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Strategic Development of Wide Area Monitoring On the Main Interconnected System in Oman

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Abstract:
The interconnection of power networks, while being beneficial to the overall stability and efficiency of the system, leads to major challenges for Transmission System Operators (TSO's). These challenges include the apparition of new dynamic behavior, in particular low frequency oscillations, and the need to coordinate among parties to achieve observability and controllability of the system state. In the countries of the Gulf Cooperation Council (GCC) this has become evident after the entry into service of the 400 kV backbone across the Region and with the complete 50Hz networks operating as a single synchronous area. Given its location at the Southern edge, the power system of the Sultanate of Oman experiences inter area oscillations in addition to the dynamic voltage performance and stability concerns due to the large amount of asynchronous motors as in the whole GCC Region. While SCADA/EMS systems remain the main tools for operating the system, their level accuracy and the awareness provided drops under transient dynamic time scales. Synchrophasor-based Wide Area Monitoring Systems (WAMS) provide a solution to increase observability and control of the Oman grid via real time synchronized voltage and current phasors. This paper presents the strategic design of a WAMS in the Main Interconnected Transmission System (MITS) of Oman and presents some keys aspects such as Phasor Measurement Units (PMU) location, WAMS architecture and applications and use for operations and tuning of Power System Stabilizers (PSS).

Key Words: Phasor Measurement Units, Wide Area Monitoring, small-signal stability, Oman.

1. Introduction

Wide Area Monitoring Systems (WAMS) have been an important tool for transmission operators across the world for improving system observability, precise-wise data collection/analysis, post mortem analysis, online/offline stability indicators and system performance [1]. Wide area monitoring relies on Phasor Measurement Units (PMU) which will be synchronised by local substation GPS taking its spatial coherence into account. The PMUs measure with highest timely accuracy voltage and current wave forms as well as phase angles. Other process values, such as active, reactive power or frequency can be measured or preferably calculated.

In the Gulf Cooperation Council (GCC) low frequency oscillations across the whole Region and have been reported and measured by the GCC Interconnection Authority (GCCIA) [2,3]. The Main Interconnected System (MIS) in the North of Oman is owned and operated by Oman Electricity Transmission Company (OETC). The existing MITS has three operating voltages, i.e. 400kV, 220kV and 132kV. Starting from 2014, the transmission system of Dhofar region in the south on Oman is also owned and operated by OETC. The Oman Electricity Transmission Company (OETC) has as a key strategic objective the deployment of a WAMS for managing and operating the Omani transmission network. The WAMS will increase observability, in particular for transient phenomena, and can be used to improve performance of the Oman grid and be a key enabler for future network developments i.e. energy exchange with the rest of the Region and renewable energy sources integration.

This paper presents the rationale behind the WAMS within OETC as well as the strategic plan by 2020. It highlights the need for monitoring, the infrastructure requirements, the preliminary design options as well as the techno-economic justification.

2. Drivers for WAMS at OETC

(a) Existing Oscillations

Due to the longitudinal shape and size of the GCC interconnection, small signal stability has been given a lot of attention. All studies carried out for the interconnection reported a significant involvement of the Oman grid in the dominant inter-area modes of oscillations [2,3]. Inter-area modes typically involve generators in different parts of the system oscillating against each other. In longitudinal systems with weak or long transmission corridors, it often happens that generators are gathered in coherent groups on each side of these transmission corridors. The frequency of the oscillation depends, amongst other factors, on the total inertia (stored energy) of, and the impedance between the oscillating areas [4-7]. The two dominant modes involving Oman in the electromechanical range of frequencies are:

Table 1-Key Oscillatory Modes for Oman

Mode	Frequency (Hz)	Oscillation pattern
1	≈ 0.3	Generators in Oman (OETC, PDO, Dhofar) oscillating against GCCIA
2	≈ 0.45-0.5	Generators in PDO oscillating against generators in OETC & Northern Emirates

The impact of these modes is related to the damping ratio which depends on the intrinsic characteristics of the system as well as the operating point. These modes have been quoted to be sufficiently damped (ξ>5%) in previous studies, when the GCC system was interconnected. OETC has installed temporary PMUs across the Main Interconnected System for the purpose of monitoring the system dynamics for approximately six months. A number of modes were identified during the measurement campaign including the two dominant modes at 0.3Hz and 0.45Hz as shown in Figure 1.

