Synchrophasor Network, Laboratory and Software Applications Developed in the STRONg^{2}rid Project

M.S. Almas, M. Baudette, L. Vanfretti, S. Løvlund and J.O. Gjerde

Abstract—**This paper presents the activities carried out in one of the work packages of the Nordic Energy Research funded project Smart Transmission Grid Operation and Control (STRONg^{2}rid). The main objective of the work package is to deploy a state-of-the-art software and hardware for developing power system operation, protection, control and automation applications. Several PMUs have been deployed at partner universities and a network of synchrophasors has been set up. In addition the Smart Transmission System Laboratory (SmarTS-Lab) has been established. This laboratory serves as a test-bench to develop and verify smart transmission grid technologies. A software development kit (S^{3}DK) was developed within the project. The S^{3}DK has been used to implement PMU-based applications and deploy them in different targets, including smart phones and tablets. Several tools and software applications which utilize synchrophasor measurements (from the laboratory or the deployed university PMU network) to perform power system monitoring, sub-synchronous power oscillation detection, etc., have been developed and are presented herein.**

***Index Terms*— Phasor Measurement Units, Phasor Data Concentrator, IEC 61850, Wide Area Monitoring, Protection and Control (WAMPAC), SmarTS-Lab, Synchrophasors, Real-Time Simulation.**

I. Nomenclature

HIL Hardware-in-the-Loop
PMU Phasor Measurement Units
PDC Phasor Data Concentrators
RTS Real-Time Simulation/Simulators

II. Introduction

The increase in electric power demand, the integration of renewable energy, the focus on emission reductions from fossil based power generation plants and the shift towards a more decentralized power system has resulted in a greater need for real-time power system monitoring and control. Phasor Measurement Units (PMUs) are considered as one of the enabling technologies for real-time applications that may allow power system operation closer to its capacity limits while maintaining system security. They are capable to report time synchronized measurements of voltage and current phasors together with frequency at a high rate (50/60/100/120 messages per second). PMUs utilize the IEEE C37.118.2 standard to stream out synchronized phasor measurements. The development and implementation of Wide-Area Monitoring, Protection and Control Systems (WAMPAC) exploiting synchronized phasor measurement data has seen a significant increase in the last few years. In the Nordic region there have been continued efforts for the development of WAMPAC with emphasis on enhanced power system monitoring and control.

In 2011, Nordic Energy Research[1] funded the STRONg^{2}rid project under its Sustainable Energy Systems 2050 program[2]. Several Nordic universities and TSOs collaborated in this project with the objective of developing better tools for operation and control of power grids interconnected across traditional national boundaries and at various voltage levels. The project was divided into different work packages allowing different partner universities and TSOs to work together on different aspects of the project. One of the major work packages within the project is "WP2: Wide Area System Development Platform" which is coordinated by KTH SmarTS Lab and aims at establishing a common platform comprised of real-time simulators, PMUs, PDCs and ICT infrastructure to carry out WAMPAC application research.

This paper focuses on the key achievements in the deployment of the "Wide Area System Development Platform" lead by KTH SmarTS Lab and Statnett SF. The accomplishments to date include the establishment of the Smart Transmission System Laboratory [1] at KTH and the deployment of a PMU network within the partner universities. Furthermore, different tools and applications related to WAMPAC [2] were developed by utilizing a synchrophasor software development kit and deployed PMU network and laboratory.

The remainder of this paper is organized as follows: Section III provides information about the general architecture of the SmarTS-Lab. Section IV presents the architecture of the PMU network deployed within the partner universities. Section V describes the developed WAMPAC applications and tools, while in Section VI, conclusions are drawn.

This work was supported in part by Nordic Energy Research through the STRONg^{2}rid project and by Statnett SF, the Norwegian TSO.

