
External	31	31	
North	1,4,5,13,18,21	17	18
Center	23,7,8,27,25	23	
South	29	29	

Table 3 shows the optimal configuration of WAMS to the Nordic power system considering the condition that at least two PMUs can reach the voltage measurement of each busbar

Table 2. Optimal configuration of WAMS in N-1 contingency case

Region	PMUs at Buses	Regional PDCs	National PDC
External	31 and 32	31	18
North	1, 4, 5, 13, 18, 21, 17, 19 and 12	17	
Center	23, 7, 8, 27, 25, 26, 20, 24 and 11	23	
South	29, 28 and 30	29	

Considering the prices of PMUs, PDCs and communication switches which are 40,000 $, 40,000 $ and 100 $, the total cost of configuring a WAMS in Nordic power system is performed in two cases namely base case (each bus is reached by at least one PMU) and N-1 contingency case (each bus is reached by at least two PMUs). Table 4 shows the financial costs required from the technical point of view to optimally configure WAMS in Nordic power system. The results show that N-1 contingency case needs more fund by 60% than that of the base case due to the presence of 28 devices (PMUs and PDCs) in N-1 contingency case.

Table 3. Total cost of WAMS in base and N-1 contingency cases

Case	Total cost
Base case	722,000 $
N-1 contingency case	1,125,000 $

7. Conclusions

The paper presents two scenarios for optimal configuration of WAMS in the Nordic power system model. The study considered the parts of WAMS and the geographical regions according to boarders in the power system. The results show that in the first scenario 13 PMUs, 4 regional PDCs and 1 national PDC are the optimal configuration of WAMS in the Nordic power system considering that each busbar has to be reached by at least one PMU. The results also show that in the second scenario 23 PMUs, 4 regional PDCs and 1 national PDC are the optimal configuration of WAMS in the Nordic power system considering that each busbar has to be reached by at least two PMUs. The second scenario gives more reliability than the first one but is more expensive by about 56%.

Conflicts of Interest: The authors declare no conflict of interest.

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