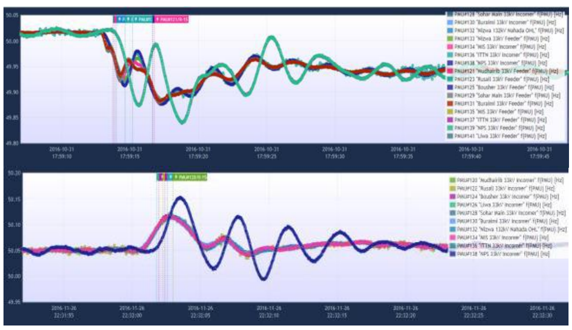

Figure 1-Modes of 0.3 & 0.45 Hz in the Main Interconnected System

In order to identify the optimal PMU locations a number of factors were assessed including the existing fault reordered currently on the OETC system (which have PMU functionality), sites which are close to mode contributing/observing generators and heavily loaded corridors close to demand centres [3].

(b) Load Dynamic & Voltage Performance

Oman Electricity Transmission Company owns and operates the transmission system within Oman; namely the Main Interconnected System and the Dhofar network [8]. Until 2022, the peak demand is expected to increase by 8 GW. This load growth will predominately consist of air conditioning load (A/C) and industrial loads in which both have a significant share of induction motors.

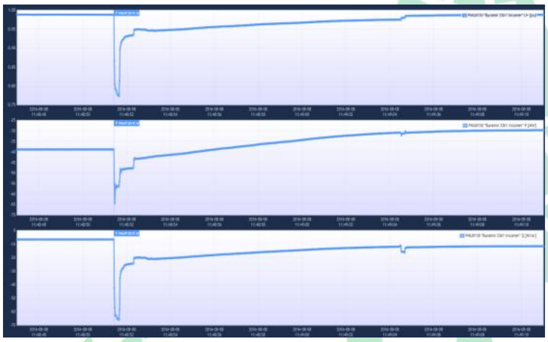

Figure 2-Load Dynamics & Voltage Recovery Performance at Buraimi substation

Therefore, the voltage recovery after a disturbance in the power system could be delayed by load dynamics (especially when margins of fast reactive power resources are insufficient or are located far from the large load centres) [9]. Figure 2 shows the impact of load dynamics on voltage recovery at the Buraimi substation during a disturbance. This event could not be captured via the existing SCADA /EMS. With this incident it can be easily seen that WAMS delivers more detailed and accurate system dynamics benefiting the planning process for ensuring an optimal power system.

(c) Post Mortem Analysis & Constraint Relief

The OETC network is currently reliant on off-line deterministic system studies to identify investment needs and system constraints. This is conducted around two operating points (peak/off-peak) in where only a few opportunities exist to validate the network model against the real system performance. The WAMS would enable network impedances and conductor ratings to be measured accurately and thus improve the quality of the models. WAMS is also a powerful tool for post-event analysis.

Most constraints and power system limits identification (congestions, stability limits, maximum transfer capability) are conducted offline. Having an online tool would provide a better understanding of the limits in a wider number of operating conditions and support measures to improve system resilience if an incident occurs, and allowing operating the system at a lower cost.

3. Existing OETC Assets & Telecommunication

(a) PMU Functionality

PMU need to be compliant with the IEEE standard C37.118, aligned with OETC's standard specification in HV substations, and compatible with the agreed WAMS functionality within the present project. Development and operation of PMUs in power transmission companies brought the progress to implement PMU functionalities into other Intelligent Electronic Devices (IED) of the substations, such as digital fault recorders or protection relays. The IEDs are standardised already due to HV substation requirements using, among others, the transmission protocol IEC 61850.