M. S. Almas, M. Baudette and L. Vanfretti are with KTH Royal Institute of Technology, Stockholm, Sweden. (e-mail: {msalmas, Baudette, luigiv}@kth.se)

L. Vanfretti, S. Løvlund and J.O. Gjerde are with Statnett SF, Research and Development, Oslo, Norway (email: {luigi.vanfretti, stig.lovlund, jan.gjerde}@statnett.no

[1] Nordic Energy Research, "Funding institution for energy research under the Nordic Council of Ministers" , online: http://www.nordicenergy.org/

[2] Smart Transmission Grid Operation and Control, "STRONg^{2}rid Project", online: http://www.nordicenergy.org/project/smart-transmission-grid-operation-and-control/

978-1-4799-6415-4/14/$31.00 ©2014 IEEE

III. SMART TRANSMISSION SYSTEM LABORATORY

In order to achieve the objectives of the STRONg^{2}rid project, a Smart Transmission System Laboratory (SmarTS-Lab) was established at KTH. The laboratory is fully equipped with hardware and software systems for developing and analyzing synchrophasor-based software applications. This section gives an update on the implemented architecture reported in [1].

The overall architecture of SmarTS-Lab is shown in Figure 1. The power system is simulated using Opal-RT eMEGAsim Real-Time Simulators (RTS) [3]. The configuration of the RTS allows simulating a fully detailed model of a power system as big as 500 buses at a step size of 50 μsec. The analog voltages and currents of the desired buses can be sent either hardwired or by using IEC 61850-9-2 [4] sampled values to the PMUs and protection relays. For the hardwired approach, the low-level analog signals from the RTS are fed to SMRT-1 amplifiers from Megger [5] to step up the level to 110 V and 1 A which are the standard inputs for the secondary injections of CT and VT modules of protection relays and PMUs. The amplified analog signals from amplifiers are fed to the analog inputs of the PMUs and protection relays. The RTS also provides the facility to send the primary analog measurements as sampled values over the Ethernet. In this case, the RT-Lab library from Opal-RT allows one of the ports of RTS to act as a merging unit and streams out sampled values at 80 samples / cycle complaint to the IEC 61850-9-2 LE standard. In the laboratory setup, two line differential relays [6] together with the RTS implement the process bus.

Once the primary analog measurements are sent to the PMUs and protection relays, the PMUs compute synchrophasors and stream data over Ethernet to Phasor Data Concentrators (PDCs) [7]. The time synchronization signal to the PMUs and protection relays is provided in IRIG-B [8] format from a substation clock [9] which receives GPS signals from the antenna mounted at the roof of the laboratory. The PMUs from SEL are also protection relays [10] which can be used to perform protection functions. The trip signals from these protection relays can be either sent hardwired to the RTS or can be sent as GOOSE messages (IEC 61850-8-1) [11]. All the relays can be configured as backup protections for each other using GOOSE coordination. The complete description of utilizing the laboratory setup for station bus and process bus is presented in [12] and [13] respectively.

In addition, the laboratory is also equipped with stand-alone protection relay test set Freja-300 [14] which can provide secondary injections to protection relays and PMUs to validate the protection settings and synchrophasor computation accuracy. Similarly an IEC 61850-8-1 stand-alone test set GOOSER [15] allows validating the station bus implementation in the laboratory. All this data (GOOSE messages and synchrophasor data) is transmitted over the Ethernet using a managed switch. This provides the flexibility to separate GOOSE traffic from synchrophasor traffic.

Synchrophasor data from all the PMUs is concentrated, time aligned and streamed out as individual streams by a SEL-5073 Phasor Data Concentrator [16]. The laboratory has a functional openPDC installation and a redundant SEL-PDC with local historians to archive PMU data being received by local PMUs in the laboratory, by other partner universities and TSOs involved in the project.

One of the outputs of the PDC stream is sent to SEL 5078-2 Synchrowave Central software [17] for visualization. Several PDC output streams are configured to send to different workstations within the laboratory. The workstations are equipped with Statnett's Synchrophasor Software Development Kit (S^{3}DK) [18] (see Section V.A). This software unwraps the PDC streams and allows raw measurements of phasor, analog and digital quantities available in the PDC streams. S^{3}DK provides these measurements in the Labview environment [19] which makes it convenient to develop real-time PMU-based applications as described in Section V.A.

