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Performance evaluation of a virtual power plant communication system providing ancillary services

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ABSTRACT

Virtual power plants are an integral part of advanced power systems providing different ancillary services. This paper presents a case study of an operational virtual power plant communication system providing manual Frequency Restoration Reserve service to the transmission system operator, aggregating two Distributed Energy Resources: a refinery facility with steam turbines and diesel generator sets, and a paper mill plant with an available flexible capacity of 30 MW in total. The study is based on the communication traffic data captured during the virtual power plant live operation over a one-month period with fourteen fully automatic activations. The study analyzes selected communication quality of service parameters—in particular, latency, packet loss, retransmissions, bandwidth, amount of traffic, and message patterns of the IEC 60870-5-104 protocol.

1. Introduction

The importance of power supply flexibility is steadily increasing with the growing number of Distributed Energy Resources (DERs) [1–4]. In order to utilize the full value of DERs, it is crucial to use advanced technologies and tools for pool management and optimization of DERs, such as Virtual Power Plants (VPPs).

VPPs have become an integral part of smart grids, combining a number of small-scale DERs: hydro, wind, and photovoltaic power plants representing renewable energy resources; other Distributed Generation (DG) units; and battery energy storage systems, electrical vehicles, and commercial, industrial, or residential loads [5–7]. Normal VPP operation requires utilization of information and communication technologies for monitoring and control, data transmission, data management, optimization, load forecasting, control, validation, and secure system components [8].

VPPs can be categorized in two ways: commercial VPPs or technical VPPs. Commercial VPPs offer a flexible capacity on the electricity market, while technical VPPs serve Distribution System Operators (DSOs) for local system management [4,9].

The ancillary services include scheduling and re-dispatching, reactive power and voltage control, congestion management, load-frequency control, balancing consumption and generation, imbalance management, etc. [4,7–9]. Commercial VPPs provide the tertiary reserve (manual Frequency Restoration Reserve—mFRR), and in the near future, they will likely deliver more demanding services, such as the secondary reserve (automated Frequency Restoration Reserve—aFRR), by aggregation of suitable DG units [7,10]. In order to achieve these goals, a comprehensive understanding of the latency of the dispatching signals during the activation process is needed.

Recent research into utilizing VPPs for providing ancillary services focuses on different aspects: economic viability [3,11], optimal control and dispatch strategies [6,12], scheduling [4], and communication [5,13–15]. In Ref. [13] the authors proposed architecture and communication requirements for VPPs providing ancillary services utilizing electric vehicles. In Ref. [14] several wired and wireless technologies have been evaluated and field tested for monitoring, control, and other grid services [14]. The communication, information, and functional requirements of VPPs are described in Ref. [5], with an emphasis on the extension of IEC 61850 and Communication Information Model (CIM) standards for interaction between Transmission System Operators (TSOs), VPPs, and DERs. In Ref. [15] the authors presented the impact of non-ideal VPP communication networks on economic dispatch, exposing how

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Nomenclature:

CIM	Common Information Model
DER	Distributed Energy Resource
DG	Distributed Generation
DoS	Denial of Service
DSO	Distribution System Operator
EMS	Electric Management Systems
ENTSO-E	European Network Transmission System Operators for Electricity
FCR	Frequency Containment Reserve
aFRR	automated Frequency Restoration Reserve
mFRR	manual Frequency Restoration Reserve
IP	Internet Protocol
QoS	Quality of Service
RTT	Round-Trip Time
RTU	Remote Terminal Unit
SCADA	Supervisory Control And Data Acquisition system
SDSL	Symmetric Digital Subscriber Line
TCP	Transmission Control Protocol
TSO	Transmission System Operator
VPN	Virtual Private Network
VPP	Virtual Power Plant

communication delays and channel instabilities affect the system's provision of ancillary services.

Communication systems are one of the key elements of the VPP concept [5]. Reliable and secure communications are crucial for a bidirectional, near-real-time information exchange in both a downstream direction, toward different DERs, and an upstream direction, toward electricity retailers, aggregators, TSOs, DSOs, or the electricity market [5,16]. Furthermore, selected communication systems can be an important cost factor that impacts the economic feasibility of VPPs.

Research results in the available literature on a communication system's impact on the performance of VPPs and DERs primarily come from the measurements conducted on test systems [5,14,17] or numerical simulations [18–20]. This paper, in contrast, analyzes communication system performance, utilizing measurements obtained from operational commercial VPPs.