Taking care for the future WAMS by applying state-of-the-art IED technology OETC used its own substation projects for installing IEDs equipped with PMU functionality.

(b) Communication Links

The implementation of PMUs and WAMS into the telecommunication network will be feasible without additional extensions. A substation node based on STM-4 technology has already been designed by OETC considering redundant 30 x 2 Mbit/s for dedicated use of PMU functionality, protection relays, fault recorders, power and energy meters, power quality meters, CCTV, VoIP and spare capacity. The telecommunication network will be continuously developed by OETC during executing HV projects for substations and transmission lines.

On average, the PMU data traffic for one device can be calculated between 20 and 100 kbit/s and should be negligible compared to the other network activities. Even if the WAMS project would involve 100 PMUs the traffic would raise between 2 and 10 Mbit/s. In addition, the very high time stamp accuracy of the synchrophasor measurement provided by the IED-GPS allows certain time delay in data transmission in case of unexpected very high traffic.

As the WAMS will be used for monitoring only certain latency can be accepted.

(c) WAMS Architecture

Primary benefits of WAMS are the ability (i) to provide in real-time a better awareness of the power system conditions and increasing stress, and (ii) to capture the power system dynamics. These unique capabilities are the result of the synchronisation by GPS and the continuous streaming of PMU data at a rate of several times per second, delivering direct measurements of angles (beside amplitudes) of voltage and current waveforms. Assuming a sufficient geographical coverage and reliable telecommunications, WAMS delivers (a) at a given time, an accurate instantaneous photograph of the system state, and (b) over time, a detailed dynamic pattern. The main system components are shown in Figure 3 as well as the used protocols. In particular, the WAMS will provide OETC with the ability to assess stability from measurements.

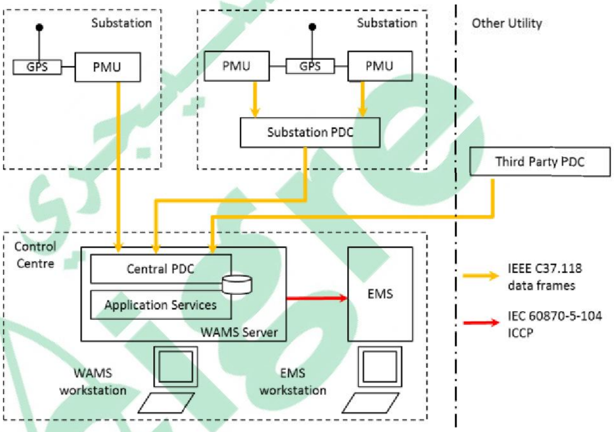

Figure 3-WAMS Interfaces and protocols

To improve reliability in case of server failures a redundant server topology can be used at a slightly higher cost (Figure 4).

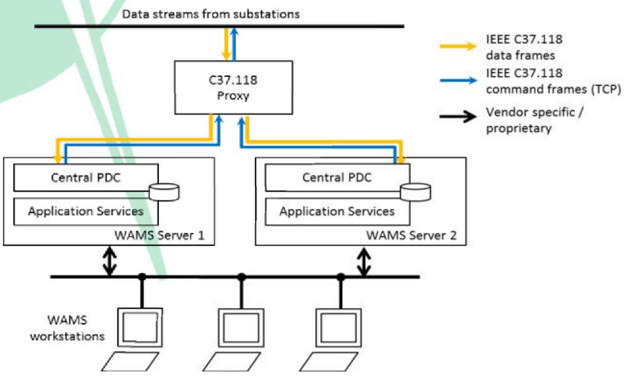

Figure 4- Redundant server architecture

In Figure 4, the C37.118 Proxy provides a C37.118 stream duplication service enabling dual servers to receive identical streams. This is convenient in case there is no duplication of the data streams.