IV. UNIVERSITY PMU NETWORK

In order to obtain synchronized phasor measurements from the Nordic region, each partner university deployed a PMU at their laboratories along with a local PDC to send and receive synchrophasor streams to other partner universities. The overall architecture of the synchrophasor PMU network is shown in Figure 2. Each partner university sends only its PMU stream to all other partners. The advantage of this architecture over a centralized architecture (with a single PDC receiving PMU streams) is that PDCs installed locally allow data archiving and real-time access for all partners' synchrophasor

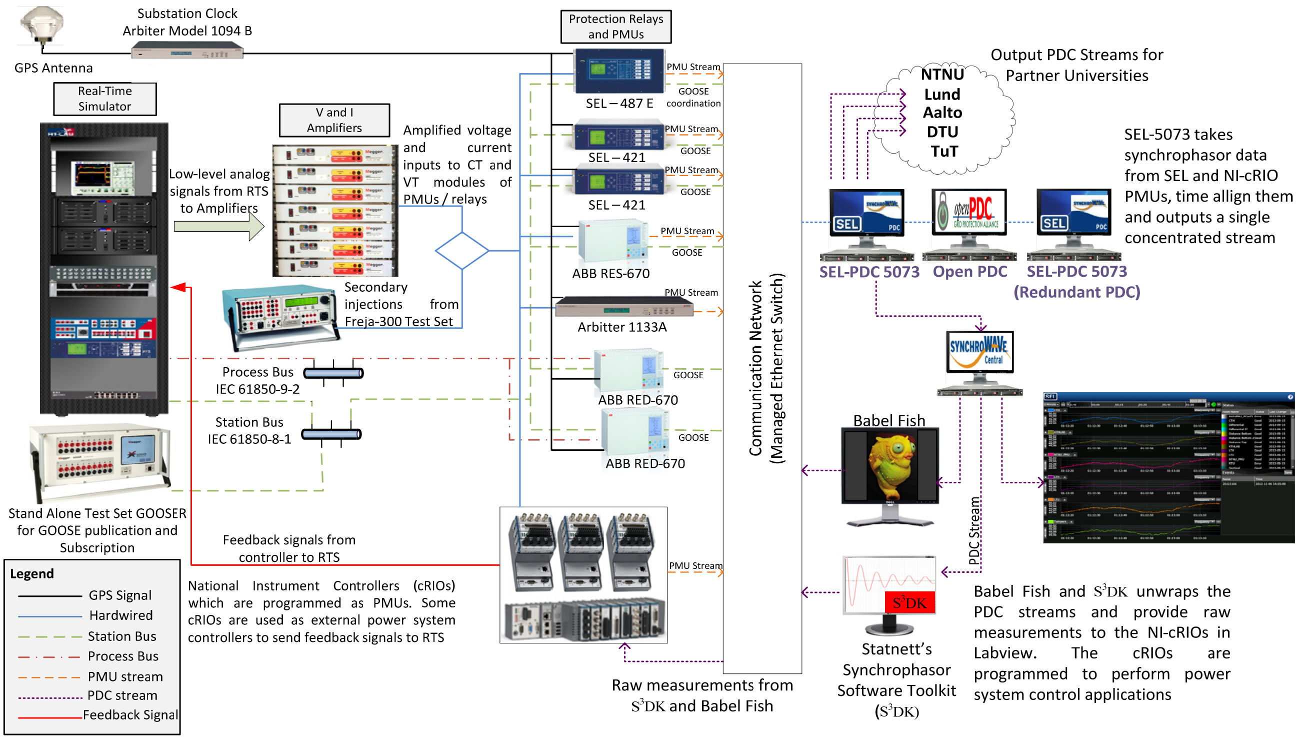

Fig.1: Architecture of SmarTS-Lab showing time synchronization signal distribution, IEC 61850-8-1 station bus and IEC 61850-9-2 process bus implementation, model to data workflow from RTS to synchrophasor application and finally WAMPAC application development using S^{3}DK and NI-cRIOs sending feedback signal to the RTS for real-time hardware-in-the-loop experiments.

data for application development. Also, if there is a malfunctioning of a PDC at any partner university, only that local PMU stream will be affected and all other partners will keep receiving the rest of the PMU streams. All the partner universities opted for PMUs from SEL, ABB or the NI-cRIO. The PDCs were procured from SEL model SEL-5073 [16]. Figure 3 shows the synchrophasor data available through the deployed PMU network.

V. Developed WAMPAC Applications

With the establishment of SmarTS-Lab and, the deployment of the PMU network and distribution of PMU streams among the partner universities, the synchrophasor data was utilized to develop WAMPAC applications. This section summarizes some of the tools developed in this project.