The most frequently employed protocols are IEC 60870-5-104, IEC 61850, Modbus, and OpenADR 2.0 [16,20,21]. The case study presented in this paper describes a VPP in which control and monitoring messages are exchanged using the IEC 60870-5-104 protocol [22]. IEC 60870-5-104 is a TCP/IP-based Supervisory Control And Data Acquisition (SCADA) system protocol providing basic functionalities such as polling, cyclic data transmission, and acquisition of events. This protocol is widely utilized due to its reliability and implementation advantages, yet it still provides sufficient solutions for current VPP operation needs. IEC 61850, in contrast, is a dominant standard for power utility automation. It incorporates information models and provides communication architecture, different data-access methods, and interoperability among various power system components. In comparison with IEC 60870-5-104, IEC 61850-7-420 [23], a substandard of IEC 61850, is more comprehensive, and its implementation inside VPPs is favorable in terms of its operability, standardized interfaces, and ability to make data available to utility SCADA systems and Electric Management Systems (EMS). The IEC 61850-7-420 protocol suite incorporates standardized interfaces between VPP servers, some types of DER units described as logical nodes, and market actors. However, the standard still lacks functionalities for DER aggregation, scheduling inside VPPs, and product prediction [5].

This paper analyzes a VPP communication system providing the mFRR services to TSOs. The analysis focuses on time-critical control messages with detailed information about the latencies of individual components inside VPPs. By analyzing the collected network traffic pattern, we can estimate the bandwidth necessary for normal VPP operation. In this paper we thoroughly investigate the message exchange to have insight into the traffic pattern under normal VPP operation, providing essential knowledge for secured communications. We analyze the characteristics and performance of the IEC 60870-5-104 communication protocol using the data captured over one month of VPP operations.

2. Communication requirements for VPP operation

The communication system must provide sufficient Quality of Service (QoS) to ensure reliable and secure VPP operation [21]. The objective is to minimize the probability of communication failures or issues by monitoring the relevant communication QoS parameters (signal transfer time, latency, packet loss, reliability, and bandwidth) during VPP operation [24]. Various power system and smart grid applications require different QoS requirements [18,25–27]. Bandwidth and latency are critical parameters that must be maintained to ensure an appropriate level of service. However, the necessary bandwidth also depends on the sent packet size and the amount of data exchanged between the VPP and DER units.

Low communication performance may be reflected in a loss of operational data or unreliable DER control. This is especially relevant for providing flexibility for the aFRR ancillary services, having significantly more demanding technical and communication requirements compared to the mFRR ancillary services [10,13,14].

An activation request occurs when a TSO or DSO SCADA system sends a set-point signal with the required capacity value to a VPP system or other generation units to deliver a certain amount of the capacity in order to cope with network unbalances [8]. Activation can be positive or negative regardless of load frequency control action type. A positive activation is triggered when there is an electricity shortage in the grid and additional generation units need to be engaged. In negative activation, some units must reduce generation or increase consumption to stabilize the grid frequency [10].

Since the current European Network Transmission System Operators for Electricity (ENTSO-E) activation rules [28] do not foresee centralized DER activation, the communication requirements for VPP operation must meet the response time defined by the market and TSOs [13]. The system performs its load frequency control as a three-step procedure, including the Frequency Containment Reserve (FCR) or primary control, aFRR, and mFRR. Each frequency control action presented in Fig. 1 has its own technical requirements (response and duration time, cycle time interval for collecting measurements, etc.) [28].

The FCR starts within seconds of an incident occurrence as a joint action of all interconnected parties (TSOs). However, in case of an incident, local units automatically respond to the change in the main network frequency. In the next step, the aFRR replaces the FCR (from thirty seconds up to fifteen minutes after an incident) to minimize the imbalance and restore the frequency to the target value of 50 Hz. The aFRR is followed by the mFRR, activated by responsible TSOs in case of an indicated or expected sustained aFRR activation. Typically, the mFRR is activated manually, but in many cases, the activation is automatic. The required DER activation time to provide the mFRR is typically up to fifteen minutes, depending on the specific requirements of an individual control area. The mFRR can be active from fifteen minutes up to several hours, depending on the market rules and the size of the event or disturbance [28].