4. Design & Recommendations

(a) PMU Location & Recommendation

Modal analysis has been conducted for Summer Peak and Winter conditions for 2016, 2018 and 2020, using the latest OETC system and GCCIA system models. This accounts for the current state of the network as well as the planned reinforcements. A number of sensitivities have also been conducted to ensure that condition driven modes are identified. The analysis concentrates on poorly damped modes (less than 5% damping) [2]. The course of action for the analysis is as follows:

- Conduct eigenvalue analysis to identify different modes in order to determine their frequency and damping ratio;
- Identify the modes which have less than 5% damping and identify their observability;
- Identify the associated participation factor which relates the mode with the most common state variables.

Figure 5 and Figure 6 show the comparison between all the years for the base case (with the GCCIA system interconnected). It can be concluded that in 2020, most of the modes have a better damping ratio than in 2016 and also than in 2018. This is due to the positive influence of numerous new network elements that lead to better electrical connections between the areas. Still, there are modes that have an insufficient damping ratio (below 5%) in the range of 0.6-0.75 Hz for peak load conditions and 0.5-0.6 Hz for off-peak load conditions. The modes in the range 0.2-0.5 Hz are however well damped in these cases.

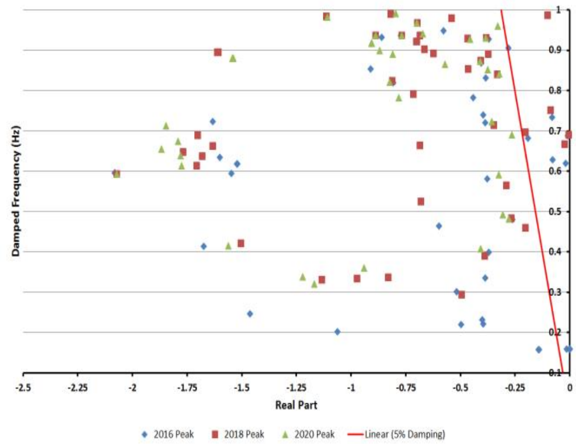

Figure 5 – Peak (Maximum) Overview

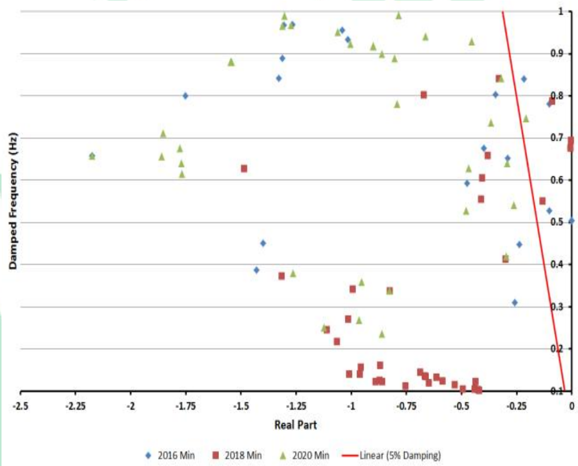

Figure 6 – Off-peak (Minimum) Overview

The proposed recommended sites are shown in Figure 7.