A. Statnett's Synchrophasor Software Development Kit (S^{3}DK) for Real-Time Synchrophasors Applications

The S^{3}DK [18] facilitates researchers to manipulate real-time synchrophasor data in the LabView environment and provides access to raw measurements of all the analog, digital and phasor quantities available in PMU/PDC streams. It also provides a library of functions as graphical blocks for real-time data manipulation. This toolkit allows fast prototyping testing in a real-time environment, and liberates researchers from complex and time-consuming synchrophasor data handling. The toolkit is fully compatible with the IEEE C37.118.2 format which makes it completely vendor independent, and thus can receive any PMU / PDC stream which is outputting data using this protocol.

B. Mode Meter

The developed application utilizes spectral algorithms to identify peaks in the spectrum and identify power system eigenvalues through measurement-driven models [20]. The synchrophasor data from the university PMU network is accessed in the Labview environment using S^{3}DK and then Labview libraries are utilized to incorporate various spectral estimation algorithms. These include (1) Welch's, (2) Auto regressive and (3) Auto Regressive (AR) method with Moving Average (ARMA) methods. The screenshot of the GUI of the developed application is shown in Figure 4. The upper part of the mode meter interface shows the measured signal in a time-moving panel (a frequency signal in this case). The second part shows the change of the spectrum through time, what is referred to as a spectrogram. The bottom right part of the interface shows average spectrum computed using longer data records (up to two hours).

C. Web-based Monitoring Tool

In order to facilitate other partner universities with real-time monitoring display of the synchrophasor data available in the deployed PMU network, a Labview based application was developed. This application allows to monitor the voltage, frequency and status of the PMUs in real-time. The GUI of the developed application was published over the internet using web publishing tools [21] from Labview. The generated web address link was distributed among the partner universities which allowed them to monitor the synchrophasor data in real-time using a standard web browser. The screenshot of the GUI of the developed monitoring tool is shown in Figure 5.

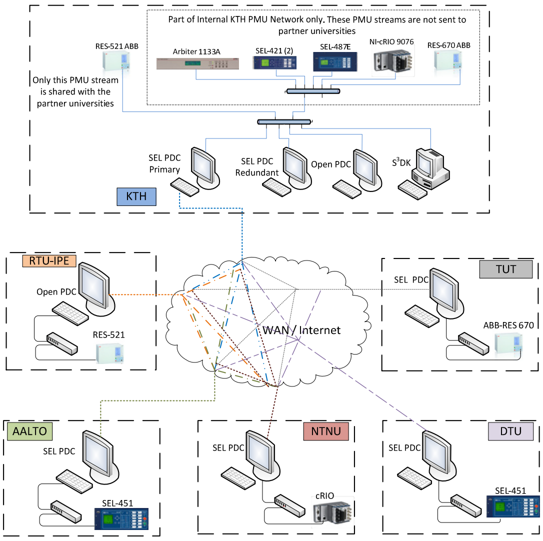

Fig.2: Architecture of university synchrophasor network deployed showing the different PMUs and PDCs installed at each university.

Fig.3: Graphical visualization of synchrophasor data available through university PMU network. The upper half shows the frequency measurements received from the PMUs at KTH (Stockholm, Sweden), LTH (Lund, Sweden), LTU (Luleå, Sweden), Tampere (Finland), AALTO (Helsinki, Finland) and NTNU (Trondheim, Norway). The lower half shows the frequency measurements from the PMU at Riga Technical University (Riga, Latvia), which is not the part of same synchronous power system as Sweden.