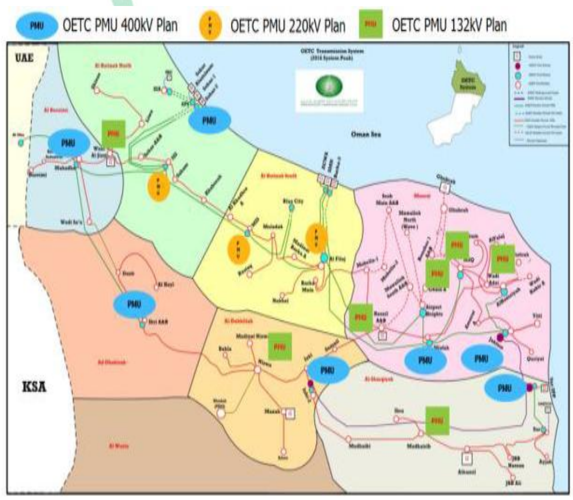

Figure 7 – MIS PMU Optimal Locations

Based on the small signal stability study, it was determined that a number of power plants had the largest participation factors throughout the three years of study. It is recommended to consider tuning the power system stabilisers of these generators. Once the WAMS is deployed, the PMUs will be very useful to support the testing and tuning of the PSS. In addition, the existing power system stabilisers should be tuned for both local and inter-area modes. This is usually carried out based upon a single machine infinite bus case with the corresponding control system for the generator, in where the generator is operating on its maximum leading power factor (as shown in Figure 8) with maximum MW output [10,11]. An example of the tuning is shown in Figure 9 for Sohar.

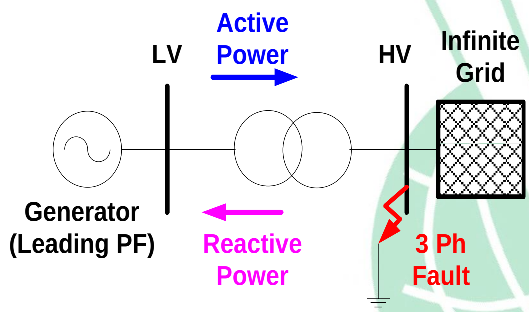

Figure 8 –PSS Tuning Methodology

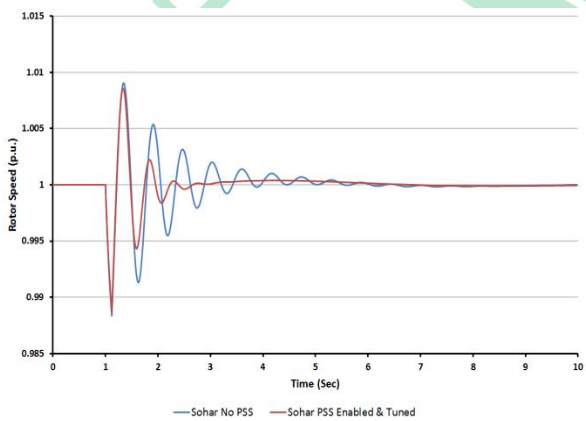

Figure 9 – Impact of PSS Tuning on Sohar Generator

(b) SCADA/EMS Integration

The SCADA/EMS covers the entire OETC power system and connecting points to neighbouring utilities. The data model is already fully developed for transmission lines and substations of different voltage levels. The WAMS will mainly focus on the monitoring of selected transmission corridors and key load centres or supply points. Hence, the WAMS will use a subset of the existing data of the SCADA/EMS and the exchange would benefit in:

- Reducing of efforts for data collection, entering and modelling;
- Presenting of consistent information to the operators and maintenance engineers;
- Data exchange of applications between both systems resulting in advanced grid operation.

The SCADA/EMS production should not be influenced by exchanging CIM/XML files. A separate file server is recommended. Modern state-of-the art SCADA/EMS provide an Application Program Interface to export data of the Energy Management System using IEC 61970. IEC defines a Common Information Model (CIM) independent of any programming language, non-proprietary and focused on standardized representation of power systems in its entirety.

The PMUs deliver to the PDC synchrophasors with an exact time stamp at a rate of 10 to 50 frames per second over IEEE C37.118. To enable the SCADA/EMS to accommodate PMU data, it is necessary to downsample the PMU data to a rate of 1 per second. The most effective solution is for the Phasor Data Concentrator to perform downsampling and deliver selected signals over a compatible protocol to the SCADA/EMS.

(c) Software & Applications

WAMS functionalities are broadly divided into two categories: real-time applications and offline applications. The offline applications are dedicated to system analysts, and are today considered as rather mature and well used by most utilities. Real-time applications, on the other hand, are still under development given that they require more work and practical experience, and their use in the control room requires intensive training and custom processes to be effective. Real-time applications can be also used offline, by replaying historical data. Table 2 shows the maturity of the software application market for WAMS.

Table 2-Applications Maturity

Software Application	Category	Maturity	OETC Key Requirement
Post Event Analysis & Offline Analytics	Offline	High	YES
Model Validation/Load Modelling	Offline	High	Optional
System Condition Monitoring	Real Time	In Use/Developing	YES
System disturbances detection and characterisation	Real Time	High	YES
Low Frequency Oscillations monitoring	Real Time	High	YES
Islanding and re-synchronisation	Real Time	High	YES
Voltage stability monitoring	Real Time	High	YES
Short-circuit capacity estimation	Real Time	In Use/Developing	Optional
Transient stability analysis	Real Time	Developing	Optional
Dynamic line rating / line thermal monitoring	Real Time	In Use/Developing	Optional
Power Quality analysis and reporting	Real Time	Developing	Optional

(d) Phasor Measurement Units

The PMU is the functionality. It can be provided as a stand-alone or as a function within another device, such as a relay or DFR. The PMU functionality must comply with the IEEE Standard for Synchrophasors C37.118.1. The described performance has to be guaranteed by manufacturers (and possibly supported by a formal certification).

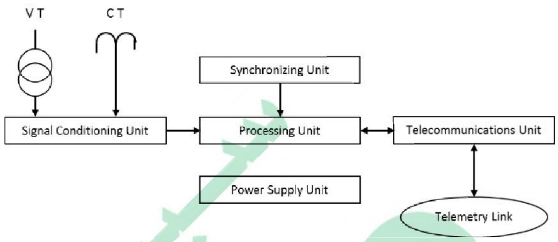

Figure 10: Schematic representation of a PMU

PMU devices deliver a phasor representation out of a filtered waveform over, typically, 2 to 8 cycles. They are therefore of limited value in detecting the fast overload conditions during fault conditions that P (protection) class measurement transformers are designed for, so it is recommended where possible to connect PMUs to M (measurement) class devices. An exception to this rule is where a PMU is performing a secondary function, for example a protection function, in which case it may be necessary to connect to P class transformers instead.

(e) Training & Knowledge Building after deployment

The initial training will be provided by the WAMS software vendor to power system engineers, LDC operators, administrators and maintenance teams. Especially the power system engineers will take over the lead for transfer of technology.

Utilities with an advanced WAMS knowledge develop and run internal trainings as well. They also will disseminate, maintain and improve their knowledge through active participation in forums, conferences and papers on the topic. This can be considered as an example to follow. Table 3 shows the expected time scale of experience building of transmission system operators from the author's experience.

Table 3-Time scale of Experience Building

< 1 year	1 to 3 years	3 to 5 years	> 5 years
Situation Awareness	Improvement in State Estimation	Advanced System Awareness	State Estimation
Small Signal Monitoring	Model Benchmarking	State Estimation	Power System Separation
Post Mortem Analysis	Parameter Estimation	Model Benchmarking	Adaptive Protection
	PS Restoration	Dynamic Parameter Estimation	Real Time Control
	Voltage Stability Monitoring	Advanced Stability monitoring	WA Stabilisation
	Stability Constraint Relief		

(f) Techno-economic methodology

Establishing a business case for WAMS tends to be a difficult exercise, due to quantifying the future constraints on the system as well as evaluating the value of lost load [12]. Many of the benefits associated with WAMS i.e. increased voltage performance, low frequency oscillation management, etc. are extremely difficult to evaluate in monetary terms as it will be function of the location, occurrences, the associated costs for resolving the issue, etc. In general, however, utilities having deployed a WAMS and performed a cost benefit analysis concluded that the estimated benefits exceed the cost of deploying and maintaining the system. Even though there is no unique methodology and some assumptions are necessary, the payback period for a WAMS should not exceed 10 years. In case of acknowledged strong grid congestions this pay off time can be significantly reduced. The process adopted to assess the need case for investment in WAMS is shown in Figure 11.