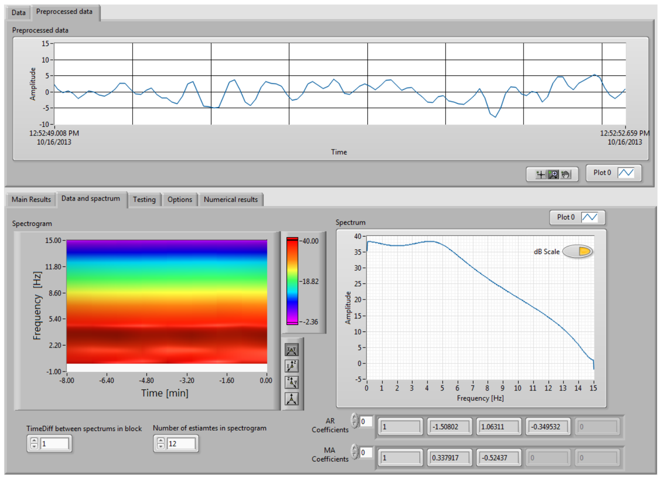

Fig.4: Mode meter application developed in Labview using S^{3}DK

D. *Monitoring Applications for Smart Phones and iPad*

To further facilitate the monitoring of synchrophasor data, applications were developed in Labview for both smart phones (iPhone) and iPad. For this purpose the synchrophasor data was transmitted over TCP/IP as network published shared variables [22]. These shared variables can be accessed from smart phones and iPad using the NI Data Dashboard application. The data flow for this monitoring application is shown in Figure 6. The developed application and its interface for smart phones and tablets allows to monitor the frequency, voltage, current and status of the power system in real-time on mobile devices. Such application is useful to obtain an instant holistic view of the power system. New features such as the activation of alarm for operator's attention in the case when frequency, voltage or current violate limits, email notifications with a screenshot of the monitoring tool, etc. , are being developed within the application.

E. *Wind Farm Oscillation Detection Application*

In power systems with a strong share of wind power, phenomena of fast oscillations have been measured with PMUs, as described in [23]. The detection of such phenomena occurring at frequencies between 5 and 15 Hz is feasible with PMU measurements, which motivated the development of a PMU measurement based detection application. The software has been developed as a real- time application implemented in LabView with the S^{3}DK. It has been successfully tested with HIL simulation, as described in [24] and with hardware emulation in [25].

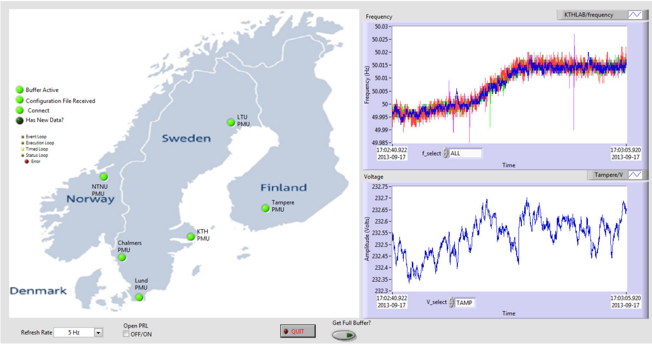

Fig.5: Web-based synchrophasor measurements monitoring tool

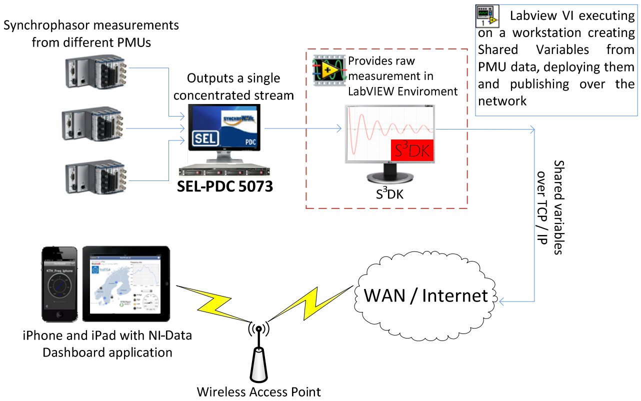

Fig.6: Data flow for iPhone and iPad monitoring tool using S^3DK, network published shared variables in Labview and the NI Data Dashboard for iPhone and iPad

VI. CONCLUSIONS

Results from one of the work packages of the STRONg^{2}rid project financed by Nordic Energy Research have been presented. One of the major achievements within the project is development of a Smart Transmission System Laboratory which serves as a test-bench where new WAMPAC software applications are developed and tested. The laboratory is equipped with real-time simulators, PMUs and other equipment for performing Real-Time Hardware-in-the-Loop (RT-HIL) simulations. IEC 61850 based station and process bus communication between different protection relays and real-time simulator have also been implemented.

A PMU network was deployed within the partner universities with local PDC installations to share the PMU streams with other partners. Several WAMPAC applications and tools exploiting synchrophasor measurements from the deployed PMU network have been developed, and can be utilized by TSOs for efficient and reliable monitoring of the Nordic power system.

The remaining challenge of this work package is to develop a closed-loop PMU-based application for inter-area oscillations control.