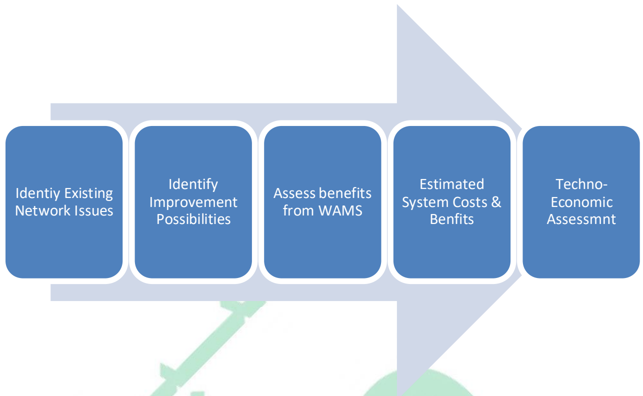

Figure 11-Business Case Process

The WECC procedure for WAMS strategy has been used as a reference for this economic assessment [12]. In OETC's case the main areas of improvement would be oscillations damping control, enhanced voltage performance, post-mortem analysis and constraint relief. In order to quantify some of these elements conservative percentage reduction should be taken for post WAMS instalment in order to obtain the worst case scenario. The annual cost of avoidance as well as penalty factors (for voltage violations, brown- & blackouts) should also be introduced in order to quantify the potential savings. In the case of event reduction/avoidance the following formula maybe used to quantify the savings:

$$Benefit = \left[(No.of\ Events \times Months\,Spent) \times Cost \times hours\right]_{PRE-PMU} - \left[(No.of\ Events \times Months\,Spent) \times Cost \times hours\right]_{POST-PMU}$$

While for voltage violations, the following formula can be used:

$$Benefit = \Delta P \times \%\,of\ customers\ effected \times PenaltyCost$$

WAMS running/maintenance costs may also be determined i.e. annual support fees, cost of staff, additional work load, etc. This should give a fixed operating cost in OMR/yr. Once the annual benefits and operating costs have been determined and the capital cost for the deployment of

WAMS has been estimated, a number of economic indicators can be used to evaluate the investment. This includes payback time, Return on Investment and Discount Cash Flows Rates of Return. In the case of OETC for a central PDC, deployment costs and training, the payback time is approximately four years as shown in Figure 12.ROI of 18% and Discount Rate of Return of is 22%. It should be noted that typical values from European states were used to quantify the benefits of the WAMS.

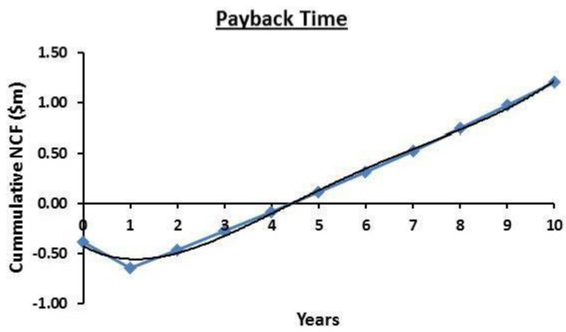

Figure 12-Payback Time of OETC WAMS

Under these values, and the corresponding outcome, an economic benefit of a WAMS system was concluded and supported the deployment of this technology at OETC.

5. Conclusions

The paper presents the rationale behind deploying a wide area monitoring system (WAMS) within OETC. OETC has identified key drivers for the implementation of WAMS on its main interconnected system (MIS) by making use of its existing infrastructure (telecom links and upgraded IED devices) which is compatible with the requirements for the WAMS technology. The paper also presents the design pathways for implementing the WAMS, as well as selecting the PMU locations. Based on the possible benefits that WAMS can provide to OETC a techno-economic assessment has been performed in order to quantify and justify the WAMS system. However, the benefits can only be realised if the ongoing support to the WAMS is upheld within OETC. This is achieved by investing in OETC staff and control room operators to become familiar with the functionality and usage of the WAMS, as they build up awareness about the dynamic behaviour of the MIS and develop valuable experience with the use of WAMS to operate the grid more efficiently.

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