REFERENCES

[1] L. Vanfretti et al., “SmarTS lab – a laboratory for developing applications for wampac systems”, IEEE Power and Energy Society, 2012 General Meeting, July 2012.

[2] V. Terzija, G. Valverde, D. Cai, P. Regulski, V. Madani, J. Fitch, S. Skok, M. Begovic, and A. Phadke, “Wide-Area Monitoring, Protection, and Control of Future Electric Power Networks,” Proceedings of the IEEE, vol. 99, no. 1, pp. 80 –93, jan. 2011.

[3] Opal-RT, “eMEGAsim PowerGrid Real-Time Digital Hardware in the Loop Simulator,” available on-line: http://www.opal-rt.com/.

[4] V. Madani, NASPI Tutorial on IEC 61850 Introductions, NASPI 61850-90-5 tutorial workshop Atlanta 2012, Atlanta, GA, USA

[5] “Current and Voltage Amplifiers by Megger,” available on-line: http://www.megger.com/cae/story/Index.php?ID=527.

[6] ABB, “Protection Relays by ABB”, available on-line: http://www.abb.com.

[7] IEEE C37.244-2013 - IEEE Guide for Phasor Data Concentrator Requirements for Power System Protection, Control, and Monitoring.

[8] IRIG Standard 200-04, IRIG serial time code format.

[9] “GPS Substation Clock by Arbiter”, Available online: http://www.arbiter.com/

[10] SEL, “Protection Relays by Schweitzer Engineering Laboratories,” available on-line: http://www.selinc.com/protection/.

[11] IEC Standard, “Communication networks and systems in substations - Part 8-1: Specific Communication Service Mapping (SCSM) - Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3.”

[12] M.S. Almas and L. Vanfretti, “Methodologies for Power Protection Relay Testing-Conventional to RT-HIL Approaches”, IPST 2013, Vacouver, British Columbia, Canada, July 2013

[13] M. S. Almas and L. Vanfretti, “Performance Evaluation of Protection Functions using IEC 61850-9-2 Process Bus through Real-Time Simulation Hardware-In-the-Loop (HIL) Approach”, CIRED 2013, Stockholm, Sweden, June 2013

[14] Megger, “Freja 300 - Relay Test System,” available on-line: http://tinyurl.com/Freja300.

[15] Megger, “GOOSER - IEC 61850 Test System,” available on-line: http://tinyurl.com/goosers.

[16] SEL, “SEL-5073 Phasor Data Concentrator (PDC) Software,” available on-line: https://www.selinc.com/SEL-5073/

[17] SEL, “SEL-5078 Synchrowave Central Software,” available on-line: https://www.selinc.com/SEL-5078-2/

[18] L. Vanfretti, V. H. Aarstrand, M. S. Almas, V. S. Perić and J. O. Gjerde , “A Software Development Toolkit for Real-Time Synchrophasor Applications”, IEEE Powertech 2013, Grenoble, France, June 2013

[19] National Instrument, “Labview-System Design Software”, available online: http://www.ni.com/labview

[20] L. Vanfretti, V. Peric, and J. O. Gjerde, ”Estimation of electromechanical Oscillations in theNordic Grid using Ambient Data Analysis”, IEEE PES General Meeting 2013

[21] National Instrument, “Labview – Web Publishing Tool”, available online: http://www.ni.com/white-paper/2911/en/

[22] National Instrument, “Labview – Shared Variables”, available online: http://www.ni.com/white-paper/4679/en/

[23] A. White and S. Chisholm, “Relays become problem solvers,” Transmission & Distribution world, November 2011.

[24] L. Vanfretti, M. Baudette, I. Al Khatib, M. S. Almas, and J. Gjerde, “Testing and validation of a fast Real-Time oscillation detection PMUBased application for Wind-Farm monitoring,” in First International Black Sea Conference on Communications and Networking, Jul. 2013.

[25] M. Baudette, L. Vanfretti, G. Del-Rosario, A. Ruíz-Alvarez, J.-L. Domínguez-García, I. Al-Khatib, M. S. Almas, I. Cairo, and J. O. Gjerde, “Validating a Real-Time PMU-Based Application for Monitoring of Sub-Synchronous Wind Farm Oscillations.” submitted to ISGT 2014 North America